ENTSO-E

Technology Factsheets

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About ENTSO-E

ENTSO-E, the European Network of Transmission System Operators for Electricity, represents 42 electricity transmission system operators (TSOs) from 35 countries across Europe. ENTSO-E was established in 2009 and was legally mandated by the EU's Third Legislative Package for the Internal Energy Market, which aims to further liberalise the gas and electricity markets in the EU.

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ENTSO-E

Technology Factsheets

With energy transition underway, we help you to keep up with the new technologies related to the Transmission System Operators. In this report you will find factsheets of different innovative and state-of-the-art technologies covering the fields of transmission system assets, as well as digital and flexibility solutions.

These sheets will help you to understand each technology, their advantages, state of the art in application and research, and also to show their technology readiness level (TRL). The TRL is an indicator of the maturity level of particular technologies and the definition used in this report follows the definition provided in Horizon 2020 Work Programmes. In this way, the TRL indication system provides a common understanding of technology status and addresses the entire innovation chain. There are nine technology readiness levels; TRL 1 being the lowest and TRL 9 the high. For full description of TRL, please refer to Annex G of the General Annexes to the HORIZON 2020 Work Programme 2016/17.

All the factsheets in this report are based on the information provided in ENTSO-E Technopedia. While report is a static document, the world of technologies is changing rapidly. We recommend you always to cross-check with ENTSO-E Technopedia, which is more dynamic tool enabled to provide the up-to-date information.

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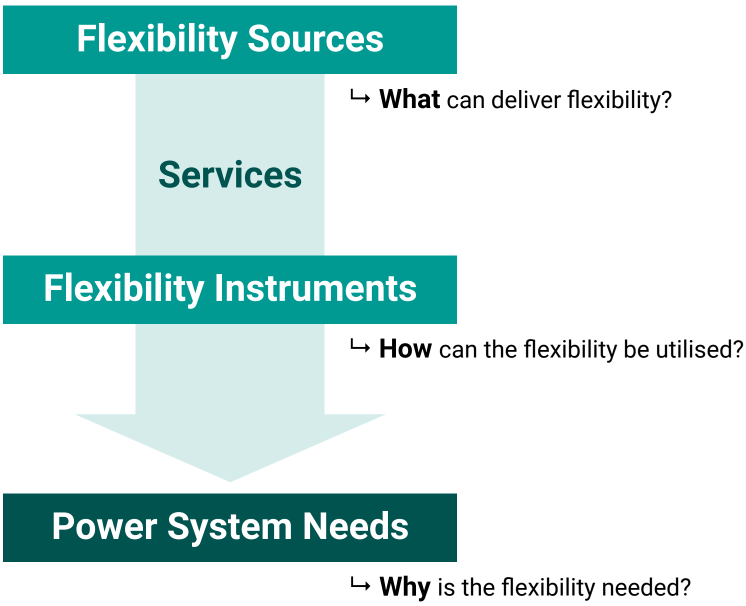
Flexibility

Europe's decarbonisation policies imply the integration of significant shares of variable renewable energy sources (RES) into its power system and, therefore, an increasing need for flexibility. In this chapter, ENTSO-E provides a standardised definition of flexibility and an overview of the main flexibility solutions based on a mapping of relevant R&D&I projects.

A flexibility solution combines **flexibility sources** and **instruments** to solve a need in the **power system** by delivering a **service.**

General framework for power system flexibility

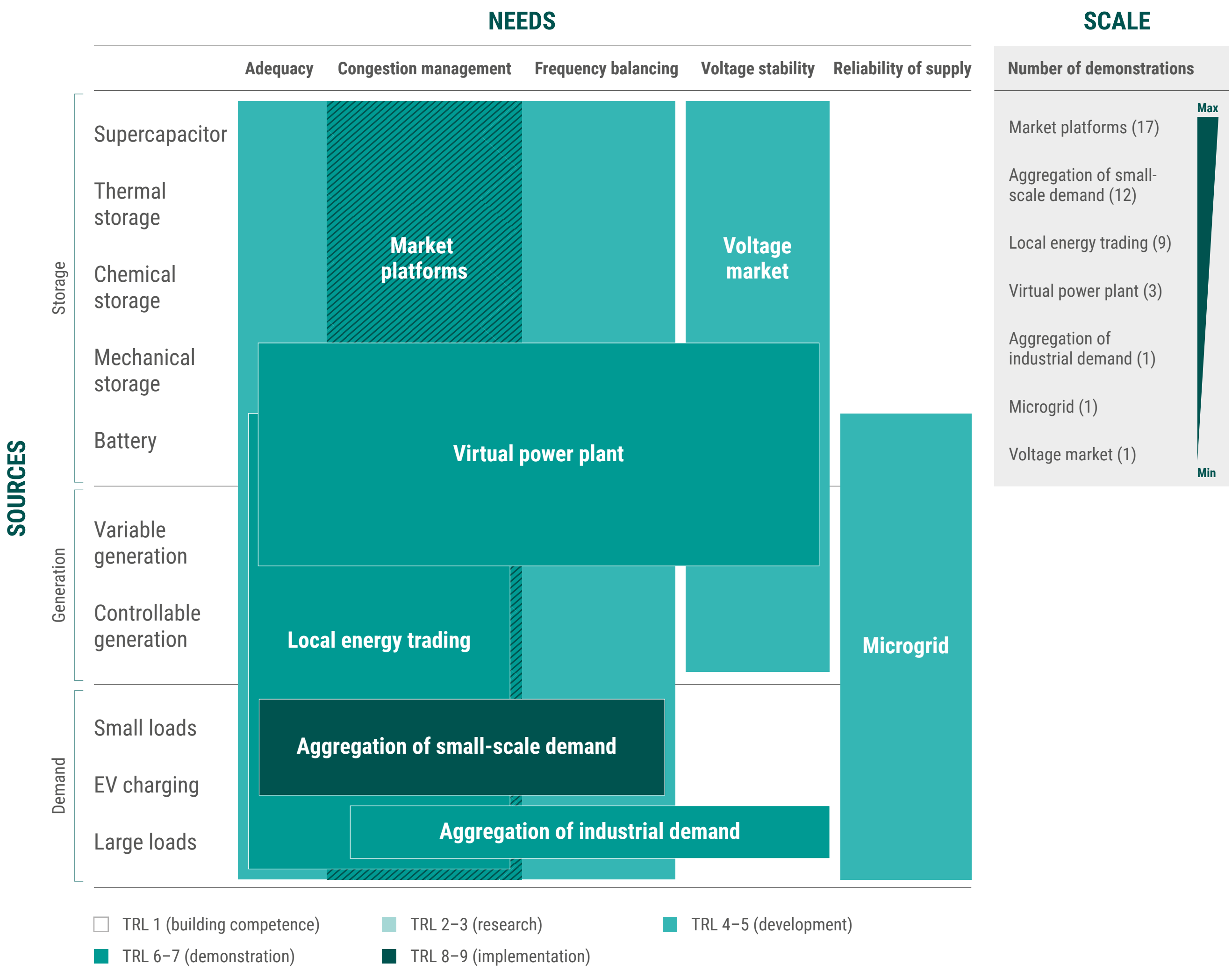


Flexibility can be defined as the ability of the power system to cope with variability and uncertainty in demand, generation and grid capacity, while maintaining a satisfactory level of reliability at all times. Flexibility needs originate from these deviations and range over all time horizons, from short-term (balancing) to long-term (adequacy). Grid operators can translate these needs into the required services for planning and managing their network. Different actors in the power system can procure these services from flexibility sources: TSOs, DSOs and market parties.

Flexibility sources are assets connected either to the distribution or transmission grid which have the ability to modify their generation injection and/or consumption patterns in reaction to an external signal, in order to provide a service. The provision of these services is enabled by flexibility instruments and regulation- or agreement-based instruments, suggesting here a potential research gap.

Based on this framework, ENTSO-E reviewed 66 research projects on flexibility, consisting of 105 demonstrations and use cases*. It clustered them into 24 flexibility solutions and described each in a factsheet. These solutions were then mapped onto the flexibility framework according to their technology readiness level (TRL) and the type of instruments involved: market-based instrument, technical solution or other instrument.

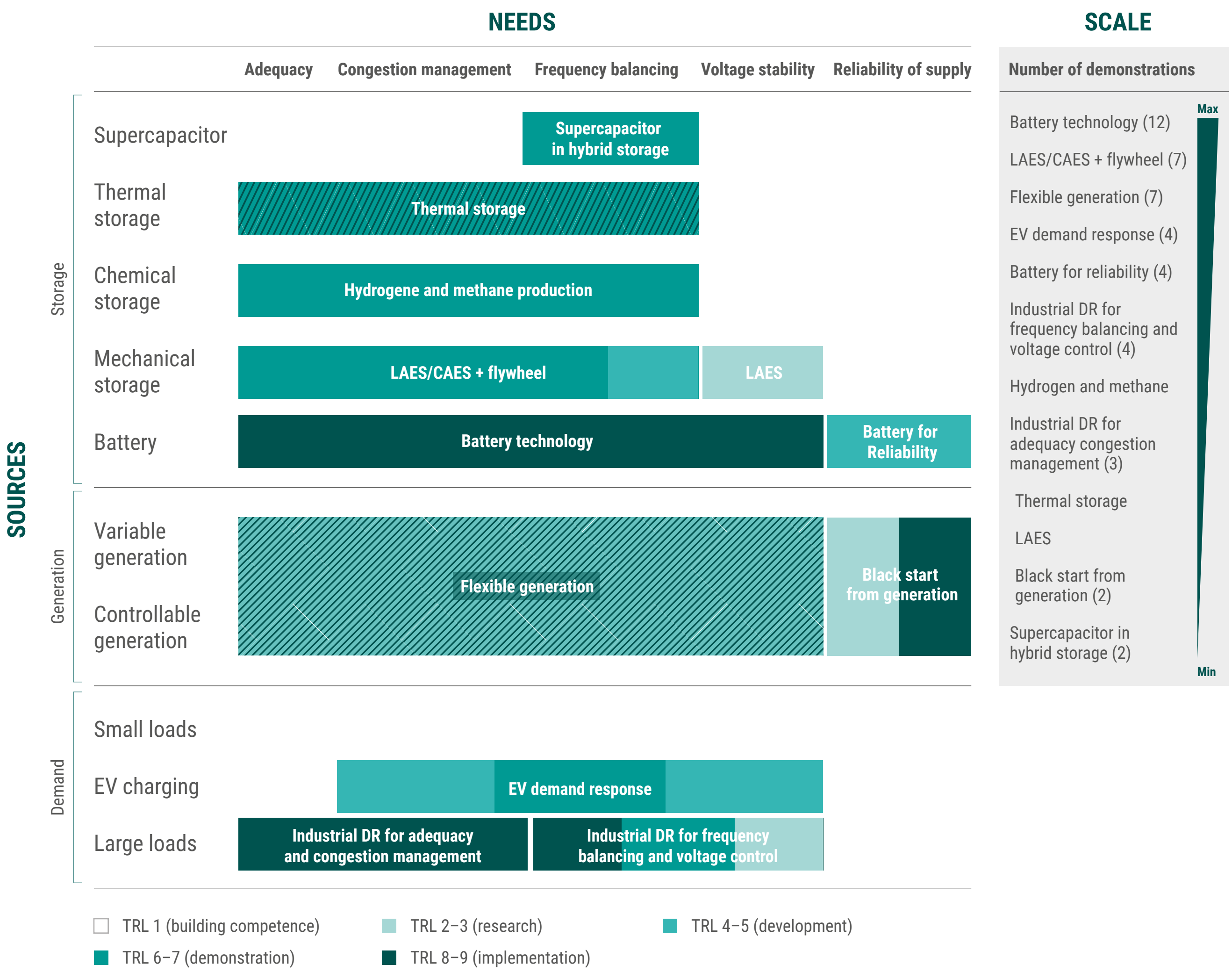
Mapping research on flexibility solutions – Market based instruments



* The list of projects was elaborated from reports by ENTSO-E, ETIP SNET and Horizon 2020 Bridge. Although they contribute to the flexibility of the power system, research on flexible grid technologies was not considered because such technologies are directly controlled by grid operators and usually do not modify generation or consumption patterns.

The mapping reveals dominant research areas such as battery storage for various power system needs, or market platforms for the procurement of balancing and congestion management services from distributed energy resources (DER). However, very few projects on regulation- or agreement-based instruments have been identified, suggesting here a potential research gap.

Mapping research on flexibility solutions – Technical



Industrial Demand Response for Frequency Balancing and Voltage Control

Large-Scale Demand Response › Frequency Balancing and Voltage Stability

Power-intensive industry has large loads and fast response time, and therefore already offer reserves for frequency balancing. Industrial loads can also adjust their active and reactive power consumption and provide voltage control services. Not all power-intensive industry is built to respond at sufficient speeds to offer frequency balancing services, and this solution concerns how industry can adjust its facilities to provide frequency balancing. The solution also addresses the technical requirements for industrial loads to provide voltage control services.

Inertia 2020, New 4.0 and WindNODE are investigating how existing industry can adjust their facilities to provide frequency balancing or improve existing reserves. OSMOSE is preparing a demonstration of how industrial demand can change its reactive and active power consumption to provide voltage control services.

Currently, industrial loads offer frequency balancing according to the products defined in balancing markets. Fast frequency response (FFR) requires a response even faster than any existing product. Until now, there has been no need for FFR as a market product because of the 'natural' inertia in power plants such as hydro and gas. The integration of more renewable resources lacking 'natural' inertia, such as wind and PV, results in a need for fast responses from new sources. A pilot of Statnett's project tested how large loads (hydro's aluminium production) can offer FFR.

Components & Enablers

- Access to balancing and / or voltage or flexibility markets for industrial loads (medium- and large-scale)
- Definition of new products, e.g. FFR and voltage control, in markets

Technical Requirements:

To offer a sufficiently fast response to help with frequency imbalances, the industry must enable its consumption to be changed relatively fast, depending on what kind of frequency reserve it wants to offer. The FFR requires that 100 % of the power offered can be activated within a period of 1 second. To participate in the frequency containment reserve (FCR) market, 50 % of the offered power must be activated within 15 seconds and 100 % within 30 seconds. The above requirement is applicable in the Nordic power system. However, in Central Europe there are different requirements.

State of the Art in Application and Research

In Statnett's pilot project with Hydro, the power offered was 30 MW within 1 second. This reserve, combined with other FFRs, was able to handle a change in frequency of 0.4 Hz. The project was successful and demonstrated the potential for large-scale industry to offer FFR, though there are some limitations to the amount of power available.

The New 4.0 project on flexibility from aluminium production was successfully able to offer FCR. It was able to offer ±25 % of the nominal load in a period of up to 48 hours. The technology developed could be scaled up within 3 – 4 years.

In STORY and TILOS, the battery storage supports the interoperability of the network systems under demand side management aspects.

Technology Readiness Level

TRL 6

FFR: TRL 8 – System complete and qualified

The Nordic project Inertia 2020 led to the implementation of the FFR product in the Nordics from the summer 2020. FFR is procured by all TSOs in the Nordic synchronous area, currently through national procurements.

TRL 9

Existing production: TRL 9 – Implementation

Many of the projects aim to offer more flexibility by decreasing the response time and increasing the capacity, but industry offering frequency reserves is common in existing markets.

TRL 3

Voltage stability: TRL 3 – Research

OSMOSE is currently preparing to demonstrate how industrial demand can change its reactive and active power consumption to provide voltage control services.

Current Focus of R&D and Research Gaps

The ongoing Nordic project Inertia 2020 will further examine the results from the FFR pilot project and establish a common product description for FFR as well as creating acquisition guidelines for FFR capacity. In May 2020, FRR will go into operation.

The CoordiNet Project opens up significant new revenue streams for consumers and generators to provide grid services, particularly on demand-response.

CROSSBOW will propose a framework for the integration of demand side management existing solutions into the regional Transport Net-work. The platform will enable the cooperation between TSOs and DSOs.

In the GOFLEX, at the Valais demo site, at least 10 industrial partners and 200 to 250 residential customers are actively involved. In addition, 10 EV charging stations are installed within the framework of GOFLEX.

REFERENCES

Inertia 2020 – FFR in Statnett with Hydro [Link]

New 4.0 [Link]
- ↳ Pilot: flexibility from heating facilities [Link]
- ↳ Pilot: flexibility from aluminium production [Link]
- ↳ Pilot: flexibility from steel production [Link]

WindNODE – Smart industrial load management in Berlin with load-shifting potential in the energy intensive industry [Link]

OSMOSE WP5 [Link]

CoordiNet [Link]

CROSSBOW [Link]

GOFLEX [Link]

Smarter EMC2 [Link]

STORY [Link]

TILOS [Link]

WiseGRID [Link]

NEBEF [Link]

Industrial Demand Response for Congestion Management and Adequacy

Large-Scale Demand Response › Congestion Management and Adequacy

Power-intensive industry can adjust its consumption of power to the production of power in the grid so that it consumes more in periods of high generation and less in periods of low. The capacity for big load shifting enables industry to be a resource for adequacy. Depending on where the industry is located, it may also offer congestion management. Some facilities currently have an agreement with the TSO whereby the TSO can cut parts of their power supply for a limited time period, typically for compensation. This will certainly help address congestion issues.

Components & Enablers

To consume energy only from renewables, the production manufacturing has to be designed in a such a manner that enables it to be turned on and off relatively fast and without incurring high shutdown/start-up costs.

State of the Art in Application and Research

Flexibility from large loads is not new, but some power-intensive industries in Europe are investigating how they can both produce a green product from renewable generation while simultaneously offering ancillary services to grid companies.

The New 4.0 project covered flexibility from aluminium production. All thee projects' electrolysis plants are in interrupt ability schemes and can be cut out for up to one hour per day by the TSO, providing them with congestion management services.

In STORY and TILOS, the battery storage supports the interoperability of the network systems under demand side management aspects.

Technology Readiness Level

TRL 9

TRL 9 – Implementation

Power-intensive industry already participates in flexibility markets. Projects research how this can be done more (cost-) effectively, and how more flexibility can be offered.

Current Focus of R&D and Research Gaps

Proton exchange membrane (PEM) electrolysis has considerable potential. Research in this area could even further increase the efficiency of hydrogen production.

By setting-up a series of standardised products for grid services at EU level, CoordiNet will define and detail mechanisms for the provision of the needed grid services at distribution and transmission level.

In CROSSBOW, the demand side management concepts extend the Regional Security Center mandatory functions – especially day-ahead adequacy forecast, coordinated security analysis, coordinating capacity calculation, congestion management and outage planning coordination.

REFERENCES

WindNODE [Link]

New 4.0 [Link]
- ↳ Pilot: flexibility from heating facilities [Link]
- ↳ Pilot: flexibility from aluminium production [Link]
- ↳ Pilot: flexibility from steel production [Link]

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WindNODE [Link]

NEBEF [Link]

Enera Markt [Link]

Hydrogen and Methane Production

Chemical Storage › Frequency Balancing, Adequacy and Congestion Management

Electricity can be stored in chemical products such as hydrogen and methane. These production facilities can adjust their consumption of power to imbalances between consumption and production in the power grid, the goal being to produce hydrogen or methane in a sustainable manner. Their electricity consumption is therefore tailored to renewable resources and has to be able to adapt quickly and frequently with a large capacity. The facilities uses this ability to provide frequency balancing, adequacy and, in some cases, congestion management. This type of chemical storage is also a method of storing renewable energy. The hydrogen or methane can participate with balancing the power grid directly by powering a gas plant or indirectly by powering hydrogen cars instead of electric vehicles (EVs).

Components & Enablers

PEM electrolysis to produce hydrogen. Important to enable rapid change in consumption, especially to offer frequency balancing.

State of the Art in Application and Research

Micro gas turbines especially designed for chemicals.

Current Focus of R&D and Research Gaps

Investigating ways to use CO_2 to create, e.g. methanol or methane.

Technology Readiness Level

TRL 7

TRL 7 – Demonstration

The response time and capacity for adjusting the production in the factories is continuously improving. PEM electrolysis has significant potential and research in this area might increase the efficiency of hydrogen production.

TRL 6 – 7

EASE TRL is 6 – 7

REFERENCES

H2Future [Link]
HyBalance [Link]
Underground Sun Storage [Link]
MefCO_2 [Link]
InteGRIDy [Link]
STORE & GO [Link]

Electric Vehicle Demand Response

EV Charging › Agreement/Market › Frequency Balancing, Congestion Management, Voltage Stability

EV chargers, particularly 'super-fast' ones, can pose challenges for congestion management, as well as provide solutions to grid operators. Aggregated demand response from electrical vehicle charging can be used to provide frequency balancing such as FFR. Vehicle-to-home (V2H)/vehicle-to-grid (V2G) technology and the control of EVs can help solve congestions in the grid and may, in the future, provide reactive power for voltage control.

Components & Enablers

- Removal of regulatory barriers
- Aggregator, TSO and DSO access to metering data
- Aggregation
- Availability of good forecasts and consumption data
- Controllability and observability

State of the Art in Application and Research

Currently, Cecovel has only developed tools and a platform for monitoring and forecasting the demand from 1,500 EV chargers. The platform is prepared to send set points (i.e. give orders from TSO to charger to charge or discharge), but regulations prevent this. Therefore, the main contribution at the moment is to aggregate information and improve demand forecasts.

Through Statnett's project, a FFR pilot with aggregated residential EV chargers through the aggregator Tibber was conducted. Access to the reserve was best at night, and Tibber provided a guaranteed reserve of 0.25 MW (from an 80 – 90 EV portfolio). The response time was within 2 seconds, but when disconnection was done through the EVs' own interface (API), only a third of the cars responded as planned[1]. This shows that EVs are capable of delivering fast frequency control (FFR) but that there is still some need for improvement. The aggregator, Tibber, is therefore planning to develop a solution which does not depend on the response time of the car interface. This suggests that offering frequency balancing services from a fleet of EVs is technically viable but still requires some improvements to the interface.

In Smart Net pilot, EVs serve as local storage and active demand to provide local services for the distribution grid (voltage regulation, congestion management) as well as services for the entire system through the connection point to the transmission grids.

In the SMILE projects, there are three demo sites, where the existing EV network will, moreover, be expanded and integrated with the control system via smart charging software.

1 See https://www.statnett.no/contentassets/250c2da4dd564f269ac0679424fdfcfc/evaluering-av-raske-frekvensreserver.pdf, p. 20

Technology Readiness Level

TRL 6

TRL 6 – Demonstration

Statnett pilot validated the ability of a fleet of EVs to provide FFR within 2 seconds. However, there are still certain challenges to resolve regarding the interface.

TRL 5

TRL 5 – Development

INVADE preliminarily tests DC V2G technology to provide congestion management and voltage control services to the DSO. The technology is available for very few EVs and has significant deficiencies, such as communications protocols. AC V2G technology is not yet sufficiently developed. Few results are available.

Current Focus of R&D and Research Gaps

REE is investigating how Cecovel can be used to provide frequency balancing and congestion management from EVs. Cecovel is planning on testing the application of EV charging control through its platform to provide frequency balancing as a market product. The pilots also test the V2G response.

A significant number of pilots in EU projects provides exploitable results on advanced demand-response EV management regarding the V2G and V2H techniques.

REFERENCES

Inertia 2020: FFR pilot
- Pilot results (in Norwegian): [Link]
- Contact info for further questions: Kari Dalen, Statnett, kari.dalen@statnett.no

Conversations with Cecovel/RES Electrica representatives:
- Victor Bermudez Llamusi, vbermudez@ree.es
- Joan Josep Manresa Ballester, jmanresa@ree.es

INVADE
- [Link 1]
- [Link 2]

ELSA [Link]

FlexCoop [Link]

Leafs

InteGRIDy [Link]

MERLON [Link]

MUSE GRIDS [Link]

Smart Net [Link]

SMILE [Link]

UPGRID [Link]

STORY [Link]

WiseGRID [Link]

WindNODE [Link]

Flexible Generation

Variable and Controllable Generation › Adequacy, Congestion Management, Frequency Balancing, Voltage Stability

Controllable power production can contribute to frequency balancing, adequacy and congestion management, but with more variable generation in the grid the need for flexibility increases. The flexibility of conventional and renewable power plants could be increased by combining generation with local storage or using advanced control algorithms.

Liquid Air Energy Storage (LAES) can increase the flexibility of coal power plants or absorb production peaks from RES, reducing the need for curtailment. Thermal energy storage can offer frequency balancing for steam power plants and open- cycle power plants or help with ade-quacy or congestion management for variable generation.

Battery storage can help both conventional generation and wind and solar plants to provide frequency balancing services and voltage control. Algorithms can enable wind and solar to provide synthetic inertia, automatic voltage control and automatic generation curtailment, even without the use of storage systems.

Components & Enablers

- Technical integration of the storage units in the generation plant, especially for thermal energy storage.

Current Focus of R&D and Research Gaps

See State of the Art / TRL.

State of the Art in Application and Research

When wind and solar power plants constitute an increasingly large share of the European energy mix, this also leads to less natural inertia. WP5 of the OSMOSE project develops innovative control algorithms for synthetic inertia provision and automatic voltage control from PV and wind power plants. These algorithms are tested in a real-environment framework, assessing their reliability and effectiveness.

OSMOSE also develops and tests generation in combination with a battery energy storage unit in WP5 of the project, to establish whether it can provide frequency balancing and voltage support services.

EnergyNest's product for thermal storage is already commercially available in the market. LAES is being tested, together with generation in a small pilot in the Kryolens project.

The CROSSBOW project not only explores how a Virtual Storage Plant (VSP) can be used by RES producers to maximise clean energy penetration, but also how a VSP can be used by system operators to increase grid stability.

EASY-RES develop novel control algorithms which will allow the penetration of up to 100 % of RES in the European energy system in a relia-ble and secure manner. Towards to this direction is also oriented WindNODE pilot project.

FARCROSS aims to address this challenge by connecting major stakeholders of the energy value chain and demonstrating integrated hardware and software solutions that will facilitate the 'unlocking' of the resources for the cross-border electricity flows and regional cooperation.

HyBalance is a project that demonstrates the use of hydrogen in energy systems, enabling the storage of cheap renewable electricity from wind turbines.

State of the Art in Application and Research (cont.)

PUMPHEAT develops an integrated, flexibility-oriented Combined Cycle Balance of Plant concept: the PUMP-HEAT Combined Cycle.

REACT's objective is to achieve island energy independency by joining RES and storage, a demand response platform and promote user engagement in a local energy community.

REnnovates transforms outdated houses into intelligent 'zero on the meter' homes, significantly extending the life of such homes and improving energy efficiency to such an extent that a 'zero on the meter' scenario can be realised.

SCO_2-flex defines and simulates future fossil fuel power plants' work-flows and scenarios for advanced and complex flexible demand operations with massive renewable integration in the network.

The SMILE project demonstrates different smart grid technologies on three different islands for the transition towards a clean, affordable and reliable energy system. Through smart grids, peak demand can be reduced and the energy grid can be stabilised. VINPOWER (WP2) is also oriented to smart grid flexibility solutions.

STORY's demos in residential and industrial zones are about showing the added value storage can bring for a flexible, secure and sustainable energy system. Furthermore, REE promotes projects for storage in the Canary Islands.

TILOS provides an optimum, real-environment smart grid control system and copes with the challenge of supporting multiple tasks, including the maximisation of renewable energy system (RES) penetration.

UPDRIG pilots gives real proven solutions to enable active demand and distributed generation flexible integration, through a fully controllable low voltage and medium voltage distribution grid.

WiseGRID focuses on smartening the distribution grid to gain advanced monitoring of the variable generation of virtual power plants and microgrids as active balancing assets with RES and batteries or heat accumulators.

Technology Readiness Level

TRL 4

Synthetic Inertia / Automatic Voltage Control from Wind / PV: TRL 4 – Development

OSMOSE will demonstrate how industrial wind power plants can provide synthetic (virtual) inertia and automatic voltage control.

TRL 9

Generation + Thermal: TRL 9 – Implementation

For thermal storage, the EnergyNest's product is already in the market.

TRL 5

Generation + LAES: TRL 5 – Development

Kryolens only has a small-scale pilot on this topic.

TRL 7

Generation + Battery: TRL 7 – Demonstration

OSMOSE tests a wind power plant in combination with battery storage for synthetic inertia provision and automatic voltage control. Flexitranstore has a similar demonstration on a combined-cycle power plant.

TRL 8

Generation Automatic Curtailment: TRL 8 – Demonstration

NAZA implements area automatons to curtail renewable generation if constraints appear in the area. A nest version of NAZA will implement distributed controls (TRL 4) and a Model Predictive Control algorithm (TRL 6).

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OSMOSE WP5
- ↳ OSMOSE website: [Link]
- ↳ Deliverable D5.1, available from: [Link]

Flexitranstore – demo 7 [Link]
- ↳ EnergyNest (thermal storage)
- ↳ Kryolens (LAES)

RTE, NAZA (New Area Adaptive Automatons), France

CROSSBOW [Link]

EASY-RES [Link]

FARCROSS [Link]

HyBalance [Link]

PUMPHEAT: [Link]

REACT [Link]

REnnovates [Link]

SCO2-flex [Link]

SMILE [Link]

STORY [Link]

UPGRID [Link]

TILOS: [Link]

VINPOWER [Link]

The Smart Grid Battery Storage Project Prottes [Link]

StoreITup-IF [Link]

WindNODE [Link]

WiseGRID [Link]

Energy Storage in the Canary Islands [Link]

Thermal Storage

Thermal Storage ❯ Frequency Balancing, Adequacy and Congestion Management

Thermal storage uses heat to store energy so that when demand peaks, the heat can produce electricity directly by initialising a steam turbine. There are different ways to store this energy. One is to use large-scale volcanic rocks that can contain a large amount of heat. This solution allows the energy to be held for up to one week, and therefore assists with adequacy and sometimes congestion management. Another way is to store heated fluids in insulated tanks. This storage system can respond very quickly, and can provide anything from short term frequency response up to longer cycles over several days. It therefore helps with frequency balancing, adequacy and congestion management. Moreover, district heating and cooling is an energy solution for satisfying urban heat and cooling demand. District energy systems which pipe steam, and hot or cold water, around a district from a central location are being used in a variety of cities worldwide because of their higher energy efficiency, which can significantly reduce the greenhouse gas emissions of cooling and heating.

Components & Enablers

- Highly flexible digital control system platforms for virtual power plants that enable renewable energy to be stored optimally.

Current Focus of R&D and Research Gaps

See State of the Art.

State of the Art in Application and Research

A pilot plant in Hamburg can store 130 MWh for up to one week, and has a goal of reaching over 1 GWh in the near future. The heat storage facility contains approximately 1,000 tons of volcanic rock as an energy storage medium. It is fed with electrical energy converted into hot air by means of a resistance heater and a blower that heats the rock to 750 °C. EnergyNest are looking at a faster storage solution. The thermal storage unit could be used for thermal power plants by directly being integrated into existing steam cycles, effectively providing a steam storage buffer between the boiler and the turbine.

This allows plant operators to run their boiler continuously while boosting or reducing the electric output on demand. Depending on the case, the system reaction time for EnergyNest can be less than 7 seconds. This means it is a solution for providing thermal power plants with the flexibility required to provide primary frequency response. It can be designed to provide a short or long response time, depending on what provides most value in electricity markets. It can also provide both adequacy and congestion management.

In EnergyNest, heat at high temperature is transferred to the thermal storage device using a heat transfer fluid (HTF) inside pipes cast into the thermal storage elements. There is no direct contact between the HTF and storage material, and the thermal elements with steel piping are compatible with common HTFs such as thermal oil, water / steam or compressed gas etc.

Eco-Stock is a heat storage made from refractory ceramics and works by heating the ceramics directly via hot fumes from the chimney.

E2District is a three year European Commission Horizon 2020 Research and Innovation project formally entitled 'Energy Efficient Optimised District Heating and Cooling (DHC)'.

In NETfficient, UC 5, the storage system is thermal and split into a day and a night deposit. The temperature of the Thermal Storage System is regulated by two cooling / heating units.

In PUMPHEAT, WP3, advanced solutions for warm / cold storage are proposed.

The REACT project deploys high-capacity and environmental friendly conventional batteries and power-to-gas solutions, such as innovative heat pumps.

REnnovates proposes a compact energy module installed near a house which includes a heat pump and a hot water boiler; the aim is to significantly extend the life of such homes and improve the energy efficiency to such an extent that a 'zero on the meter' scenario is possible.

In the SENSIBLE demo in Nuremburg, Germany the integration of electrical and thermal storage together with heat pumps, CHP and different energy vectors is done by means of a Building Energy Management System that minimises the building's energy procurement costs.

Based on the results of the preliminary research project 'StoreITup-IF!', polymer-based-PCM storages are constructed and tested in laboratory and operational environment. The storages are expected to be industrially producable and economically viable (< 50 € / kWh)

In the STORY project, system thermal energy storage based on hot water storage tanks is considered. The innovative aspects of the Beneens demo in the STORY project are:

- Efficiency enhancement and active control of ORC through the use of thermal storage.
- State of charge estimation of thermal energy storage with limited sensors.
- Potential optimisation of the thermal grid through double use in intervals.

Furthermore, in Lecale, Northern Ireland, the STORY demonstration unit takes electricity from the grid to drive a compressor for storing compressed air in air storage cylinders. It is the first time such a system has been tested outside of a lab environment. The heat released in this process is recovered and stored in molten salt tanks.

In WiseGRID, the integration of the renewable energy storage systems in the network, such as heat accumulators, is tested. Similar pilots are the Lisboa-Portugal pilot of the InteGRIDy project and the Samsø-Denmark pilot of the SMILE project.

The energy storage projects in the Canary Islands serve as tools for the system operator to guarantee supply, improve system security and optimise the integration of renewable energy in the Canary Islands. The construction of the pumped-storage hydropower station between the Soria and Chira reservoirs, which responds to these objectives, will be an

State of the Art in Application and Research (cont.)

essential element to progress towards the sustainability of the new energy model in the Canary Islands.

A pilot plant in Hamburg can store 130 MWh for up to one week and has a goal of reaching over 1 GWh in the near future. The heat storage facility contains approximately 1,000 tons of volcanic rock as an energy storage medium. It is fed with electrical energy converted into hot air by means of a resistance heater and a blower that heats the rock to 750 °C. EnergyNest are investigating a faster storage solution. The thermal storage unit could be used for thermal power plants by directly being integrated into existing steam cycles, effectively providing a steam storage buffer between the boiler and the turbine. This allows plant operators to run their boiler continuously while boosting or reducing the electric output on demand. Depending on the case, the system reaction time for EnergyNest can be less than 7 seconds. This means it is a solution for providing thermal power plants with the flexibility required to provide primary frequency response.

Technology Readiness Level

TRL 7

Large-scale volcanic rock: TRL 7 – Demonstration

New 4.0 has a pilot plant in Hamburg that can store 130 MWh for up to one week; the next step is to use its storage technology in commercial projects and scale up the storage capacity and power to reach the goal of over 1 GWh in the near future.

TRL 9

Heated fluid in insulated containers: TRL 9 – Implementation

EnergyNest and Eco-stock are already commercial.

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STORY [Link]
WiseGRID [Link]
Energy Storage in the Canary Islands [Link]

LAES/CAES + Flywheel

Mechanical Storage › Frequency Balancing, Congestion Management and Adequacy

Mechanical storage includes storage methods such as compressed air energy storage (CAES), liquid air energy storage (LAES) and flywheel. These solutions can provide frequency balancing by producing electricity with a rapid response time. Flywheels have the most rapid response time and can provide inertia as well as other immediate frequency balancing products. CAES involves compressed air which can be expanded and used to drive a turbine that creates electricity. LAES entails cooling down air until it becomes liquid, which also can expand and be used to drive a turbine that creates electricity. CAES and LAES can provide both frequency balancing, congestion management and adequacy, whereas flywheel is suitable only for frequency balancing.

State of the Art in Application and Research

The projects address different technologies.

CAES:

- Story: A use case where compressed air is stored in containers in combination with tidal energy production.
- ADELE: A project the focus of which is how adiabatic compressed-air energy storage for electrical supply can increase its efficiency and re-sponse time.

LAES:

- CryoHub: Investigates the potential of large-scale LAES at refrigerated warehouses and food factories to use the stored energy for providing both cooling on site and electrical generation during peak demand periods.
- Hybridised LAES: Demonstration facility that uses peak power to liquefy air by cooling it down. The liquid air is then stored in insulated tanks for later use.
- KryoLens: Increase of the TRL of the bulk energy storage technology for LAES

Flywheel:

- Schwungrad Engine – Rhode Hybrid Test Facility: The Schwungrad Engine will develop and perform the operational testing of a flywheel energy storage plant (4 × 150 kW units).
- OSMOSE demonstrates a flywheel as part of a hybrid storage solution to provide synthetic inertia.

There are two CAES plants in operation today, but the efficiency is only 54 %. ADELE aims to improve this to 70 %.

Technology Readiness Level

TRL 7

LAES: TRL 7

Hybridised LAES had a demonstration plant which showed that the plant could provide short term operation reserve. They found that the start-up time needs to increase because fast-reacting short term storage is most important for power plant utilities.

TRL 7

CAES: TRL 7

There are two CAES plants that are in operation today, but the efficiency is only 54 %. ADELE aims to improve this to 70 %.

TRL 9

Flywheel: TRL 9

Schwungrad Engine will develop and perform operational testing of a flywheel energy storage plant (4 × 150 kW units).

Flywheel is a mature technology which is completely introduced in the industrial market. The TRL is therefore 9; however, prototypes such as the Schwungrad Engine aim at improving the technology.

OSMOSE applies flywheel technology as part of a demonstrator (WP4) to optimise flexibility services (synthetic inertia, frequency balancing and congestion management) from a hybrid storage solution which also includes battery storage and supercapacitors.

Current Focus of R&D and Research Gaps

LAES:

The start-up time needs to increase because fast-reacting short term storage is most important for power plant utilities. There is also potential in increasing the efficiency and reducing the costs.

Flywheel:

More research on technology is required for it to be competitive with other energy storage solutions.

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Battery Technology

Battery Storage › Frequency Balancing, Voltage Stability, Congestion Management and Adequacy

This solution consists of utilising the fast and versatile nature of batteries to provide ancillary services to DSO and TSOs. The primary services are frequency balancing, voltage support and congestion management. The battery types addressed in this flexibility solution are medium size batteries and aggregated small domestic batteries. It is also possible to address adequacy by adjusting charging and discharging to peak in an hourly perspective so the demand curve is more stabilised.

Components & Enablers

The following components are required to utilise the flexibility potential of batteries:

- Installed battery banks, either aggregated domestic batteries or larger district batteries.
- Energy consumption/production forecast to predict battery state of charge.
- Algorithm/control system to control and map the available flexibility in the batteries.
- A market solution whereby the user can sell the flexibility the battery provides.
- Change in the current regulatory framework to allow for medium batteries (reduce fees or charging/discharging, reduce minimum power offers in markets, etc.)

State of the Art in Application and Research

Home batteries have recently caught the public's attention, with products such Tesla's Powerwall and similar products from other manufactures. However, the aggregation of these batteries are currently only in the pilot phase. District batteries are not as common, but a number of different pilots are investigating their potential advantages.

Medium-scale battery banks have a large power output compared to their energy capacity relative to other storage technologies. This, combined with their fast reaction time, makes them well suited to provide primary reserve. Simulated primary reserve orders from DSO/TSOs have been tested in the pilot project and, in general, show good results. The ELSA project tested a similar order under actual grid conditions and was able to fulfil the order from the DSO, validating the viability of the solution.

The ability of medium- and small-scale battery banks to deliver secondary and tertiary reserve is limited due to the energy required. However, their fast reaction time enables them to provide 'virtual inertia', where the battery acts as a spinning reserve, reacting to small fluctuations in frequency.

Some pilots have tested the batteries' capability to provide voltage control as they have the ability to control their reactive power consumption. These pilots (ELSA, SENISBLE) have proven that medium-scale banks have the ability to accurately control the phase angle of the energy they provide to the grid.

The technical aspect of the solution is, for the most part, ready. For the solution to mature further, certain economical and legislative barriers must be overcome. New markets have to be established so that the economical potential of ancillary serves offered by batteries can be fully exploited and further development of the existing market rules. Legislative action must be taken to give smaller players get access to this market to realise the full potential of this service. ICT platforms for the optimal control of charging and discharging must be established.

OSMOSE covers how to combine battery storage with flywheel and supercapacitors to provide a combination service of synthetic inertia, frequency balancing and congestion management services in two demonstrators. Furthermore, OSMOSE demonstrates a lithiumion battery connected at high voltage in DC to provide voltage control services.

COORDINET utilises batteries for congestion, voltage and islanding operation problems at the grid.

CROSSBOW's objective is to demonstrate a number of different, though complementary, technologies, offering the regional transmission network higher flexibility and robustness through novel energy storage solutions, both distributed and centralised.

EASY-RES aims to develop methodologies to make the converter-interfaced Distributed Renewable Energy Sources/Battery Energy Storage Systems (DRES/BESS) behave like or even better than controllable synchronous generators (SGs) during dynamic and transient events (WP2).

Flexitranstore's objective is to increase flexibility across the energy industry value chain by integrating BESS, supporting the provision of ancillary services by RES at points such as: the TSO/DSO interface or wind farms and gas turbine plants.

The GIFT project addresses synergies between the electricity, heating, cooling, water and transport networks in the WP5 through storage. Storage for electricity will be provided through batteries and hydrogen, and synergies with the transportation sector will be achieved through the development of V2G solutions (both naval and terrestrial). In addition, there is a synergy between the heating network and the electricity network thanks to innovative energy storage devices that allow heat to be recovered.

The GRIDSOL solution is based on solar firm hybrid power plants. This power plant combines a core of synchronous and non-synchronous generators under a dynamic control system (DOME). The control system of the electricity dispatch is self-regulated and able to provide ancillary grid services because of firm and flexible generation on a single output, tailored to a specific location and relieving pressure on the TSO.

InterFlex investigates the combined implementation of complementary services in dedicated storage assets, with the aim of making the battery a competitive system asset. The combined services cover local grid congestion management,

State of the Art in Application and Research (cont.)

islanding support and customer services such as renewable self-consumption as well as ancillary services.

The overall purpose of NAIDES is to develop a battery technology based on the sodium ion technology for sustainable electrical energy storage (EES) that would result in a radical reduction in cost with respect to the lithium ion technology while ensuring sustainability and performance in terms of safety, cycle life and energy density.

REACT deploys high-capacity and environmental friendly lithium-ion and aluminium-carbon batteries and conventional vented and valve-regulated lead-acid batteries and power-to-gas solutions to form a viable solution that reduces GHG emissions, adapts to energy needs and can be easily replicated across the EU island community.

In SMARTNET, WP2 focuses on the design of market architectures that can foster and leverage the provision of ancillary services by DERs; namely, distributed generation and storage and demand response.

The main objective of TILOS is the development and operation of a prototype battery system based on NaNiCl2 batteries, provided with an optimum, real-environment smart grid control system which can cope with the challenge of supporting multiple tasks. The battery system will support both stand-alone and grid-connected operation, while proving its interoperability with the rest of the micro grid components, such as demand side management aspects and distributed, residential heat storage in the form of domestic hot water. In addition, different operation strategies will be tested to define the optimum system integration.

One of UPGRID's objectives is the participation of customers, distributed generation and energy storage in network management.

Wisegrid aims to optimise the market deployment of storage systems, manage and balance the network optimally, respond better to changes in demand while simultaneously reducing losses in distribution.

Technology Readiness Level

TRL 8

TRL 8

Although battery technology is capable of addressing all the needs mentioned, the projects research how to address barriers to flexible participation in the power system. However, currently it is not profitable. The batteries' efficiency and lifetime are insufficient for this purpose. Regulatory and technical barriers prevent batteries from working together with other components in the power system, such as local generation and demand forecasts. Various pilots and demonstrations address potential solutions to these barriers.

Current Focus of R&D and Research Gaps

There is currently a large amount of research being done in the field of battery technology, with research into improving energy density, price, safety, longevity, etc.

Research directly applicable to this solution is research in to how different battery technologies behave when used for grid operation. Especially regarding how the charge/discharge cycle effects the longevity of the battery and what the self-discharge rate is.

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INVADE [Link]

The Smart Grid Battery Storage Project Prottes [Link]

REnnovates

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SENSIBLE – Nottingham [Link]

CoordiNet [Link]

CROSSBOW [Link]

EASY-RES [Link]

FLEXITRANSTORE [Link]

GIFT [Link]

GRIDSOL [Link]

InterFlex [Link]

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Nobelgrid [Link]

REACT [Link]

SMARTNET [Link]

STORY [Link]

TILOS [Link]

UPGRID [Link]

VINPOWER [Link]

WINDNODE [Link]

WiseGRID [Link]

Supercapacitor in Hybrid Storage

Supercapacitors › Frequency Balancing

This solution describes a supercapacitor which is used in combination with flywheel and battery storage. Combined, the three technologies provide frequency balancing, including both synthetic inertia, frequency control and congestion management. The contribution of supercapacitors is frequency balancing. There is little information available on the details of the demonstrators, which are currently being set up.

Components & Enablers

- Supercapacitor technology

State of the Art in Application and Research

Supercapacitors can provide high power very fast but for a limited time. They are, therefore, useful in providing frequency balancing. OSMOSE develops two demonstrators where supercapacitors are included (WP3 and WP4).

The supercapacitors are part of a hybrid storage solution. The demonstrators cover the optimisation of supercapacitors, flywheel and battery storage in combination to provide frequency balancing (incl. synthetic inertia) and congestion management services.

Current Focus of R&D and Research Gaps

See State of the Art.

Technology Readiness Level

TRL 9

Supercapacitor Technology: TRL 9 – Implementation

Supercapacitors are available and in use for commercial and grid application.

TRL 6

Hybrid Storage: TRL 6 – Demonstration

OSMOSE develops two demonstrators where supercapacitors are included (WP3 and WP4). The supercapacitors are part of a hybrid storage solution. The demonstrators cover the optimisation of supercapacitors, flywheel and battery storage in combination to provide frequency balancing (incl. synthetic inertia) and congestion management services.

REFERENCES

OSMOSE WP3 + WP4
↳ OSMOSE website: [Link]

Email exchange with project coordinator, see note file

Battery for Reliability of Supply

Battery Storage › Reliability of Supply

To avoid blackouts or to enable a black start, it is useful for the power grid that parts of it can be disconnected, so-called 'islanding'. A battery makes this possible because it can both store energy so that the generation can meet the demand and offer the services which the system needs to run separately from the rest of the power grid. These batteries can, for instance, be used in microgrids (see microgrid solution).

Components & Enablers

- A battery system based on NaNiCl2 batteries, provided with an optimum, smart grid control system and able to cope with the challenge of supporting multiple tasks

State of the Art in Application and Research

In TILOS, the battery system proposed supports both stand-alone and grid-connected operation, while proving its inter-operability with the rest of micro grid components. Different operation strategies are investigated to define the optimum system integration.

In OSMOSE, a storage operator plans to install batteries to provide balancing services. By locating their solution in a network-constrained area, they could simultaneously contribute to the management of congestion and thereby reduce the cost to society.

A CROSSBOW Hybrid RES Dispatchable Unit (RES-DU) integrates non-dispatchable and dispatchable RES along with energy storage units under an advanced control system, leading to a more secure, stable and cleaner electricity supply. In addition, CROSSBOW proposes a Regional Storage Coordination Centre to provide real-time supervision and control, incident management, seamless interaction with system operators and the optimisation of installations. Furthermore, the CROSSBOW Virtual Storage Plant is a platform capable of integrating the characteristics and limitations of distributed individual storage units while maximising their performance and reducing the additional costs.

In EASY-RES, Fast Storage Systems (FSS) are placed and controlled at the DC bus of each converter-interfaced Distributed RES, enabling the provision of adaptable and controllable inertia independent of the Distributed RES operating status. This enables the real-time values of inertia to be adjustable according to the optimisation criteria set following bilateral communication and agreement between the TSO and DSO.

FlexCoop optimises self-consumption by leveraging cost-effective storage solutions.

In MUSE GRIDS, the battery is added to test the combination of centralised and decentralised flexibility and the effective communication and order of operation in the event of a blackout.

NAIADES's mission in this project is to develop a battery technology for sustainable EES that would result in a radical decrease in cost while ensuring sustainability and performance in terms of safety, cycle life and energy density.

The project NETfficient demonstrates and deploys local storage technologies in a real electrical grid on Borkum Island and develops ICT tools to exploit the synergies between them, the smart grid and the citizens.

State of the Art in Application and Research (cont.)

During the SMILE Madeira pilot, one of the aims is, therefore, to evaluate how BESS can be integrated in Madeira island. In addition, in the Samsø pilot, the energy demand in the marina is very inconsistent as it is dominated by the demand from berthed yachts and associated tourism. This results in significant fluctuations of demand on a daily basis. To solve this, the project will seek to implement an integrated energy system at the marina comprising renewable generation (PV and wind) linked to storage (battery and thermal).

In STORENET, the International Energy Research Center is working with Electric Ireland to test solar panels and battery storage units in Ballyferriter.

STORY wants to demonstrate and evaluate innovative approaches for energy storage systems. The challenge is to find solutions, which are affordable, secure and ensure an increased percentage of self-supply. The project consists of eight different demonstration cases each with different local / small-scale storage concepts and technologies, covering industrial and residential environments.

The advantage of the battery used in the Battery storage project at the Prottes windpark lies in its capabilities in the millisecond range, making it possible to stabilise network frequency and offset voltage fluctuations.

In WindNODE, the technical integration of the charging infrastructure of battery-powered utility vehicles is demonstrated first in the city of Berlin, and subsequently in the project at up to ten other locations.

Also in the scope of this project, BVG Systems is developing grid-compatible and system-conductive charging of EV fleets and testing them in practice.

The WiseGRID project gives real, proven solutions for microgrids-smart grids as active balancing assets with RES and batteries.

The Suvilahti district of the Helsinki electricity storage facility is best for compensating for brief peaks and dips in output which need rapid reaction. In addition, the electricity storage facility is a multipurpose tool for the smart grid of the future.

Technology Readiness Level

TRL 5

TRL 5 – Development

TILOS has tested a stand-alone operation, but results from this demo were not found. EMPOWER applied batteries in their microgrid but did not specifically research battery technology.

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Battery storage project at the Prottes [Link]
UPGRID [Link]
VINPOWER [Link]
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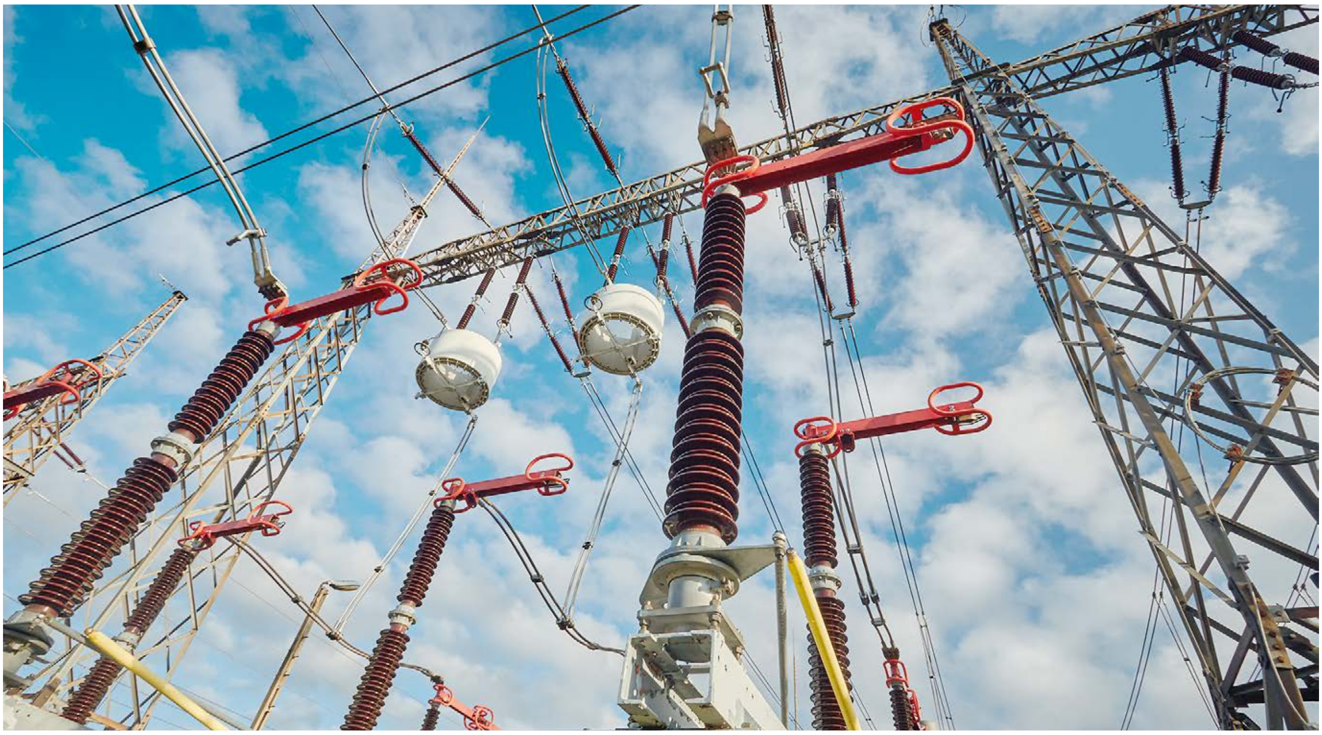
Storage in the Canary Islands (REE) [Link]
Suvilahti BES (Finland) [Link]

Black Start from Generation (Distributed Energy Resources)

Controllable and Variable Generation › Reliability of Supply

The large growth in DER presents an opportunity to develop a new approach to black-start; however, there are significant technical, organisational and commercial challenges to address.



Components & Enablers

Enablers / requirements

- A minimum load is required when islanding for generators to start safely
  - ↳ A load bank can provide this in incremental steps
- the anchor generator will be required to provide frequency and voltage control, which must be installed / enabled
- a minimum fault level is required for converter connected generation (e.g. wind) to connect. This may not be available when operated as an island; in this case, manufacturers would have to look for alternative means

Main issues identified for islands

- low fault level
- low system inertia
- voltage control at LV (typically provided by grid transformers)
- high variability of load and generation

State of the Art in Application and Research

Distributed ReStart explores how DER in Great Britain can be used to restore power in the highly unlikely event of a total or partial blackout of the National Electricity Transmission System.

Participants

- natural gas turbines
- biomass generators
- embedded hydro-power stations
- wind turbines
- solar panels

Methods

1. Restarting an electricity system from a DER, or combination of DERs, from a blackout (without external power supply).
2. Maintaining energisation of the newly-created distribution Power Island of aggregated DER and blocks of demand.
3. Expanding and synchronising with other Power Islands, energising further generation and establishing a skeleton transmission network

EASY-RES preserves the long-term grid security, even under very large DRES penetration, by reducing reserve requirements after fault recovery. This is accomplished by introducing fault-ride-through (FRT) capability and coordinated contribution to fault current for each Distributed RES type, in a similar manner to the conventional SGs. Each Distributed RES will contribute to fault currents according to its rated power and relative location to the fault. The aim is to preserve the current level of fault clearing coordination with the existing protection means even under increasing Distributed RES penetration.

A main objective of FLEXITRASTRORE is to increase the flexibility of conventional generators by installing novel power system stabilisers, restoring low rotational system inertia and simulating grid behavior after major events on a representative grid model, which will allow better insight into grid dynamics and stability.

A number of projects (STORY, TILOS, The Smart Grid Battery Storage Project Prottes, WiseGRID) are focusing on the storage challenges of black start on generation.

Technology Readiness Level

TRL 3

TRL 3

It is envisaged that the Distributed ReStart project will demonstrate a world first – coordinating bottom up from distribution networks to transmission level to provide a safe and effective Black Start service. The project is currently at the initial phase, with key concepts having been developed.

TRL 4 – 8

Technology: TRL 4 – 8 – Research, Development, Demonstration and Implementation

Distributed ReStart focuses on technology that has already reached TRL 4 – 8 for providing black start services.

TRL 7

Battery + Generation: TRL 7 – Demonstration

Flexitranstore demonstrates how a new, large-scale battery energy storage system connected to conventional generation can help provide black-start.

Current Focus of R&D and Research Gaps

Distributed ReStart is currently in its early phase, but is researching both technical feasibility and the coordination between TSO / DSO / other agents in the event the solution is necessary, as well as the regulatory framework.

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Distributed ReStart [Link 1] [Link 2] [Link 3]

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EASY-RES [Link]

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VINPOWER [Link]

Aggregation of Small-Scale Demand

Small loads and EV charging › Market › Congestion Management, Adequacy & Frequency Balancing

Aggregation of small-scale demand is necessary in the present power systems for small loads to be able to participate in wholesale and balancing markets and also in self-balancing and own portfolio optimisation. This solution covers how aggregated small-scale demand and EVs during charging can contribute to frequency balancing, congestion management and adequacy, from two perspectives. First, TSOs are defining the products that small-scale demand can deliver to markets; second, aggregators are defining a business case and technical solutions for the aggregation of small-scale demand. Aggregators can be either independent service providers or an electricity supplier. DSOs can be added as the small-scale loads are connected to the DSO network.

Components & Enablers

- Regulatory: clear role defined for aggregators
- Access for small-scale demand to wholesale and balancing markets, and new flexibility markets
- Smart home technology
- Access to metering data for aggregators

State of the Art in Application and Research

Aggregator projects assess the optimisation of strategies, IT technologies and portfolios. Smart-home appliances and cost-effective storage are typically included to increase demand-side flexibility. Currently, aggregated demand has limited opportunities to participate in markets. TSO projects therefore examine how to continue to develop existing balancing and wholesale markets to enable aggregated small-scale demand to participate. This can include the development of new products in the markets, lowered barriers of entry and revised pre-qualification mechanisms and criteria.

FlexCoop addresses how ICT platforms and solutions can be developed for cooperative aggregators. The model covered by the project can offer services to the DSO, TSO and wholesale market. The algorithm of the project aims to accurately forecast demand flexibility, monitor events and optimise aggregator-operated microgrids and portfolios. The prosumers gain an increased awareness of their own consumption patterns and are provided with a framework for optimised demand response and self-consumption, and access to open IT infrastructures. Pilots are being conducted in Heeten, the Netherlands, and Catalonia, Spain.

BestRES found that aggregated small-scale demand, particularly through automation, is a feasible business model and is ready to be implemented. Market design, however, still provides barriers to many otherwise profitable business models.

In France, the RTE project NEBEF researched the participation of demand response in day-ahead, intraday and balancing markets. TenneT has projects covering facilitating small-scale assets for balancing markets in the Netherlands (both FCR and automatic frequency restoration reserve [aFRR]) as well as congestion management in Germany. Terna has researched small-scale resources for frequency balancing and congestion management. The aims of the TSO projects include improving competition and technology neutrality, the

State of the Art in Application and Research (cont.)

participation of all types of assets, reduced procurement costs for TSOs, and the facilitation of aggregator participation.

In Ireland, the Power Off & Save project tested whether aggregated demand from residential consumers could contribute to dealing with congestions in the grid. Residential consumers had a notification sent to their phone by their electricity supplier when there was conges-tion in the grid and were awarded with a reduction in their electricity bill if they responded. The 1,400 customers contributed to a total reduction in peak demand of up to 560 kW, which illustrates that aggregated demand can contribute.

The Norwegian Inertia 2020 pilots tested and validated that EV aggregators are capable of providing frequency balancing services from a portfolio of EVs.

The CoordiNet project will help to demonstrate how DSOs and TSOs will act in a coordinated manner and use the same pool of resources to procure grid services in the most reliable and efficient way.

GIFT integrates a Flexibility Market system, which allows DSOs and balancing responsible parties (BRPs) competing for the localised aggre-gated flexibility, offered by Aggregators for a number of congestions points.

MERLON introduces an integrated modular local energy management framework for the holistic operational optimisation of local energy systems in the presence of high shares of volatile distributed RES.

MUSE GRIDS project aims to demonstrate, system-wide and in real-life operational conditions, a set of both technological and non-technological solutions adapted to local circumstances, targeting local urban energy grids to enable the maximisation of affordable local energy independency thanks to optimised management of the production via end

State of the Art in Application and Research (cont.)

users' centred control strategies, smart grid functionalities, storage and energy system integration.

NETfficient has deployed and demonstrated local energy storage technologies and developed smart technologies to exploit the synergies between energy storage, the smart grid and the citizens. Such tools include an energy management system which allows the integration of renewable energy generation, forecasting and storage into a smart grid.

REACT's objective is to achieve island energy independency by joining RES and storage, a demand response platform and promoting user engagement in a local energy community.

The SmartNet project aims to provide optimised instruments and modalities to improve the coordination between the grid operators at the national and local level (respectively the TSOs and DSOs) and the exchange of information for the monitoring and acquisition of ancillary services.

In the STORY project, the aim of case studies 1 and 2 is to demonstrate the synergy of a neighbourhood strategy for flexibility and grid balancing. This demonstration contributes to highlighting the value of storage for the end user, the distribution grid operator, the energy provider and a potential third party aggregating the flexibility.

UPGRID develops and validates solutions to enable the implementation of advanced functionalities over existing technology, to form a truly integrated intelligent system.

WiseGRID integrates, demonstrates and validates advanced ICT services and systems in the energy distribution grid to provide secure, sustainable and flexible smart grids and further empower the European energy consumer.

Technology Readiness Level

TRL 8

TRL 8 – Implementation

Aggregator business models have been developed, and aggregators are ready to participate commercially in the relevant markets. See BestRES and FlexCoop.

TRL 6

TRL 6 – Demonstration

A range of pilots have been conducted for participation in balancing and wholesale markets. See TSO projects, incl. Inertia 2020

Current Focus of R&D and Research Gaps

See State of the Art.

A main challenge of aggregated small-scale demand is its distributed nature. An aggregator would have to know the location of available flexibility, if activated flexibility is to contribute to congestion management or at least which congestions are prevented from occurring in the grid when e.g. frequency reserves are activated.

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TSO projects: ENTSO-E TSO/DSO mapping (2018)
- ↳ Terna ancillary services pilots
- ↳ SmartNet Denmark
- ↳ TenneT: aFRR, FCR, congestion management
- ↳ NEBEF

EU-SysFlex WP8

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MERLON [Link]

MUSE-GRIDS [Link]

NETfficient [Link]

REACT [Link]

SmartNet [Link]

STORY [Link]

UPGRID [Link]

WindNode [Link]

WiseGRID [Link]

Realvalue

STORENET

Aggregation of Industrial Demand

Large Loads ❯ Market ❯ Frequency Balancing, Congestion Management, Voltage Control

The aggregation of industrial demand can increase participation in balancing and flexibility markets from large loads. This solution covers both proposals for new regulation for aggregators of industrial demand, criteria for market products and testing of the reliability of this type of flexibility solution. The solution also includes economic analysis and the development of an IT-based aggregator platform.

Components & Enablers

- Market access for aggregators
- Clearly defined role for aggregators
- IT-based aggregator platform

Technology Readiness Level

TRL 8

TRL 8

OSMOSE (WP5) is preparing for a demonstration on aggregated industrial demand in Italy.

State of the Art in Application and Research

aFRR provision will be tested in accordance with the existing grid code in the OSMOSE project.

Congestion management technical requirements:

- Every unit must be located in the same aggregation perimeter, defined by the TSO
- A whole 'virtual unit' must be able to increase or decrease its power consumption by at least 1 MW and maintain it for 120 minutes

REFERENCES

OSMOSE WP5
↳ Deliverable D5.1, available from: [Link]

Email exchange with project coordinator, see note file: [Link]

Horizon 2020 project. STORY – Added value of STORage in distribution sYstems. Grant agreement ID: 646426. [Link 1] [Link 2]

Windnode [Link]

Virtual Power Plants

Battery & Mechanical Storage, Variable Generation › Market › Adequacy, Frequency Balancing, Congestion Management, Voltage Control

The aggregation of distributed renewable energy generation and batteries enables their participation in balancing, wholesale or flexibility markets. Furthermore, aggregation services provide prosumers and small generators with the necessary technology and control, and the aggregator acts as a responsible party in the power and flexibility markets. This means that small-scale flexibility resources which could otherwise not have participated can offer their flexibility to TSOs and DSOs. Projects cover ICT tools, definition of products to be offered and business models for the aggregation of small-scale renewables.

Components & Enablers

- Controllability and observability of the technical devices
- Regulatory: Clearly defined role for virtual power plants
- ICT platforms

State of the Art in Application and Research

Large-scale generation and storage units are currently able to participate in balancing and wholesale markets on their own, or through their BRP. Smaller generators or storage units, however, require aggregation services to reach the required scale for participation in these markets.

Aggregation through virtual power plants (VPPs) also reduces the risk to each generator or smaller storage unit of providing flexibility, as the risk is taken by the aggregator and diversified through the presence of several flexibility providers. Current markets are not.

EU-SysFlex (WP7, Portugal) tests the aggregation of generation and storage in a concept grid. This includes FFR, FCR, FRR, congestion management, adequacy and voltage support. One of the demonstrations include a pumped hydro storage plant and wind power plants connected at TSO level, providing aFRR (secondary reserve) in a capacity market, as well as participation in day-ahead and intraday markets.

SmarterEMC2 tests mechanisms for voltage control in a lab / simulation setting.

The main aim of COMPILE is to demonstrate the opportunities of energy islands for the decarbonisation of energy supply, community building and the creating of environmental and socioeconomic benefits.

The DOMINOES project aims to enable the discovery and development of new demand response, aggregation, grid management and peer-to-peer trading services by designing, developing and validating a transparent and scalable local energy market solution.

inteGRIDy aims to integrate cutting-edge technologies, solutions and mechanisms in a framework of replicable tools to connect existing energy networks with diverse stakeholders, facilitating optimal and dynamic operation of the distribution grid (DG), fostering the stability and coordination of DERs and enabling collaborative storage schemes within an increasing share of renewables.

State of the Art in Application and Research (cont.)

MERLON introduces an integrated modular local energy management framework for the holistic operational optimisation of local energy systems in the presence of high shares of volatile distributed RES.

The MUSE GRIDS project aims to demonstrate, both system-wide and in real-life operational conditions, a set of both technological and non-technological solutions adapted to local circumstances, targeting local urban energy grids to enable the maximisation of affordable local energy independency thanks to optimised management of the production via end users' centred control strategies, smart grid functionalities, and storage and energy system integration.

The Smart Grid Vendée project aims to experiment with, at the level of the Vendée department, new solutions for controlling and modernising the distribution of electricity.

Technology Readiness Level

TRL 7

TRL 7 – Demonstration

EU-SysFlex tests the aggregation of generation and pumped hydro storage in a concept transmission grid. It includes FFR, FCR, FRR, congestion management, adequacy and voltage support.

Current Focus of R&D and Research Gaps

See State of the Art.

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- WP8: [Link]
- Work packages: [Link]

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COMPILE [Link]

DOMINOES [Link]

InteGRIDY [Link]

Flexturbine

InteGRID [Link]

MERLON [Link]

MUSE-GRIDS [Link]

REALVALUE

STORENET

WindNode [Link]

Smart Grid Vendée [Link]

ECCo [Link]

Market Coordination Platforms

Demand, Storage and Generation › Market › Congestion Management, Frequency Balancing & Voltage Control

Flexibility market platforms offer integrated solutions for purchasing and selling flexibility. They enable system operators to access local, aggregated flexibility from local small- and large-scale demand, storage and generation which is currently not available in day-ahead, intraday, capacity or reserve markets.

Both flexibility from demand, generation and storage is offered on these platforms, and services include congestion management, adequacy and frequency balancing. Voltage control can be offered more long-term (see separate solution). All pre-qualified actors can place bids to buy or sell flexibility. All bids contain a location tag and are traded on an internet-based platform.

Components & Enablers

- Regulatory: Different barriers in different countries
- Overall: increasing market access, defining the role of aggregators (see separate solutions)
- Smart meters and data exchange: Developing an effective platform + IT security
- Local forecasting of congestions
- Ability to verify physical delivery
- A large market is necessary to ensure real competition. Otherwise, a price cap is necessary.
- Measures to avoid undesirable market behaviour

Important features:

- Independent
- Non-discriminatory
- Role of TSO / DSO (coordination)

State of the Art in Application and Research

Currently, access to day-ahead, intraday and balancing markets are typically limited to larger agents and, in particular, do not include aggregated small-scale loads. Therefore, any new market structure which enables access to new participants, such as small-scale loads, valorises flexibility and lower the barriers to entry. This will increase the accessibility of the flexibility resources.

NODES has gone commercial in early 2019, but is not yet implemented at full-scale. It is part of a wide range of demonstrations in both Norway and Germany. Results from pilots run on the NODES platform show that flexibility platforms which enable access to local flexibility are, in general, feasible. Local flexibility is an effective and cheap alternative to the traditional curtailing of renewable generation. However, regulatory challenges stand in the way of full-scale deployment.

Enera (German platform for congestion management) saw its first trade in February 2019. All system operators have used the market, all technologies have been traded and all flexibility providers have undertaken trades, showing that the processes work.

State of the Art in Application and Research (cont.)

GOPACS and the ETPA market platform are currently commercially active and running on a national level in the Netherlands. ETPA is the platform for congestion management, which runs parallel to existing markets. GOPACS is connected to ETPA and acts as the platform which allows TSOs to purchase flexibility on ETPA, as well as organise TSO / DSO coordination.

Technology Readiness Level

TRL 9

Congestion management: TRL 9 – Implementation

ETPA is in commercial use and is implemented for congestion management. It operates in addition to existing markets. GOPACS is used to coordinate flexibility purchases between TSO / DSO.

TRL 7

Congestion management: TRL 7 – Demonstration

NODES demonstrates congestion management in a wide range of pilots.

TRL 5

Integrated markets: TRL 5 – Development

Balancing markets exist in many countries. The inclusion of frequency balancing and adequacy in integrated market platforms with new flexibility sources is currently being developed.

Current Focus of R&D and Research Gaps

The main focus of ongoing R&D is congestion management. Can such a market-based approach reduce the costs for congestion management? Can a sufficient number of providers be found to make such a flexibility market work in the long run, and can the designed solution serve as a coordination mechanism between TSOs and DSOs, to efficiently access flexibilities?

Projects vary across regions and countries due to differences in the regulatory framework, power exchanges, balancing markets, etc. Therefore, state-of-the-art solutions are not necessarily directly applicable in other regions and countries. Some projects, such as NODES, claim to be independent of country-specific characteristics. Others, such as Flexitranstore and CROSSBOW, have pan-European ambitions, aiming to provide one common flexibility market platform for a common European electricity market. Some flexibility market platforms contain matching algorithms that can balance between congested areas (as well as optimise for system operators), e. g. GOPACS.

Piclo Flex is a software platform already active, which presents an independent market place for trading flexibility online.

REFERENCES

NODES [Link 1] [Link 2]

Enera [Link 1] [Link 2] [Link 3]

ETPA / GOPACS [Link 1] [Link 2]

C / sells [Link]

Nobel grid [Link]

Norflex (NODES)
- ↳ https://nodesmarket.com/2019/02/01/norflex-receives-enova-funding-nodes-is-a-proud-partner/
- ↳ Project application submitted to Enova (in Norwegian, available from Statnett)
- ↳ https://vimeo.com/341747653/99399ef919

Dynamo [Link]

GoFLEX [Link]

OSMOSE WP2, WP6 [Link 1] [Link 2]

Flexitranstore (demo 5) [Link]

Flexiciency [Link]

Piclo Flex [Link]

Futureflow [Link]

TSO PROJECTS
- ↳ REE: Flexibility resource participation to AS (Spain)
- ↳ MARI
- ↳ TERRE
- ↳ PICASSO
- ↳ Source: TSO – DSO mapping (by ENTSO-E)

Voltage Market (for Distributed Energy Resources)

Generation and Storage › Market › Voltage Stability

Voltage control services are required when there are sudden changes in demand. This is because the amount of reactive power changes, which affects the voltage and quality of supply. The increasing penetration of non-synchronous, renewable energy in modern power systems replaces synchronous generation and affects voltage stability. This drives the need for additional voltage control sources. A market for voltage control services allows DERs connected to the distribution grid to provide reactive power support through an ICT platform. The advantage of DERs is that reactive power can be produced where voltage problems occur, thereby providing a more suitable solution to the problem.

Components & Enablers

- ICT platform that supports a technical and commercial solution. Must be able to provide network support at transmission level, while respecting constraints at the distribution level.
- The participants do not need to change their technology, but they need to integrate the control system, DERMS (distributed energy resources management system).

Technology Readiness Level

TRL 5

TRL 5 – Development

This new market platform is being tested in a simulation environment; it is still in a research / development phase and is not fully operational. It is preparing to conduct trials in the live system in 2019.

State of the Art in Application and Research

Voltage control services are not typically part of existing markets. The new market solution uses DERs connected to the distribution grid to provide reactive power support. DERs will be instructed via a centralised ICT platform called DERMS. In theory, everyone can participate in the market (PV power plants, wind farms, batteries and storage sites, SGs and aggregators).

Until now, Power Potential has not been able to include aggregators, but the goal is that every producer of power can participate. It is still in the testing phase, and the results will not be available until 2020.

The required response time for participation in the voltage market is under 5 seconds. This means that it is sufficiently fast to handle quick reductions in voltage, for example from when a big load disconnects from the power grid. The market has been tested in 400,000 houses, but it is still in the testing phase.

Current Focus of R&D and Research Gaps

The main challenge for the project is to implement and integrate the ICT platform into existing systems. The research focus also covers enabling aggregator participation.

NODES is looking to integrate voltage control services into its market platform in the future, but this is currently at an early research stage.

In addition to National Grid ESO reactive power / voltage control markets many TSOs / DSOs already mandate or remunerate the delivery of voltage control from any grid user.

EU-SysFlex has also done research regarding the liberalisation of 'voltage markets': Commercial Control of Reactive Power in an Electricity Distribution Company.

CoordiNet integrates a voltage market in the context of an integrated platform for TSO / DSO coordination..

REFERENCES

Power Potential [Link]

EU-SysFlex [Link]

CoordiNet [Link]

Local Energy Trading

Demand, Batteries and Generation › Market › Congestion Management, Adequacy

Market platforms for local energy trading, including peer-to-peer trading, are currently being developed and tested. The platforms are limited to a single region or community, typically defined by grid limitations. They enable increased local production and consumption and relieve transmission and distribution grids, particularly during peak time, thereby limiting congestions. The key projects considered here are EMPOWER and Cornwall. Another aspect is the trading of flexibility which can be conducted between participants within a local energy trading platform. The key projects covering this issue are INTERRFACE and COORDINET.

Local energy markets improve adequacy and prevent congestion through incentivising self-consumption, using local flexibility from production, generation and storage. At the core is an ICT market platform organising the energy cooperative, which enables peer-to-peer trading, operating in addition to existing electricity, wholesale and balancing markets. Local battery storage and instalment of smart home appliances increases the available local flexibility. Economic incentives are provided, either through rebated prices for local consumption or subsidised prices for local production. As such, demand is incentivised to adjust to the situation when there is surplus prosumer or renewable generation locally.

Components & Enablers

The most important enablers for local energy markets are:

- A well-functioning ICT solution (marketplace)
- Machine learning prediction of production and consumption down to a 15-minute level
- Removing regulatory barriers
- Energy data from DSO / smart metering
- A unified research approach
- Efficient battery technology
- Prosumer acceptance
- Blockchain, which facilitates the transparency of the transactions and enhances the system' trustworthiness

Technology Readiness Level

TRL 7

TRL 7

EMPOWER has conducted three pilots (Malta, Norway and Germany) and commercialised part of the concept. Centrica is currently undertaking a pilot in Cornwall, UK. Several other project pilots have been completed or are ongoing. INTERRFACE will test a prototype for the TSO–DSO flexibility market with blockchain based, smart contract and smart billing. CoordiNet is going to demonstrate in WP4 the peer-to-peer energy trading through blockchain technology.

State of the Art in Application and Research

In EMPOWER, economic benefits for peer-to-peer trading were provided through the community, whereby external agents (e.g. providers of PV panels or smart- home appliances) took a commercial interest in the investments of the community. This illustrated an economic feasibility of energy communities. Adequacy is provided through local self-consumption within the area, increased generation and storage. Local energy markets typically organised within one distribution area, and congestion management is therefore improved when relying less on the central grid.

EMPOWER pilots in Hvaler, Norway, showed that load reduction can be offered to the DSO and thus contribute to congestion management. In the German pilot, the load shifting potential in households was greater than that of public buildings.

EMPOWER built Norway's first pilot microgrid in Hvaler. The area produced 171 MWh/year from solar and wind. Includes storage. Residential homes (consumers and prosumers), municipal recycling facility, storage units. EMPOWER showed both the technical and economic feasibility of energy communities and local trading.

SENSIBLE tested how installing storage units in buildings and communities can be controlled to increase local consumption in a pilot in Nottingham, UK.

PEBBLE's goal is to design, develop and operate a blockchain-based platform for local energy trading (using a peer-to-peer or 'P2P' model) and to integrate grid usefulness into the market mechanism in regional 'energy-supply areas'.

INTERRFACE will develop and operate a market framework for distributed flexibility exchange between key stakeholders, to develop technical procedures to manage grid and system limitations via the aggregated control of consumption and generation.

Enervalis is developing a proof of concept, compatible with blockchain, in a real-life local market setting, to demonstrate a Layered Energy System (LES), which is a community market-based model.

The CoordiNet pilot in Sweden is developing a P2P trading supported with Blockchain technology in order to facilitate customer engagement and reduce transaction costs.

Current Focus of R&D and Research Gaps

INVADE builds on research results from EMPOWER. INVADE investigates aggregation through a flexibility operator, providing ancillary services to BRPs and DSOs. INVADE also has a wider range of participants (i.e. EV chargers, commercial).

P2P-SmarTest simulated how connected areas can participate in voltage control in a medium-voltage distribution grid.

The INTERRFACE demo consists of a 3-phase approach to enhancing a prototype for flexibility market with blockchain-based, smart contract and smart billing, as follows: (a) development of a custom prototype where basic use cases can be simulated and where market players are invited to test, (b) evolution to a Minimal Viable Product (MVP), capturing the fundamental functions and architecture of the platform and (c) initiation of a continuous growth cycle by checking the use cases of the different players (prosumers, TSO and DSO), the transparency in data and control and by validating the correctness of transactions (in the market/procurement process) and the transaction capacity, automatic level and speeds of market/procurement process. Sub-tasks include setting-up technical requirements and flexibility market arrangements for the test case; enhancing a prototype for the flexibility market with blockchain based, including proof of concept; and demonstrating TSO–DSO procurement for flexibility.

The CoordiNet project demonstrates how TSO – DSOs can act in a coordinated manner to procure grid services in the most reliable and efficient manner. Innovative grid services such as demand response, storage and small-scale (RES) generation are considered in this project. In addition, the blockchain maturity for peer-to-peer energy trading is being investigated and further developed in a Swedish pilot site.

PEBBLES focuses on a) developing a local trading platform which encompasses market mechanism, market and network optimisation, and decentralised architecture, b) developing business models for the future of the energy market on a local level, c) developing a Smart Contract Library for energy applications, d) pinpointing potential savings in the operation of supply grids by actively identifying prosumer behavior and e) analysing the technical and regulatory aspects of the demonstrator within the distribution grid area.

ENERVALIS, with the RENNOVATES project, aims to decrease the total energy consumption of homes by more than 60%, although there are currently insufficient statistical data available to draw definitive conclusions. In addition, the solar panels will generate approximately 4 to 7 MWh per year. Consequently, the houses will effectively meet the zero-on-the-meter scenario, which is one of the primary objects of the project.

Research is also focused on both aggregation and allowing the DSO, and sometimes the TSO, to procure ancillary services (frequency response, voltage control) from local flexibility. This is still at the research stage and is currently considered covered by the flexibility market platforms solution.

Cornwall: In Cornwall (south-west England) a local energy market pilot is currently being tested. The local energy market trial tests an ICT-based market platform which involves both local pricing and flexibility provision through explicit incentives for a DSO. In the virtual marketplace, the DSO places bids onto the market place and participants (households and private firms) make offers to buy and sell energy or flexibility. Participants receive a payment for their response. End-to-end solution. A 2.5 MW 'smart' solar farm.

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P2P-SmarTest [Link 1] [Link 2]

Dominoes [Link]

Enervalis [Link 1] [Link 2]

SENSIBLE (Nottingham pilot) [Link]

Nobel grid [Link]

Skagerak Energilab [Link]

INTERRFACE [Link]

PEBBLES [Link]

COORDINET [Link]

Microgrid for Reliability of Supply

Demand, Generation, Battery › Market › Reliability

Microgrids become increasingly independent of the grid when there is communal storage and increased local self-consumption / peer-to-peer trading.

Components & Enablers

The most important enablers for local energy markets are:

- A well-functioning ICT solution (marketplace)
- Removing regulatory barriers
- Energy data from DSO / smart metering
- A unified approach – currently, local energy markets are piecemeal projects (i.e. not coordinated), even within the same country

State of the Art in Application and Research

The EMPOWER project built and developed a microgrid in Hvaler, Norway. The 'energy community' consisted of residential prosumers, a municipal recycling facility and office buildings. The large communal battery and local generation and consumption provided by the local energy market platform made the microgrid self-sufficient for up to 20 hours. The system operator could disconnect the microgrid in case of a major system or grid event without incurring large expenses or consequences for the customers in the microgrid.

The pilot in Hvaler was successful, but the required battery technology and instalments were too expensive for large-scale testing or deployment. Further research could investigate a system consisting of several similar cells, able to be increasingly independent of the grid. Due to very large production from PVs in the period when the microgrid was disconnected, PV production had to be curtailed.

Flexens has identified the opportunity to develop and build a full society-scale energy system based on renewables on Åland – an island with ideal wind and solar conditions and an ambitious climate- and energy strategy, as well as a population dedicated to sustainability.

The LEMENE smart grid is an energy self-sufficient grid which will mainly operate as part of the public electrical grid, but it can also operate as a supporting reserve system, or as an independent off-grid, on demand. It includes a variety of smart technologies that will respond to changing electrical demand, enabled by automation solutions adapted to the microgrid. This is a unique implementation in the world on such a large scale. Also, an important part of the project is to secure energy availability as renewable energy production varies.

The GOFLEX project at the Cypriot pilot test aims to test the microgrid case of a university, exploring the offered flexibility by the public sector testing.

SDN-Microgrid investigates distribution grid restoration in real world microgrids.

The Muse-grids project investigates the contribution of different energy networks to the decarbonisation of the municipal microgrid in the pilot site of the city of Osimo.

The TILOS project developed an energy management system and simulator for a microgrid.

Wisegrid implements a micro control room for microgrids to manage and monitor their own grid, offering security and reliability of supply.

Technology Readiness Level

TRL 5

TRL 5

A successful pilot was conducted in Hvaler, Norway, by EMPOWER. The technology is not yet mature for full- scale deployment.

Nonetheless, there are hundreds of different TRL-level micro-grid examples in Europe.

REFERENCES

EMPOWER
↳ Communications with Bernt Bremdal at Smart Innovation Norway [Link]

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LEMENE [Link]

Sdn-microgrid [Link]

Muse-grids [Link]

GOFLEX Cypriot Pilot [Link]

TILOS [Link]

VINPOWER [Link]

Wisegrid [Link]

Demand Response to Price

Small-Scale Demand Response, EV Charging › Price › Congestion Management, Adequacy

Variable spot prices, time-of-use (ToU) tariffs and variable grid tariffs provide incentives for small-scale demand to adjust the time or quantity of electricity they consume to the needs of the power system. When end user prices vary depending on the balance between demand and generation, demand response can address adequacy. If prices vary depending on the time of day or limitations in the grid, demand response could help congestion management. Although the spot prices are decided on an hourly basis in the day-ahead market, the end user price is also influenced by grid tariffs. Some projects examine the response to variable/dynamic spot prices, others focus on ToU tariffs. Most projects consider small-scale residential demand, whereas some also consider service buildings and EV charging.

Components & Enablers

- Providing customers with information about their consumption and prices
- Smart home appliances

State of the Art in Application and Research

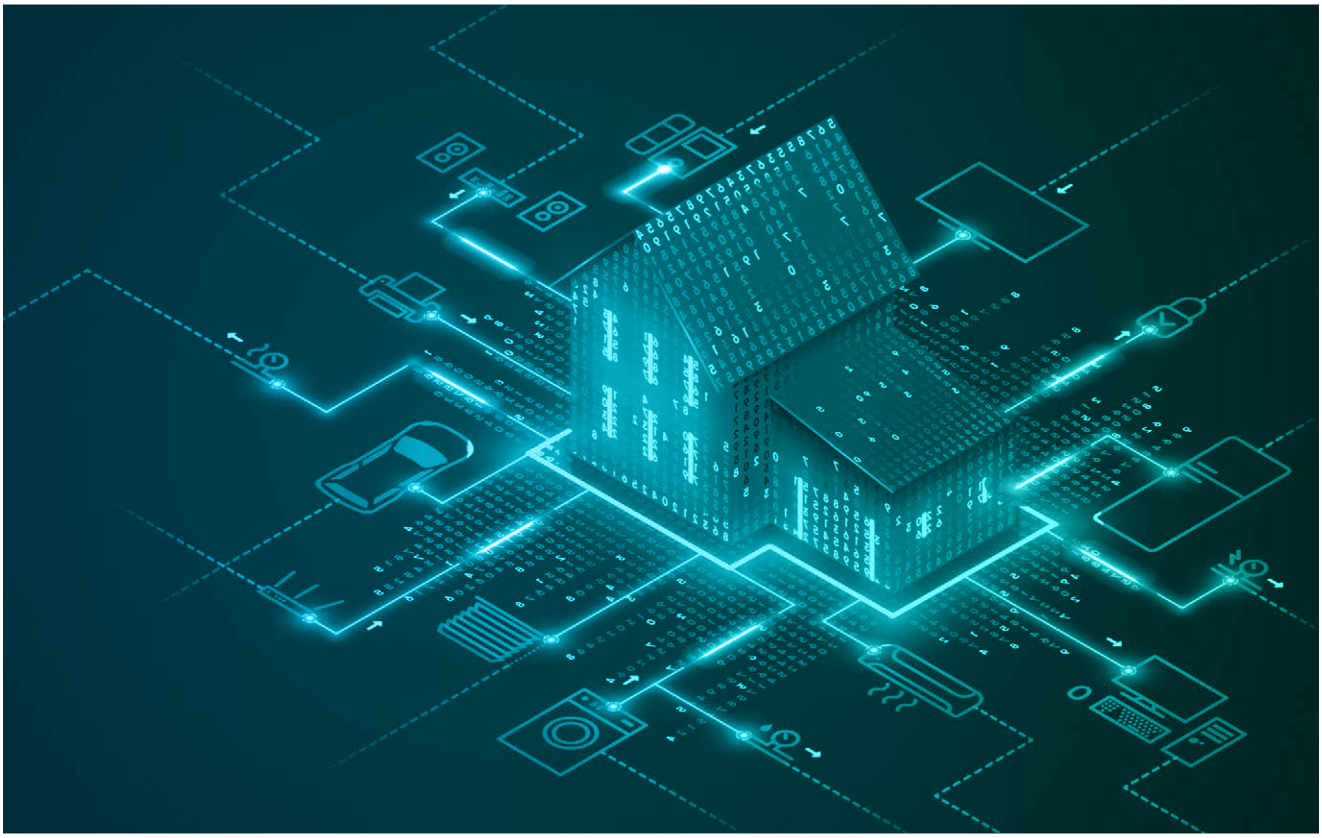
A range of projects investigating dynamic prices and ToU tariffs have been conducted in Europe and the US. Variable spot price contracts are available in many European countries; however, variable grid tariffs are currently rare.

In ECOGRID EU, approximately 2,000 residential customers participated in the project, which addressed flexible demand response to real-time price signals. The pilot took place in the Danish island of Bornholm, with more than 50% RES.

Customer-Led Network Revolution conducted trials in the UK on ToU tariffs. They found that demand was reduced by 10% in the 4–8 pm evening peak, reducing customer energy bills. Specifically, they found that 'Household chores such as laundry and dishwashing were the most commonly used to flex the times of electricity usage. Customers with PV were successful at adjusting their electricity usage to take advantage of their own generation and were arguably the most engaged customers of all'[1]. Families and customers of older age were less flexible than other customers.

In AnyPlace, users participate in new energy services and take advantage of dynamic price tariffs to minimise energy costs.

1 http://www.networkrevolution.co.uk/conclusions/domestic-customers/



Technology Readiness Level

TRL 9

TRL 9

A range of projects have been conducted, and spot prices are commercially available today.

For general price response, there is some research available to fully understand expected response or how to maximise it in Europe. Many projects have been performed on dynamic pricing in the US. Research is ongoing in some countries on how to design variable grid tariffs, but this has not yet been implemented large-scale.

TRL 9 refers to the demand response to wholesale energy price. The TRL level regarding capacity or grid capacity pricing is not there yet, as illustrated below with the R&D focus.

Current Focus of R&D and Research Gaps

Statnett, the Norwegian TSO, will conduct a demand response pilot with dynamic grid tariffs, called iFlex.

Contact: matthias.hofmann@statnett.no

Research is ongoing in several countries on how to design variable grid tariffs.

REFERENCES

RealValue [Link]
SmartTariff [Link]
ECOGRID-EU [Link]
Linear Customer-Led Network Revolution [Link]
AnyPlace [Link]
FLEXCoop [Link]
NETfficient [Link]
NobelGrid [Link]
Project-Enera [Link]

Demand Response to Information

Small Loads › Information › Adequacy

Information about own consumption patterns, and sometimes electricity prices or the consequences of this for the power system, can contribute to consumers adjusting their demand. Often, information is provided via a smartphone app. This means that demand can be shifted from periods of peak demand to periods of low demand and/or periods of high variable generation. This can, in turn, contribute to a better balance between supply and demand both long-, medium- and short-term. The reference projects mainly researched residential demand, but one demonstration also covered a municipality.

Components & Enablers

- Smart metering
- Effective sensors
- Removal of regulatory barriers: some countries do not allow customers/third parties direct access to metering data

State of the Art in Application and Research

In Ireland, the Power Off & Save project tested whether and how fast residential consumers would respond to a notification sent to their phone when there was congestion in the grid, and awarded customers with a reduction in their electricity bill. It found that the incorporation of smart homes leads to peak reduction, particularly in the mornings and evenings. Most participants responded to a request to reduce their consumption within 5–25 minutes.

The NEBEF mechanism (RTE) allows consumers to participate in energy markets through load reductions.

Flexiciency and Power Off & Save both found that automatic control appliances, both in homes, on EVs and in municipal buildings, increase the efficiency of the information measure. Automatic control maximises customer comfort and minimises the required effort.

In most Flexiciency pilots, consumption was reduced when consumers were informed about consumption. The results from the Swedish pilot are ambiguous, but this might be due to a small sample. The positive results might be due to the motivation of participants in the project rather than information in itself – the projects are unable to confirm whether this has been controlled for.

The FLEXCoop project increases the awareness of the prosumers by increasing their local intelligence via an energy Management and Control Decision support framework that locally optimises demand response.

Project Enera, through the Enera app, provides energy saving tips to consumers based on their electricity consumption for easy implementation.

Technology Readiness Level

TRL 7

TRL 7

ENOVA is currently conducting seven large-scale pilots. Flexiciency has previously done the same. Information about consumption and apps communicating this have proven feasible and have beneficial results.

Current Focus of R&D and Research Gaps

Seven Norwegian ENOVA AMS pilot projects are currently testing whether access to real-time information about own electricity consumption can lead to changes in the consumption pattern. The goal of the project, which in total has more than 20,000 participants, is mainly to test whether consumption is reduced but also when there is peak demand.

REFERENCES

Power Off & Save [Link 1] [Link 2]

ENOVA AMS-målere piloter [Link]

Flexiciency: Italy, Spain and Sweden
↳ Final report: [Link]

STORY – pilot 2

RealValue [Link]

Flex4Grid [Link]

FlexCoop [Link]

Project Enera [Link]

NEBEF mechanism [Link]

Network Code for Connection Points

To overcome technical barriers regarding the new generation of RES inverters, the high penetration of power electronics in the transmission network, and the meshed offshore grids, a roadmap for the connection rules should be established. The solution covers recommendations and methodologies based on the most impacted European connection codes, i.e. the High Voltage Direct Current (HVDC) connection codes, the Demand Connection Code (DCC), and the Requirements for Generation codes (RfG). The improvement of Connection codes is crucial for the successful integration of all the existing assets in Europe in a common unique infrastructure, and also addresses some interoperability issues from a technical perspective (i.e. cross-border trading).

Components & Enablers

- Enabling up to 100% power electronic driven grid
- High RES integration in the new power systems
- Harmonisation in common framework for all the power sectors members in EU.

State of the Art in Application and Research

In RESERVE, the regulatory for the transition up to 100% RES is studied. The new generation of converters provide new functions for frequency and voltage control. The new power system with a low level of available inertia requires new connection codes regarding the high penetration of power electronics.

Furthermore, in MIGRATE the concept considered concerns the transmission grid, to which 100% converter-based devices are connected. The goal is a set of requirement guidelines for converter-based generating units, as far as possible at the connection point, which ease the implementation of control and management rules.

PROMOTioN aims to develop testing procedures and guidelines for meshed HVDC offshore transmission networks. To fully exploit the technical work, a Harmonisation Catalogue provides the state-of-the-art regarding the harmonisation of HVDC systems, identifying gaps in this harmonisation, and analysing how findings in the PROMOTioN project can contribute. In addition, deployment is constrained by limitations inherent to the existing European regulations regarding the development of cross-border offshore infrastructures.

Current Focus of R&D and Research Gaps

To enhance the confidence in the controllability of meshed DC grids as well as their interaction with AC transmission systems and offshore wind farms, a DC network demonstrator embedded in a real-time simulation environment of wind farms and AC grids is set up within PROMOTioN WP 16.

To detail the technical and regulatory barriers concerning the Power Electronics dominated networks, a pilot test with impacts on the present grid codes is realised in MIGRATE, regarding the proper scaling and replication of the grid connection rules and power system control laws. In addition, in the Trial Site Open Day in Ireland, held in the context of the RESERVE project, a major topic investigated is how inverter-based devices can help enable a 100% renewable electricity network.

REFERENCES

PROMOTioN [Link 1] [Link 2] [Link 3] [Link 4] [Link 5]

MIGRATE [Link 1] [Link 2] [Link 3]

RESERVE [Link 1] [Link 2] [Link 3] [Link 4]

Network Code for Operations

System operation Network code contains details about the requirements and principles of operational security, rules and responsibilities for the coordination and data exchange between TSO/DSO/significant grid users, and rules aiming to establish a common framework for frequency control and services. Specifically, the solution covers recommendations about emergency and restoration code, and system operations code. The recommendations to these codes can be implemented by investigating the new frequency control concept, system swing dynamics, requirements of minimum system inertia and the new voltage control concept.

Components & Enablers

- High RES integration in the new power systems
- Harmonisation in common framework for all the power sectors members in EU.
- Enabling proper coordination between different participants in the grid.

Current Focus of R&D and Research Gaps

Currently, the RESERVE project is mainly striving to extract recommendations through simulations in the area of Network code operation. This is the only project entirely dedicated to making recommendations about the regulatory framework in the new era of power systems. Thus, there is a research gap in this area, specifically regarding investigating the rules and the responsibilities in the coordination and data exchange between different actors of the power system.

State of the Art in Application and Research

In the RESERVE project, the regulatory requirements for the transition up to 100% RES is being studied through simulations. First, the new concept for frequency control is investigated by introducing New ICT architecture. Second, the requirements for minimum inertia are explored. For the faster and more accurate protection and automatization of the system, linearised wing equations are proposed. Finally, a new voltage control concept between DSO and prosumers is investigated, by considering new ICT requirements and inverters generation.

In the INTEGRID project, the role of DSOs is being investigated through the regulatory recommendation for the countries participate in the project.

In the AnyPlace project, regulatory recommendations regarding the deployment of smart metering platform will be proposed. Specifically, recommendations will mainly focus on energy, security and telecommunication standardisation. The recipients of this proposal are future projects, regulation and policies for EU citizens, utilities and grid operators, together with industry and market.

In the EU-SysFlex project, an assessment of the regulatory framework in the context of provision innovative system services is being made.

REFERENCES

RESERVE [Link 1] [Link 2] [Link 3] [Link 4]
INTEGRID [Link]
AnyPlace [Link 1] [Link 2]
EU-SysFlex [Link]

Network Code for Market

The network code family focusing on the market perspective in the grid can be decomposed into the capacity Allocation & Congestion Management Code, Forward Capacity Allocation Code, and Electricity Balancing Code. In addition, this category includes recommendations regarding the legal regulatory framework in business models introduced in the new era of power systems.

Components & Enablers

- Define the regulatory framework for new business models in the new era of power systems.
- Harmonisation in the common framework for all the power sectors members in the EU.
- Deployment of new markets suitable for the new era of power systems.

Current Focus of R&D and Research Gaps

The RESERVE project mainly proposes new regulatory recommendations for the inertia and voltage control concept. BestRES, in parallel with the deployment of business models for aggregators, attempted to propose a legal framework for the proper operation of these.

There is a significant research gap in this group of network codes. There are no projects focusing on recommendations regarding the Congestion Management Code and Forward Capacity Allocation Code.

State of the Art in Application and Research

In the RESERVE project, the regulatory for the transition up to 100 % RES is being studied through simulations. An investigation of the requirements for minimum inertia is taking place. In addition, a new voltage control concept between DSO and prosumers is being investigated by considering new ICT requirements and inverters generation.

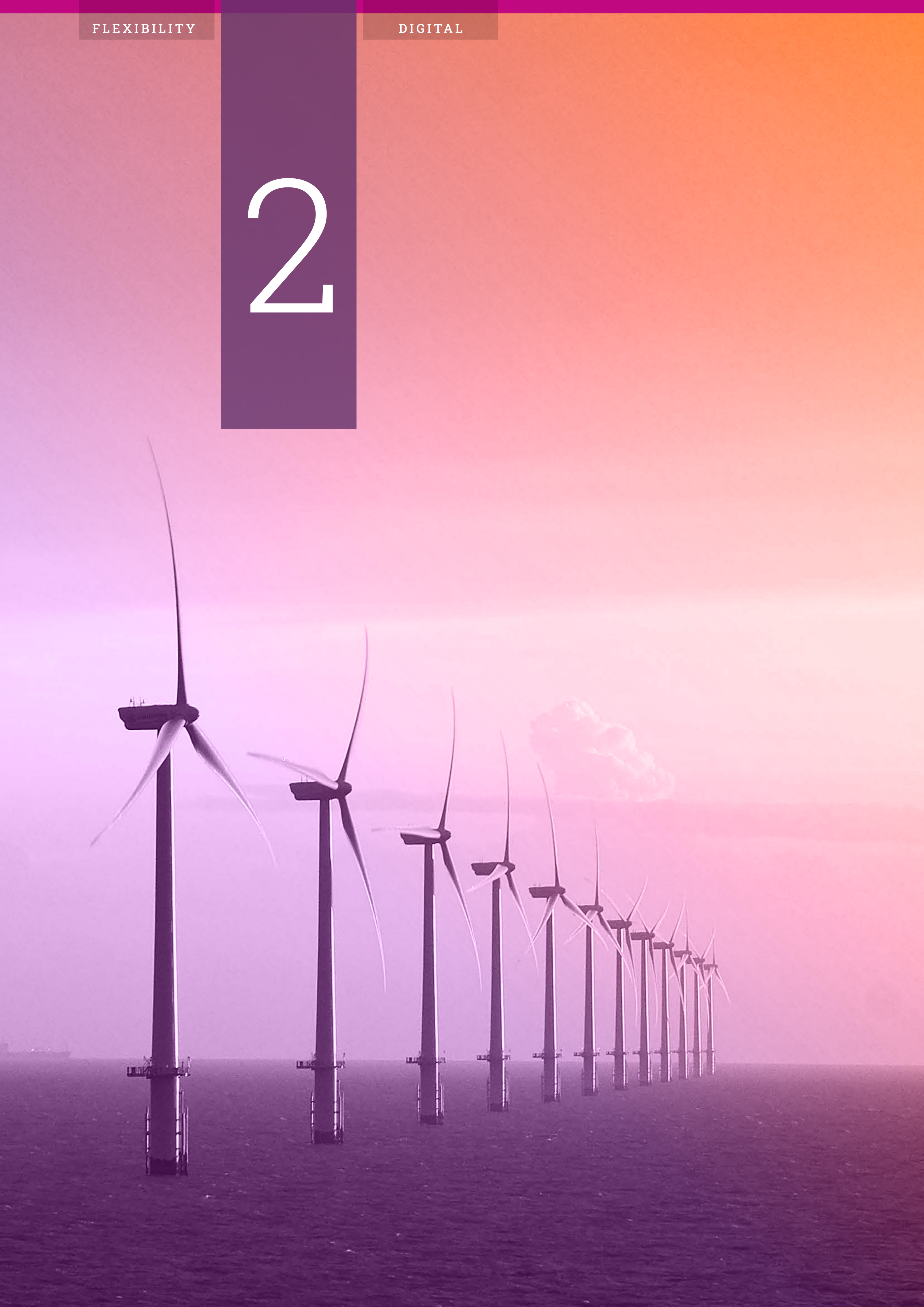
In the BestRES project and specifically in D5.2 and D5.3, recommendations are being made for a national and European legal framework for the development of business models for renewable energy aggregation.

REFERENCES

RESERVE [Link 1] [Link 2] [Link 3] [Link 4]

BestRES [Link]

2

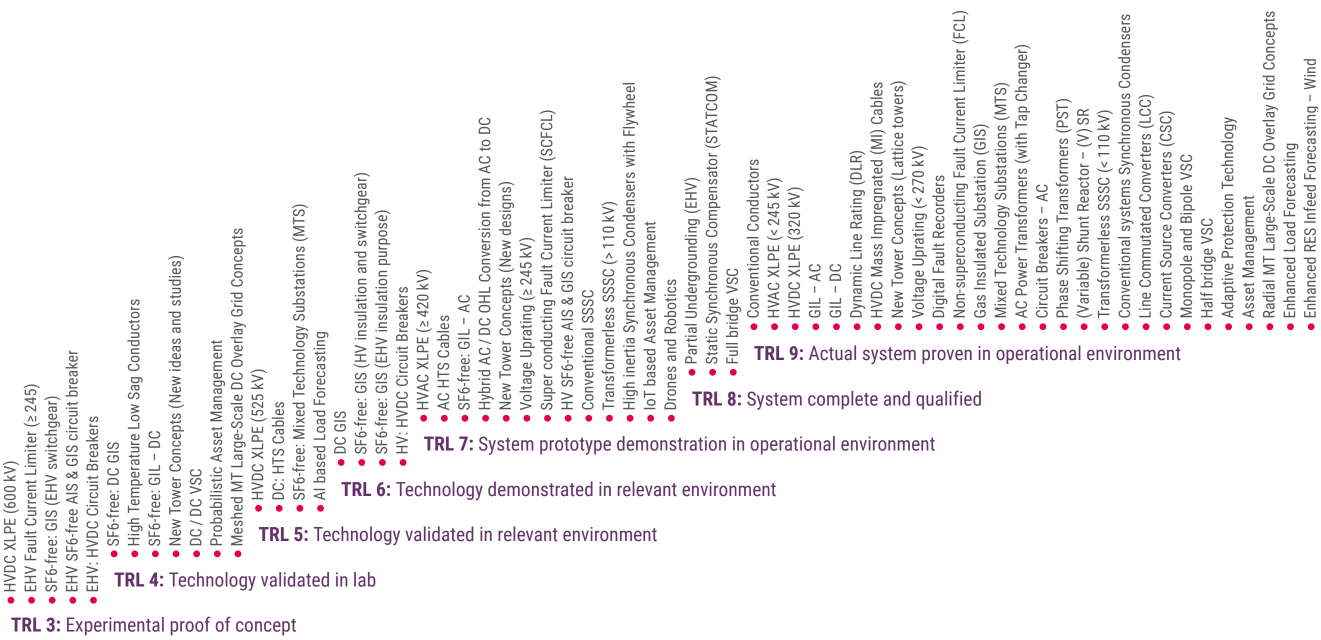


Assets

The high voltage and extra high voltage primary technologies are the key assets of the energy transmission system. The present infrastructure is designed to cope with challenges that arose 5 or 10 years ago. Correspondingly, some present requirements related to changed generation and load centres or to the new environmental challenges need to be covered by more robust and new primary technologies. In the future, there will always exist a mix of state-of-the-art and new technologies and both will have their own learning curves, innovation cycles and TRL.

The figure below presents an extensive mapping of primary transmission system technologies, which are presented in this section, considering their current TRL. It is common that for technologies which are in transition from development to demonstration, the visibility and related expectations are at the peak (TRL 1 – 5), but these expectations sharply decline after pilot results are completed and technology enters the final development stages and application in the operational environment (TRL 6 – 9).

The primary technologies related to the energy transmission system according to the current TRL



In total, 34 assets related technology factsheets are presented in this section. Each factsheet consists of a short technology description, main technology types, main application fields, advantages or application restrictions and use-cases. Moreover, the TRL is introduced, including the estimate of the TRL development in the future (if available). The factsheets also highlight the ongoing and further research and development needs and trends.

DC Gas Insulated Switchgear – DC Gas Insulated Substation

Gas-insulated switchgear assemblies for DC application (DC GIS) provide a compact technical solution with a high functional density, optimised for projects with limited space as in offshore HVDC converter platforms, onshore HVDC converter stations and transition stations between different transmission media. Compared with technically equivalent air-insulated switchgear, DC GIS require up to 95 % less space. Hence, the size of an HVDC offshore converter platform can be reduced by up to 10 % and the footprint of a transition station, e.g. for long DC cable lines, by up to 90 %.

Technology Types

The technology type of DC GIS is defined by the gas mixture used to insulate the assembly. Two types of DC GIS exist:

- SF6 DC GIS
- SF6 free DC GIS
  (e.g. Fluorntiril-based, clean air based)

Components & Enablers

- Encapsulation
- Insulating gas (commonly SF6)
- Cast-resin insulators
- Disconnector and earthing switches
- Interface modules: gas-to-air bushing, cable connection module, DC GIL connection module
- Current measuring device (e.g. Zero Flux)
- Voltage measuring device (e.g. RC divider)
- Surge arrestor

Advantages & Field of Application

Space-saving installation

DC GIS help to significantly reduce the size of HVDC transition and converter stations for on- and offshore applications. Compared with technically equivalent air-insulated switchgear, DC GIS require up to 95 % less space for a typical bay layout.

Climatic resistance

DC GIS operate safely and reliably onshore and offshore in the temperature range of -30 °C to +50 °C and with modifications even under severe conditions such as polluted and aggressive atmosphere.

Containerised arrangements available

DC GIS can be commissioned in prefabricated container modules to reduce environmental impact as well as local erection and commissioning efforts.

High safety

DC GIS are fire resistant and do not contain flammable material. They are sealed for lifetime and essentially involve no ageing of insulating materials, resulting in low maintenance and low lifecycle costs. In the event of internal arcs, no fragmentation or burn-through of the enclosure occurs, but decomposition products of SF6 are toxic.

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Technology Readiness Level

TRL 6

For EHV applications:

2020: TRL 6 (SF6) [1], TRL 4 – 5 (SF6 free)
2025: TRL 7 (SF6) [2]
2030: TRL 9 (SF6)

For lower DC voltages of 250 kV, TRL 9 is reached in the Japanese DC GIS installation of Kii Channel Link, which has been in operation since 2001 [3].

Research & Development

Current fields of research: Demonstration of the technology's long-term applicability, alternative gases to SF6, partial discharge measurement.

Innovation priority to increase overall TRL: Investigation of long-term effects (gaining operating experience), insulating gas (substitutes for SF6).

Best Practice Performance

The first commercial DC GIS has been in operation since 2001 in Japan with ±250 kV in ±500 kV design. In 2019, a new installation in Japan is going into operation with a rated voltage of ±250 kV. The first offshore installation with ±320 kV rated voltage is expected to be in operation in 2023. The development of DC GIS up to ±550 kV is completed.

Rated voltage range: ±250 kV to ±550 kV

Rated current range: up to 5 kA

Rate of failure: Since DC GIS are based on well-proven AC GIS technology, rate of failure can be derived from relevant Cigré surveys. In TB 513, failure rate is given at 0.88 per 100 years.

Expected lifetime: 50 years, derived from AC GIS

Selected Best Practice Application

Location: Anan converter station and Yura switching station, Japan [3]

Year of commissioning: 2001

Description: Technology of DC GIS was chosen because of the heavy salt contamination in the coastal area. Furthermore, the space for the installation was greatly reduced.

Design: Disconnector and bus bar, particle traps

Results: Reliable and space-saving station design

Location: Arnhem, Netherlands [1]

Year of commissioning: 2018

Description: Within the EU project PROMOTioN, the installation of a 320 kV HVDC GIS was completed and commissioned in order to perform a long-term test to demonstrate that the technology of HVDC GIS is ready for application. The test is being performed in the DNV GL's KEMA High Voltage DC Laboratory near Arnhem.

Design: ±320 kV DC GIS

Results: The long-term test over one year is expected to demonstrate that the technology is ready for real-world application in order to achieve cost savings due to the compact design of the HVDC switchyard.

Location: DolWin6 platform, North Sea [2]

Year of commissioning: 2023

Description: DolWin6 grid connection with HVDC technology. Space-saving DC GIS in DC switchyard for reducing platform size and weight.

Design: ±320 kV DC GIS.

Results: Reduction of size and weight of the platform by 10 % due to the installation of space-saving DC GIS.

Location: Gotland, Sweden [4]

Year of commissioning: 1986

Description: 30 MW and 150 kV Gotland HVDC line featured the first DC GIS with mixed voltage stress (AC+DC).

Design: DC busbar with superimposed DC voltage of ± 150 kV.

Results: The DC GIS has enabled the better use of available space due to its compact size and high reliability.

Conventional Conductors

High Voltage AC Overhead Lines (OHL) are most commonly used for the transmission of energy. Thereby, the current flows through conductors that are fixed through insulatorsto crossarms of the towers. The conductors are spanned between two towers. To increase the amount of energy transmitted, the conductors are frequently bundled. The conventional conductors are characterised by linear dependence between current, conductor temperature and sag of the conductor.

Technology Types

The major technology variations relate to the material used and build-up of conductor:

- All Aluminium Alloy Conductors (AAAC)
- Aluminium Alloy Conductor Steel Reinforced (AACSR)
- Aluminium Conductor Steel Reinforced (ACSR)
- All Aluminium Conductor (AAC)
- Aluminium Conductor Alloy Reinforced (ACAR)

The conductors are characterised by

- Maximal current currying capacity
- Maximal operating temperature
- Sag behaviour
- Diameter
- Surface treatment

Advantages & Field of Application

Aluminium-based conductors on HVAC overhead lines are a proven technology that is a century old. The first three-phase AC overhead line using conventional conductors was built in 1891 connecting the cities of Lauffen and Frankfurt in Germany. Today, the largest part of the transmission lines (exceeding 220 kV) on land are HVAC overhead lines and, even with the many new developments to be realised using HVDC technology and / or underground cables, its relative share will remain fairly stable over the following decade in Europe.

The main advantage of the technology is its clear standardisation process and extended supply chain, which are optimised in terms of material, transportation, erection, maintenance, costs, lifetime and appearance, and minimises the risk of bottlenecks.

Technology Readiness Level

TRL 9

TRL 9 – System ready for full scale deployment

Research & Development

Current fields of research:

- Reduction of the corona (noise emission):
  - ↳ surface treatment
  - ↳ coatings
  - ↳ expanded conductors
- Anti-icing by surface treatment

Best Practice Performance in Europe

Maximum capacity per circuit: 2600 MW

Current rating: 4.0 kA per phase of quad bundled conductor (AL / ST 550 / 70)

Maximal operating voltage: 420 kV

Selected Best Practice Application

Location: France

Year of commissioning: 2002 – 2008

Description: A specific AAAC conductor is used, which is considered to be the best technical optimisation technique using Aluminium Alloy.

Design: Two three-phase circuits on the same tower and four conductor bundle for each phase.

Results: The energy losses are the lowest recorded for AAAC lines.

Location: The Netherlands – Germany

Year of commissioning: 2016

Description: Commissioning of the 380 kV transmission line Dötinchem–Wesel which supports the expansion of the north-west European electricity market.

Design: 22 km of 380 kV OHL with 54 innovative tube wind-track pylons and an interconnector capacity of 2,600 MW.

Results: Not described.

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High Temperature Low Sag Conductors

High Temperature Low Sag Conductors (HTLS) can withstand operating temperatures of up to 210 °C, thus carrying higher power compared to conventional conductors. These conductors can be applied when there is a need to use an existing OHL that has clearance problems (ampacity limitations) and restrictions to the use of new and higher towers. HTLS conductors will allow an increase of the ampacity without the need to modify most of the existing towers.

Technology Types

HTLS conductors can be one of four types [11]:

- **Type 0:** Conventional steel core reinforced aluminium conductors ACSR or ACSR/TW for operating temperatures < 100 °C
- **Type 1:** Conductors consisting of a strength member made of steel, coated steel or steel alloy, and an envelope for which the high temperature effects are mitigated by means of thermal-resistant aluminium alloys (TACIR, TACSR)
- **Type 2:** Conductors consisting of a strength member made of steel, coated steel or steel alloy, and an envelope for which the high temperature effects are mitigated by means of annealed aluminium (ACSS)
- **Type 3:** Conductors consisting of a metal-matrix composite (MMC) strength member, and an envelope for which the high temperature effects are mitigated by means of thermal-resistant aluminium alloys or annealed aluminium. (ACCR, ACMR)
- **Type 4:** Conductors consisting of a polymer-matrix composite (PMC) strength member, and an envelope for which the high temperature effects are mitigated by means of annealed aluminium or thermal- resistant aluminium alloys for HTLS applications (ACPR)

The aluminium alloy or annealed aluminium will give the conductor the characteristics to withstand high temperatures without losing mechanical properties. The special core will give the low sag characteristics due to low coefficient of thermal expansion (CTE) and high Young modulus.

Advantages & Field of Application

The cost and thermal losses of HTLS conductors are typically higher than conventional conductors. The main advantage is that HTLS conductors can enhance security reserves and transmission capacity without impacting the negotiated right-of-way, ideally with minor modifications of towers (mostly clamps of the conductors and their mountings or light tower's reinforcement) and sometimes fewer towers. Although existing corridors are used, in some countries such projects have to go through an authorisation or impact assessment procedure again, especially when magnetic field levels are increased, as the expected currents are higher.

Technology Readiness Level

Due to the variety of possible material solutions, not all conductor types can be seen as mature technology (e.g. PMC) but many mature conductor types are already commercially available and ready for full-scale deployment.

TRL 4 – 9

2020: TRL 4 – 9
2025: TRL 6 – 9
2030: TRL 8 – 9

Research & Development

Current fields of research: Electrical and mechanical aging, surface treatment, expanded conductors, thermal modelling, system integration, thermal design margins, environmental loading conditions including high wind and / or ice loading and high temperatures, grid planning with HTLS conductors

Innovation priority to increase overall TRL: Conductor material, electrical and mechanical aging, reducing cost of special cores using other materials

Other: For future new materials and compositions of conductors: Full-scale outdoor tests are necessary to conclusively verify the results obtained in the research laboratory

Best Practice Performance

Maximum thermal capacity per circuit: ca. 3,200 MW (380 kV line)

Current rating: 5.0 kA per quad bundle (ZTAL / HACIN)

Standard definition: IEC 62818 ED1 (expected in 2019)

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Selected Best Practice Application

Location: Ireland

Year of commissioning: 2010

Description: 80 km of 220 kV gap-type HTLS overhead line was installed to achieve a capacity increase of 50 %.

Design: G(Z)TACSR conductors.

Results: Higher temperatures are tolerated, allowing increased power transmission.

Location: Northern Germany

Year of commissioning: 2014

Description: In Northern Germany, different HTLS conductors were installed for field testing. Measuring equipment for tension, ambient temperature, irradiation and wind speed were added.

Design: ACCR, HACIN / ZTAL and ACCC conductors were installed on a 220 kV line to replace existing conventional conductors.

Results: Increase in power transmission capacity and field testing for the technology.

Location: Ragow, Germany

Year of commissioning: 2017

Description: BEST PATHS Demo 4 research focused on the need to improve and repower existing power lines and enhance technical knowledge with new conductor technologies among European TSOs. Among others, Demo 4 developed and tested innovations in novel insulated cross arms (Belgium by Elia), HTLS conductors (Ragow, Germany), new composite towers, dynamic line rating (Fuendetodos – María line, Spain) and innovative live-line working (Hungary). BEST PATHS stands for 'BEyond State-of-the-art Technologies for rePowering AC corridors and multi-Terminal HVDC Systems'. The project involved 39 partners from 11 European countries, with a budget of EUR 63 million.

Design: Specific to HTLS, experts developed new mechanical and electrical long-term tests for HTLS conductors to obtain reliable data on their ageing mechanism, reliability, and their mechanical and electrical performance.

Results: The applied testing scheme allowed, for the first time, a direct and comprehensive comparison of different HTLS wire types.

HVAC XLPE (Cross-linked Polyethylene)

HVAC cables are typically used as an alternative transmission technology when overhead lines are not appropriate, e.g. in densely populated and reserved areas, across a river or offshore. Extruded cables are insulated using cross-linked polyethylene (XLPE). With improvements in material science, XLPE has achieved a high dielectric strength, low dielectric constant, high insulation resistance and good mechanical properties, making it an excellent insulation medium for underground power transmission.

Technology Types

HVAC XLPE cables can be categorised into two types:

- Onshore cables
- Submarine cables

Each type can further be distinguished by the number of cores (conductors) laid up together to form the cable. Their configuration may be single or three cores.

HVAC cables are widely used at voltage levels up to a maximum voltage of 550 kV at a global scale. The extruded XLPE insulated cables have been currently applied at 275 kV since year 1995 and at 400 kV since roughly 2000.

HVAC extruded insulation cables are also commonly used for the submarine connections. Today, HVAC cables with extruded insulation cover transmission system voltages up to 550 kV.

Components & Enablers

Onshore cable:

- Conductor (Al or Cu)
- Insulation material (XLPE)
- Metallic screen
- Waterproof layer
- Non-metallic outer sheath

Submarine cable:

- Conductor (Al or Cu)
- Insulation (XLPE)
- Metallic screen (lead sheath)
- Core sheath (semiconductor)
- Armouring (galvanized steel wires)
- Outer serving (bitumen and polypropylene yarn)

Advantages & Field of Application

The major advantage of XLPE as insulation for medium and high voltage cables is its low dielectric loss. The dielectric loss factor is about a tenth of that of paper insulated cables and about a hundred times lower than that of PVC-insulated cables.

In addition, improvements in manufacturing and installation process have led to a dramatic increase in the utilisation of this type.

XLPE cables have a lifetime of at least 40 years. HVAC XLPE permits a temperature of 90 °C and a maximum short circuit temperature of around 250 °C. When implementing HVAC XLPE cables, some challenges need to be tackled, e.g. long outage times after damage or failure, transient behavior and reactive power produced by cables. Specific risks for network operation have to be carefully analysed case by case.

Technology Readiness Level

TRL 9

TRL 9 for offshore HVAC cables and onshore HVAC cables with a voltage rating equal or less than 245 kV

TRL 7

TRL 7 for onshore HVAC cables with a voltage rating equal or higher than 420 kV

Research & Development

Current fields of research: System integration margins due to reactive power compensation, partial discharge detection, fault localisation, new environmentally friendly lying methods, bedding materials, 4,000 mm² conductors, long term thermal stability of insulating material.

Best Practice Performance

On-shore:

- Maximum capacity: 1,250 MVA (3-phase cable system)
- Current rating: 1.8 kA
- Voltage rating: 420 kV

Off-shore:

- Maximum sea depth: 100 m
- Maximum length: 162 km*

* This cable length corresponds to a cable connected to 145 kV with a capacity of 55 MVA. It is the cable installed at the Martin Linge offshore gas field and is the longest AC submarine cable in the world.

Selected Best Practice Application

Location: Berlin, Germany

Year of commissioning: 1998

Description: A 400 kV underground XLPE transmission link was built in 1998 in the centre of Berlin. The cable is located in a tunnel 6.3 km in length, 25 m below the surface.

Design: 400 kV XLPE AC, 1100 MVA power transmission.

Results: Long-term reliable performance of high power transmission is promised through the XLPE cable compared to the former low-pressure oil-filled cable.

Location: Croatia, Brac / Adriatic Sea

Year of commissioning: 1995

Description: Two XLPE cable types were supplied to connect the islands of Croatia to the mainland in 1995.

Design: Types of XLPE cables are 1) three-core 35 kV AC cable 23 MVA, 21 kg / m with 3 × 150 mm² Cu, 100 km length and 2) 100 kV AC cable, 100 MVA, 1 × 300 / 400 mm² Cu, 14 kg / m, length 100 km. The cores are twisted together with a filling material in a trefoil. Swelling powder and tapes are used under the lead sheath to protect from water.

Results: Reliable supply of electricity to the Croatian island economy.

Location: France, West Brittany, St-Brieuc – Lorient

Year of commissioning: 2018

Description: A major 225 kV underground cable to enhance the reliability of energy supply to West Brittany customers. Energisation was done in 12 / 2018. It was the longest cable ever put in service in France.

Design: 76 km in total length (three unipolar cables and two fibre optic cables in PEHD pipes) in two sections 46 km and 30 km with an intermediate substation. 83 % is 2500 mm² Al and 17 % is 2000 mm² Cu, 58 joint chambers, 56 water flows to cross. 26 months of field work.

Results: Reliable supply of electricity to West Brittany.

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HVDC XLPE (Cross-linked polyethylene)

Favourable installation, operation and testing parameters have led to the development of extruded insulation cables for HVDC application. Extruded cables are insulated using XLPE as an alternative to oil or MI. Thermal properties of XLPE allow a continuous maximum conductor temperature of 90 °C and a maximum short circuit temperature of 250 °C and, therefore, higher transmission capacity per cable compared to other technologies.

Technology Types

The following technology types of XLPE cables can be differentiated:

- Lying method
- Onshore
- Submarine
- Voltage level
- Conductor type and its diameter
- Aluminium
- Cooper
- Insulation of single wires
- Insulation material (depending on manufacturer different Additives)
- Metallic screen
- Outer sheath

Advantages & Field of Application

Polymeric HVDC cables are used mainly with VSCs that enable power flow to reverse without polarity reversal. Today, this technology has been implemented for voltages up to ±320 kV with a capacity of 1,000 MW for a symmetrical monopole. For voltages up to ±525 kV, cable systems are now under prequalification, but no pilot project exists. The basics for HVDC submarine cables are the same as those of HVDC land cables, except for mechanical features. Their advantages are related to their weight (20 – 35 kg / m) and diameter (90 – 120 mm), which make them very competitive compared with the other insulated DC cable types.

Technology Readiness Level

TRL 3 – 7

Onshore:

TRL 9 (2019) Extruded HVDC, 320 kV
TRL 5 (2020) Extruded HVDC, 525 kV
TRL 3 (2020) Extruded HVDC, 600 kV

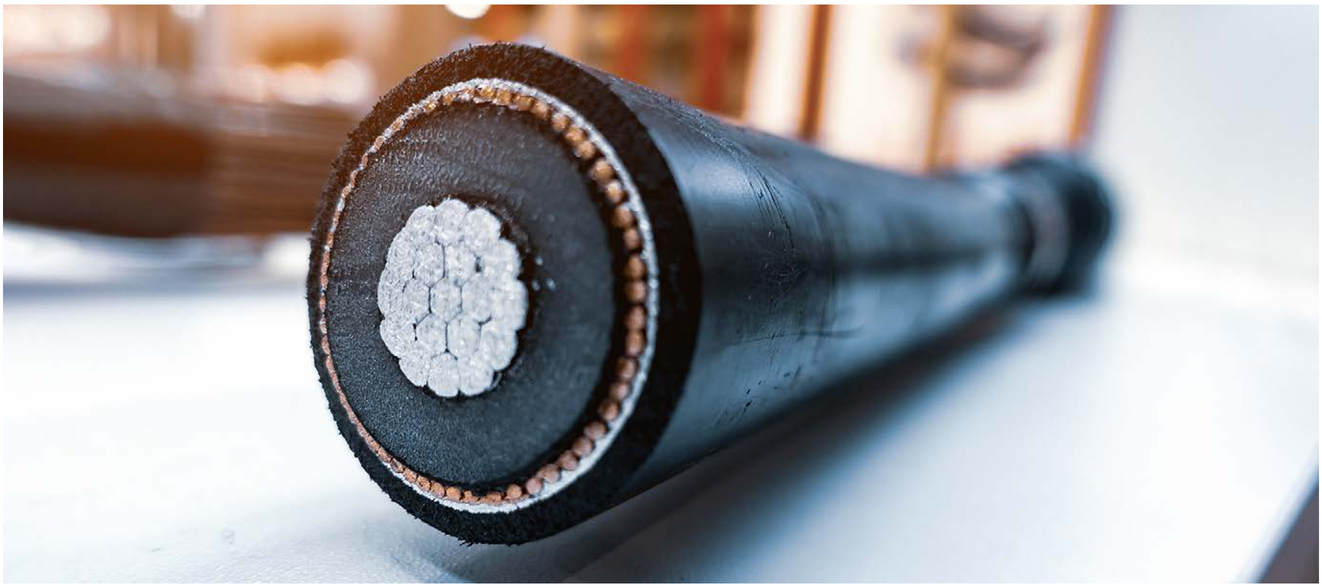
Research & Development

Current fields of research:

- Increase in voltages up to ±600 kV
- Increase in conductor size from 2,500 to 3,000 mm²
- Development of new extruded materials other than XLPE
- For subsea cables, the laying depth should reach more than 2.5 km by 2050.

Other:

There are issues with uneven distribution of charges inside the insulation which, in the case of rapid polarity reversals, can cause localised high stress which results in the accelerated ageing of the insulation.



Best Practice Performance

Maximum capacity: Approximately 1,000 – 1,200 MW today, expected to increase to 1,900 MW in 2020 with an increased conductor size

Current rating: 1.9 kA

Voltage rating: ± 525 kV

Longest distance: No limitation for the cable itself

Maximum sea depth: 1,000 m

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Best Practice Application

Location: UK (Kent), Belgium (Zeebrugge)

Year of commissioning: 2019

Description: A cable system with a 130 km subsea route and 11.5 km on land, installed and taken into commercial operation early 2019.

Design: DC ± 400 kV, transmission capacity 1 GW.

Results: Compared to conventional cables, higher temperatures can be reached. In addition, oil is no longer required as an insulation, making it more environmental-friendly.

Location: Ireland, Great Britain

Year of commissioning: 2013

Description: 'East-West Interconnector' 500 MW Sea Link between Ireland and Great Britain, installed in 2013.

Design: Two parallel submarine cables were installed. The DC voltage is rated at 200 kV. The total length is 262 km, with a submarine cable share of 186 km.

Results: Better insulation allowing higher temperatures. Submarine construction enabled.

Location: France, Great Britain

Year of commissioning: 2020

Description: 'IFA 2' 1 GW, ± 320 kV DC Sea Link between France and Great Britain, to be installed in 2019 – 2020.

Design: The total length is 230 km, with a submarine cable share of 202 km. Energisation should occur in 2020.

Results: Water crossing possible through submarine construction with the help of XLPE insulation.

High Temperature Superconductor Cables

Superconducting cables are based on special superconducting materials that are cooled down to extremely low temperatures (e.g. – 180 °C) using liquid nitrogen (or liquid helium for MgB_2) to activate the superconductivity phenomenon (very low resistance).

These conductors are placed in a pipe with vacuum (cryogen) which thermally isolates the superconductor from the remaining environment. They carry five times the current of a conventional cable system with the same outer dimensions, and they do not emit any heat to the environment. When comparing the cost benefit of HTS vs. conventional conductors, the losses of the superconducting cables are equivalent to the energy required to keep low nitrogen temperatures and its circulation. The technology requires special cable joints and specific cable termination for extreme temperature differences and permanent cooling for keeping cryostat. This factsheet focuses on voltage levels above 110 kV, although the operational properties of HTS allows operating voltages at lower levels.

Technology Types

Three types of superconductors are commercially available for AC or DC power cables:

- $Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO) with a critical temperature of – 160 °C
- $YBa_2Cu_3O_7$ (YBCO) with a critical temperature of – 180 °C
- MgB_2 with a critical temperature of – 235 °C

Components & Enablers

The main components are:

- HTS tapes or wires
- High voltage insulating material (dielectric)
- Cryostat wall
- Liquid nitrogen (for BSCCO and YBCO)
- Copper and hollow former
- Polyethylene sheath
- Cooling system
- Cable joints and terminations.

Two main types of superconducting power cables according to the type of dielectric used are existing:

- The ‘warm dielectric design’ is based on a conductor, cooled by the flow of liquid nitrogen surrounded by a cryogenic envelope using two concentric flexible stainless steel tubes with vacuum and superinsulation in between; the outer dielectric insulation, the cable screen and the outer cable sheath are at room temperature.
- In the ‘cold dielectric’ design, the liquid nitrogen is used as a part of the dielectric system. Although more ambitious to manufacture, the cold configuration has the advantage of containing the electromagnetic field inside the superconducting screen, which significantly reduces the cable inductance.

The design of superconducting HVDC power cables is very similar to the design of superconducting HVAC power cables. The inner HTS layers are separated through the dielectric from a screen, consisting of copper wires only.

Advantages & Field of Application

HTS cables offer several advantages compared to conventional cables, depending on the case study:

- **Easier and shorter installation time.** Grid operators can benefit from shorter installation time as HTS cables are compact and can be routed underground through existing gas, oil, water or electric corridors or along highway or railway rights of way. In addition, HTS cables are actively cooled and thermally independent of the surrounding environment, making them easier to install. These aspects pave the way for higher capacity transmission corridors. However, a careful analysis of the magnetic field impact will be carried out on the infrastructures sharing the same corridors.
- **Low impact on the environment.** Reaching much higher levels of current density enabling compactness and higher capacity power transmission over the cables than conventional cables constitutes a key advantage for the operators and the environment. A superconductor system also has a smaller footprint in an underground installation as a result of not requiring large separation between cables.
- **High Power carrying capacity.** Achieving higher levels of current density means that operational voltages can be reduced while still facilitating bulk power transfer at high capacities. Lower operating voltages reduces the size and volume of the electrical equipment required at both ends of the cable.

Due to the low electromagnetic fields generated by HTS cables, the effect on the surrounding area is significantly reduced.

Despite the superconducting properties with electric resistance close to zero at temperatures below the critical temperature, HTS cables are still subject to energy losses, mainly taking the form of thermal leaks (the induced current in the metallic part remaining low). Energy losses in an HTS cable depend on the load and, therefore, on where the cable is placed in the power transmission grid. For an HTS cable at 2 kA, losses could be at a level of approximately 25 % of the losses in the conventional cable system (but at no-load, the losses in the HTS cable are larger due to the thermal leak).

The significant reduction of transmission losses is thus counter-balanced by the necessary cooling requirements. The no-load losses due to a non-ideal thermal insulation will therefore result in deploying HTS cable in connections with high load current in a large part of the time.

HTS DC Cable are well suited for long-distance high power transmission and bulk energy transfer.

As of today, it is observed that a high number of HTS cables are being installed in urban areas requiring high current capacity at medium voltage levels.

Technology Readiness Level

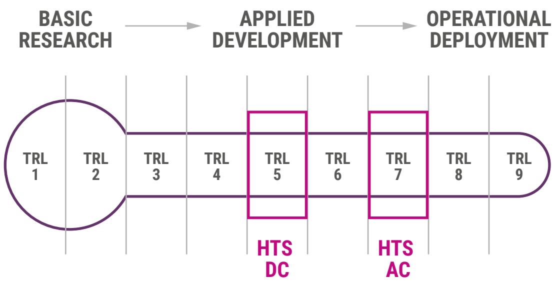

Figure 1: Technology readiness level for HTS transmission from [8]

- **TRL 5 to 6** for HTS in DC transmission systems. The literature provides a TRL of 5 as testing on integrated systems is still limited, but the recent demonstration nb.5 of the FP7 funded Best Paths project, with a range of 5 – 10 kA at 200 – 320 kV, indicates a TRL of at least 6.
- **TRL 7 to 8** for HTS in AC transmission systems. TRL 7 for high power HTS AC transmission systems or HTS distribution systems for congested urban areas, as integrated pilot systems have already been demonstrated. The Shingal Project in South Korea is the first-of-a-kind commercial project and has achieved a TRL of 8. In particular, several projects have been discussed in Jeju (South Korea) with 154 kV and Long Island (US) with 138 kV.

Research & Development

Current fields of research: Magnetic design and stress analysis on new superconductor material e.g. Bi_2 or MgB_2, cable stability analysis against internal flux jumps and external thermal perturbations, electromagnetic field analysis for HVDC superconducting cables, applications in HV and EHV.

Innovation priority: Optimisation of the cryogenic cooling system, optimisation of manufacturing process and material physical footprint.

Best Practice Performance

HVAC: 350 kV, 700 kVA, 4 kA

HVDC: 650 kV, 10 kA

Impulse voltage: 1,200 kV, 60 kJ

Cooling temperature: –208.15 °C to –193.15 °C

Pressure: up to 1.5 MPa

Selected Best Practice Application

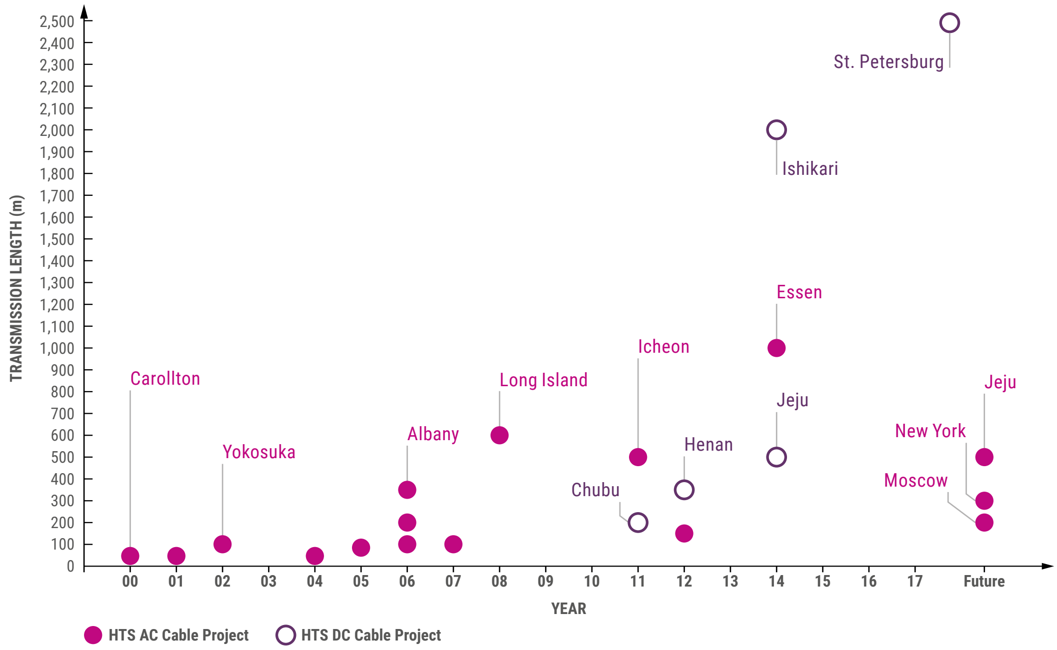

Figure 2: Overview of HTS transmission projects over the last two decades from [8] (NB: visual includes HV and MV)

Location: Shingal, South Korea

Year of commissioning: 2019

Description: The Shingal Project is a 1 km 23 kV AC HTS cable connecting the 154 kV substations of Shingal and Heungdeok.

Design: 23 kV, 1.6 kA triad configured HTS cable with 50 km of HTS tape used. The cable will act to share the supply capacity between the Shingal substation and the underutilised Heungdeok substation.

Results: The system operated as planned and, during commissioning, all tests proved successful. This has led KEPCO to investigate the further application of the 23 kV system as well as AC 154 kV HTS cables in succession to the Shingal Project success. [16]

Location: Ishikari, Japan

Year of commissioning: 2015

Description: National project in which a 500-m cable connected an Internet data centre (iDC) to a large scale array of photovoltaic cells to supply DC power.

Design: Construction of two DC superconducting power cables of 500 m (Line 1) and 1,000 m length (Line 2) respectively. The cable of the Line 1 is installed into the underground and composed of two cables.

Results: The heat leak of the cryogenic pipe is ~1.4 W/m, including the cable pipe and the return pipe. The heat leak of the current lead is ~30 W/kA in the test bench. Finally, a current of 6 kA/3sec and a current of 5 kA/15 min were achieved in Line 1.

Location: Saint Petersburg, Russia

Year of commissioning: 2016

Description: Cables between two substations in downtown St. Petersburg spanning a distance of 2.5 km. Connecting the 330 kV 'Tserntralnaya' and 220 kV 'RP-9' substations will provide reserve power network capacity, allowing new consumers to connect to the system and improve system reliability and limit fault currents for existing end users.

Design: 50 MW, 20 kV HTS DC cable on 2.5 km

Results: Tests were conducted on two 30-meter cable samples, two 430-meter cables, three pairs of current leads and three joints. Critical current (IC) tests were carried out at 68 K to 78 K; resistance remained stable and the cable performed as expected. The cables also passed high-voltage testing.

Location: Germany, Hungary, Norway, Belgium, Sweden, Spain, Denmark, Switzerland, France, United Kingdom and Italy

Year of commissioning: 2017

Description: BEST PATHS was a collaborative project of 40 leading European organisations from science and industry, supported by the EC FP7 (2014–2018). The project investigated the feasibility of technological innovations that could advance high-capacity transmission links. This included a demonstrator project dedicated to superconducting electric lines, to validate the novel MgB_2 technology for GW-level HVDC power transmission.

Design: Through insulated cross-arms, long-term tests with HTLS as well as dynamic line rating, existing lines are to be optimised to maximise power transmission.

Results: The operation of a full-scale 320 kV MgB_2 monopole cable system that can transfer up to 3.2 GW was demonstrated (demonstration nb. 5 of the project).

Location: Essen, Germany

Year of commissioning: 2014

Description: The AmpaCity project is a 1 km 10 kV HTS cable installed in 2014 to replace a 110 kV underground cable system connecting two 10 kV substations in Essen Germany.

Design: The three-phase, concentric cable replaces the conventional 110 kV copper line connecting two substations in central Essen and eliminates the need for a high-voltage transformer at one of the substations.

Results: The cost of the energy required to cool the cable down to eliminate its resistance over its lifecycle was found to be 15 % lower than the equivalent cost of compensating losses in conventional 110 kV cables. HTS are mentioned as the best technical and economically viable solution to avoid the necessary extension of the 110 kV grid in urban areas.

Location: Oak Ridge National Laboratory (Phase 1), Yonkers, NY (Phase 2), USA

Year of commissioning: 2016

Description: The HYDRA project Phase 1 was a 25 m prototype that was successfully tested at Oak Ridge National Laboratory. Phase 2 consists in connecting two substations in Westchester County. This HTS FCL Cable installation will allow the asset sharing of a 13.8 kV transformer combined with fault current protection to equipment.

Design: Phase 1 using 25 m HTS FCL Cable, phase 2 aims at connecting 2 Con Edison 13.8 kV substations with a cable length of 170 m.

Results: Phase 1 of the projects helped the qualification of HTS FCL cable for Power Network.

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Gas Insulated Lines – AC

In Gas Insulated Lines (GIL), the inner conductor is located in a pipe the approximate diameter of which is 50 cm. It is kept central using disc or support epoxy resin insulators. The pipe is filled in with insulating gas. Compared to OHL and underground cables, the electric and magnetic field is very low. Nowadays, GIL are mainly used in short lengths within substations, in densely populated areas or to connect industrial / power plants to the transmission network transferring current.

Technology Types

The technology type is defined by:

- The gas mixture used in a GIL.
  - ↳ 100 % SF6 insulated – majority of projects commissioned between 1970 and 2000
  - ↳ Gas mixture: N2 and SF6 mixture – majority of projects commissioned after 2000
  - ↳ Alternative (synthetic) gases – currently under development
- Disc insulator design
- Assembly for the 15 – 20 m GIL pipe sections
  - ↳ welding
  - ↳ flanged connection
- Application type:
  - ↳ Air insulated substations
  - ↳ Tunnels
  - ↳ Direct burying in earth

Components & Enablers

- Outer sheath (usually an aluminium tube of around 50 – 60 cm diameter)
- Inner aluminium conductor
- Epoxy-resin insulators
- Insulation gas (5 – 7 bar)
- Additional outer coating for direct burial
- Elongation compensators
- Angle components

Advantages & Field of Application

GIL are an alternative to OHL or underground cables if high capacity in narrow and complex routing is required.

Reactive compensation

Due to capacitance comparable with overhead lines, GIL systems typically do not require compensation.

Electromagnetic fields

The construction of GIL results in a complete shielding of electric fields and many times smaller magnetic fields comparing to cables and overhead lines.

High safety

GIL are fire resistant and do not contain flammable material, nor do they emit noxious fumes under fire conditions. In short circuits inside the GIL system, toxic products may occur, but the arc does not leave the GIL compartments.

Lifetime

The gas used as insulating media does not age. In typical application, the doubling of lifetime comparing to conventional VPE cables can be expected.

Routing

Realisation of 90 degrees, vertical, curved sections with narrow spacing of phases is possible

Technology Readiness Level

TRL 7

For EHV application:

2020: TRL 7 – GIL (SF_6 free)
2025: TRL 8 – GIL (SF_6 free)
2030: TRL 9 – GIL (SF_6 free)

* GIL by pure SF_6 or SF_6 mixture is a mature technology. TRL is 9.

Research & Development

Current fields of research: finding substitute to SF_6 and adapt design accordingly, speeding up construction and assembly time on-site.

Best Practice Performance

Maximum capacity: 2850 MVA (at 500 kV)

Maximum current rating: up to 4,500 A

Typical voltages: 245 kV-500 kV

Longest distance: 3.3 km (realised, 275 kV)

Energy losses: 0.0015 %/km at 500 kV and 260 MW

Standard definition: IEEE Std C37.122.4-2016 – IEEE Guide for Application and User Guide for Gas-Insulated Transmission Lines, Rated 72.5 kV and Above

Expected lifetime: >60 years

Selected Best Practice Application

Location: South East of England

Year of commissioning: 2017

Description: National Grid applied; a SF_6-free 420 kV GIL. The 230 meter long, gas-insulated circuits connects the substation to the OHL in the ElecLink project, via a 1 GW HVDC cable.

Location: Frankfurt, Germany

Year of commissioning: 2011

Description: The underground connection of the GIS substation close to Frankfurt Airport was needed. The aim of the project was to demonstrate the alternative to cable and reduce the trench size.

Design: Two three-phase 380 kV welded GIL systems were laid directly in the ground, with a length of 900 m each. Gas mixture consists of 80 % N_2 20 % SF_6. Both conductor tube and enclosing tube are made of aluminium.

Results: No need for reactive power compensation.

Location: Shinmeika-Tokai line, Japan

Year of commissioning: 1998

Description: Connection of a power plant to the grid to deliver energy into the Nagoya high industrial region.

Design: Two three-phase 275 kV welded GIL, designed to transport 1 × 2,850 MVA. It is one of the longest GIL in the world, with a length of 3.3 km each. The GIL is installed in a tunnel where space for the assembly work is limited and atmosphere is dusty. Gas: 100 % SF_6.

Results: High voltage power transmission was made feasible given the geographic constraints.

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Gas Insulated Lines – DC

Direct Current Gas Insulated Lines (GIL), known as DC CTL – Compact Transmission Line for HVDC, is a newly under development transmission technology. The challenges for the DC CTL is posed by the special design of the components, considering their specific properties at high direct voltages. In DC CTL similarly to AC GIL, the inner conductor is located in a pipe of approximate dimeter of 50 cm. It is kept central using disc or support epoxy resin insulators. The pipe is filled in with insulating gas.

Technology Types

The technology type is defined by:

- The gas or gas mixture as insulating medium
- Disc insulator design
- Assembly for the 15 – 20 m GIL pipe sections
  - ↳ welding
  - ↳ flanged connection
- Application type:
  - ↳ air insulated substations
  - ↳ tunnels
  - ↳ direct burying in earth

Components & Enablers

- Outer sheath (usually aluminium tube of around 50 – 60 cm diameter)
- Inner aluminium conductor
- Epoxy-resin insulators
- Insulation gas (5 – 7 bar)
- Elongation compensators
- Angle components

Advantages & Field of Application

GIL are an alternative to overhead lines or underground cables if high capacity in narrow and complex routing is required

Electromagnetic fields

The construction of AC GIL results in a shielding of electric fields and in 15 to 20 times smaller magnetic fields in the vicinity of the installation than with conventional power transmission systems.

High safety

GIL are fire resistant and do not contain flammable material, nor do they emit noxious fumes under fire conditions. In short circuits inside the GIL system, toxic products may occur, but the arc does not leave the GIL compartments.

Lifetime

The gas used as insulating media does not age. In typical application, the doubling of lifetime compared to conventional VPE cables can be expected.

Routing

Realisation of 90 degrees, vertical, curved sections with narrow spacing of phases is possible

Technology Readiness Level

TRL 4 – 5

For EHV applications:

2020: TRL 4 – 5 *(N2 / SF6 mixtures)
2025: TRL 6
2030: TRL 8

* based on ~30 IEEE publications in this domain, mostly from Europe and published after 2016

Research & Development

Current fields of research: Finding a substitute to SF6 and adapting basic design accordingly; the design of the epoxy resin insulators and their long term dielectric performance; particle-free assembly or particle treatment; measurement of electrical performance (partial discharges); speeding up construction and assembly time on-site.

Best Practice Performance

Currently, DC GIL have not yet been realised in extra high voltage network. DC GIL with following technical specifications are under development and are expected to be available in the future:

Maximum capacity: 5 GW

Current rating: 5 kA

Voltage rating: 525 kV

Selected Best Practice Application

Location: Germany

Year of commissioning: Began 2014 and still ongoing

Description: In collaboration with three German universities, Siemens is developing and testing the first DC GIL in Germany designed to transfer 5 GW. The project is also funded by the federal German government.

Design: The DC CTL is based on the technology of the existing GIL, which consists of two concentric aluminium tubes. A mixture of gases is used as the insulating medium. The challenge for the DC CTL is posed by the special design of the components, considering their specific properties at high direct voltages.

Results: Enabling the compact DC transmission of electricity. HVDC systems, in conjunction with DC GIL, will make the transmission grid with superimposed DC a reality. It will also allow for the space-saving design of substations and transmission corridors.

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Dynamic Line Rating

The Dynamic Line Rating (DLR) of OHL uses the fact that the ampacity of OHL depends on ambient conditions and the OHL are designed for high summer weather conditions. As less severe weather conditions exist for most of the year, the ampacity of the existing lines can be significantly increased (up to 200 %). The major task, therefore, is to derive the present conductor temperature (or sag), forecast the future ambient conditions and integrate these monitoring results to dispatch centre processes, considering adequate security margins.

Technology Types

The application of DLR requires knowledge about the maximal allowable temperature of OHL conductor, which is also proportional to sag. As sag has a relatively small time constant, the maximal temperature can be reached quickly (approximately 15 min). For TSOs that do not have the quick and direct possibility to reduce line load, DLR requires weather forecasts to allocate the possible additional capacity to the market in system operator processes (IDCF intra-day congestion forecast, DACF day ahead congestion forecast, WAPP week ahead).

In general, there are two main technology groups (contact and non-contact) to acquire the sag or temperature of OHL conductors:

- **Contact technologies:** the conductor temperature is measured with the help of temperature sensors:
  - Calculation of sag through measurement of tension
  - Calculation of sag based on the vibration frequency of conductors
  - Calculation of sag based on the angle of the line at the span point[1]
- **Non-contact technologies:** the ampacity and conductor temperature are calculated based on meteorological models and/or locally measured weather:
  - Calculation of the ampacity and conductor temperature based on regionally (faraway of OHL) measured weather conditions near thermal hot spots of OHL line
  - Calculation of the ampacity and conductor temperature based on meteorological models, considering the whole line
  - Direct measurement of sag using optical technologies

The technologies differ, especially in terms of the effort required for installation, need of modelling and the ability to make a reliable long-term forecast of the ampacity of the line. For non-contact technologies, there is no need for the de-energising of line for installation and maintenance, and all the weather parameters required for local weather forecast can be measured directly. However, the models require adequate validation. For some of the contact technologies, there is a possibility of installing the sensors using helicopters or bare-hand installation techniques (live working) and acquiring some of the weather parameters for forecast. Non-contact solutions based on advanced meteorological models are very suitable for hilly terrains, where weather conditions can vary within just a few kilometres and each line-span or at least each tension field should be securely monitored.

Due to the different specific requirements of TSOs (especially need for forecast), different approaches are used across Europe.

1 Fixing point of the conductor to the insulator

Advantages & Field of Application

An increase of ampacity can be achieved up to 200 % depending on the weather conditions and required confidence intervals. The highest potential is observed in areas of high wind RES where similar weather conditions exist along OHL.

An increase in ampacity supports grid operators in making more efficient use of existing grid assets and avoiding congestion restrictions.

Typically, the permitted line capacity equals the nominal current of the conductor. If there is a need to increase the capacity of the old line up to the nominal current, the following points are important:

- Check the ability of OHL and equipment in substations to carry higher currents
- Check the clearances for defining maximal allowable temperature / line capacity
- Identify line hot spots for installation of monitoring
- Check the static line protection settings
- Design a data delivery into the dispatching centre and the data processing
- Tailored algorithm for transmission capacity calculation
- Forecasting algorithms
- Replacing static line rating (SLR) by DLR in the TSOs' EMS for processing dynamic line ratings in congestion calculations.

Increasing the line capacity above the permitted value (nominal current) typically requires, in addition to the above-mentioned points, additional proof and permits in relation to:

- The maximum allowable inductive influence of parallel infrastructure (e.g. gas pipelines)
- The potential increase of the magnetic field below OHL
- The need of adaptive change of line protection settings

Technology Readiness Level

TRL 9

TRL 9

Best Practice Performance

Maximum capacity increase: Enhancements of +40 % and +100 % compared to static line rating.

Average capacity increase: Typical ampacity gains in Europe of 10–15 % can be expected over 90 % of the time. However, the results are highly case-specific and depend on the impact evaluation methodology.

Research & Development

Current fields of research: Mid-term and long term forecast adequacy of ampacity; integration into long term forecast processes to fulfil system stability requirements; accuracy of derived values; enhanced combination with weather forecasts.

Other: In 2015, 11 ENTSO-E TSOs had DLR in operation in different extensions.

Selected Best Practice Application

Location: Belgium / France

Year of commissioning: 2008 – 2020

Description: DLR systems are installed on 27 lines including all HVAC interconnection lines and both real-time and forecast DLR data are used in intraday and day-ahead operation planning and market capacity allocation processes. The recent development of the system and its validation through surveyor measurements of sag demonstrated that up to 200 % of rated capacity was available in certain circumstances.

Design: Commercially available sensors were used to measure real-time sag directly on 70 kV, 150 kV, 245 kV and 400 kV lines. Up to 60 h-ahead forecast module has been developed.

Results: Intraday rated capacity is raised up to 130 %, whereas for CORESO processes it is raised up to 110 % based on statistical risk assessment.

Location: Fuendetodos – María line, Spain

Year of commissioning: 2017

Description: The research for BEST PATHS is focused on repowering existing power lines and enhancing the technological knowledge and application of conductor technologies through different innovations. DEMO 4 has addressed the following objective through the development of a prototype DLR system based on low cost sensors, allowing for higher temperature operations of current line technologies. Part of the BEST PATHS project is the implementation of the DLR sensors on a transmission line in Spain.

Design: Using 7 DLR sensors on existing 220 kV live line variations in a catenary angle of 0.005 ° or 10 cm in sag will be measured and communicated for optimal line loading.

Results: Using data from DLR sensors, existing corridors were optimised to carry more power. A transmission capacity increase of 15 – 30 % was measured over the duration of the experiment, which lasted 3 months.

Location: Germany

Year of commissioning: Circa 2015

Description: DLR is used on many heavily loaded OHL. The system is integrated into most of the German TSO's dispatching centres that exchange the ratings online.

Design: There are different approaches for weather forecasts based on local and regional measurements as well as seasonal settings. The maximal derived ampacity differs depending on the region.

Results: Rated capacity was raised up to 200 %

Location: Slovenia

Year of commissioning: 2013 – 2017

Description: The DLR system covers 29 lines (6 × 400 kV, 4 × 220 kV and 17 × 110 kV). The system is fully functional and integrated into the daily operation. The main applications that support real-time operation and operation planning are the mitigation of N and N-1 overloading operational situations and calculations of transmission capacities for up to two days ahead. The system also features an inverse DLR algorithm for icing prevention and alarms for extreme weather conditions along the lines.

Design: Indirect (non-contact) DLR system based on macro and micro-scale meteorological models supported by weather measurements. Calculations are performed for each line span. The system allows the definition of maximal operating temperature per tension field. Comprehensive modular IT system with data quality monitoring and uncertainties modules, integrated with the SCADA / EMS.

Results: On average, 92 – 96 % of the time the DLR system offers a higher transmission capacity with a median increase of 15 – 20 % of the nominal capacity. Over 20 events in N and over 500 in N-1 topologies are mitigated annually by the DLR system.

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Hybrid AC/DC OHL Conversion from AC to DC

Hybrid AC / DC OHL is a technology used to increase the transmission capacity of existing mainly AC OHLs through converting an existing AC circuit into a DC circuit. This also creates a bypass to the AC grid with better power flow control.

Technology Types

The major factors in the design of hybrid AC / DC OHL are the internal and external air clearances as well as emissions (noise, electric and magnetic field, ions). Depending on those factors, the voltage rating and design of DC system can be achieved. The hybrid AC / DC OHL use the same components as pure AC or pure DC lines. Although there are no special requirements concerning the conductors and towers, the insulators should be designed for hybrid AC / DC voltage stress.

Technology Readiness Level

TRL 7

2020: TRL 7
2025: TRL 9
2030: TRL 9

Components & Enablers

- Towers
- Conductors
- Insulators

Research & Development

Current fields of research: Hybrid AC / DC corona effects, insulator design.

Other: Long term full-scale outdoor pilot projects are necessary to conclusively verify the theoretical developed approaches

Advantages & Field of Application

Due to the need for new transmission line capacity and public concerns about the erection of new transmission lines, increasing transmission capacity by converting one of the existing HVAC lines to HVDC may be an interesting option.

The conversion of existing OHL can be done by the replacement of insulators only and by keeping the conductors and towers as they are. However, the maximum operating voltage must be chosen properly to maintain the given internal and external electric clearances and avoid corona associated levels of noise and ionisation of air.

Best Practice Performance

Maximum capacity: Based on the Ultranet project, an increase of transmission capacity of approximately 10 – 20% can be expected. This results in ca. 2,200 MW per converted 380 kV circuit

Voltage rating: 420 kV

Current rating: 2.7 kA

Selected Best Practice Application

Location: North Rhine-Westphalia and Baden-Württemberg, Germany

Year of commissioning: planned for 2024 (commissioning planed)

Description: An existing 3-phase HVAC OHL will be converted to a bipolar HVDC system on the same tower. Converter stations are built at either end of the transmission line.

Design: Full Bridge Technology converters will be applied based on requirements concerning the fast clearing of inter-system faults, frequent performance of auto-reclosing actions and better reactive power support to the AC system.

Results: The project is making use of the existing pylons to increase the capacity of the network in an efficient and resource-friendly manner.

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HVDC Mass Impregnated Cables

HVDC Mass Impregnated (MI) cables are a very consolidated and traditional technology mainly deployed for subsea applications. Initially, MI cables were used with LCCs. Currently, this technology is mainly deployed for Extra High Voltage (EHV) DC subsea applications. MI cables are composed of a very high viscosity impregnating compound which does not cause leakage in the event of cable damage or failure. The latest innovation allows voltages of up to 600 kV.

Technology Types

There are three main types of cables based on the solution used to insulate the conductor: self-contained fluid-filled cables, paper insulated (lapped insulated) cables and extruded cables.

MI cables belong to the mass paper insulated cables types, which comprise:

- MI or paper-insulated lead-covered (PILC); the MI insulation consists of a MI paper with high-viscosity insulating compound.
- Paper polypropylene laminated (PPL) cables, where the insulation comprises an extruded sheet of polypropylene, on either side of which are bonded two layers of thin paper.

Advantages & Field of Application

MI HVDC cables are currently the most used cables for HVDC submarine applications. Compared to oil filled cables, the compact design makes them particularly suitable for deep water applications. In contrast, their use for land applications is limited compared to extruded XLPE cables.

Benefiting from approximately 50 years of experience in service, with a proven high reliability, they can be provided by European manufacturers at voltages up to ± 600 kV and 1,800 A, which makes approximately 2,200 MW per bi-pole.

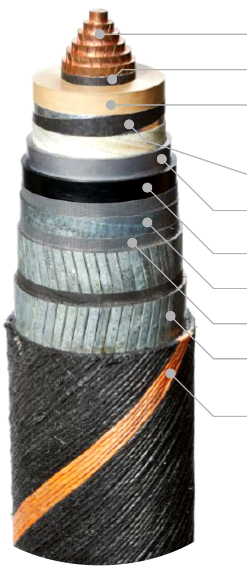
Cable industry experts expect an improvement of this mature technology (underground and submarine) in several directions: an increase of power transmission level above 2,300 MW for a dipole, reduced level of losses (consequence of the upgrading of operating voltage).

Components & Enablers

The main components of MI HVDC cables are:

- The copper or aluminium (Al or Cu) Conductor
- The mass impregnated paper insulation
- The lead alloy sheath
- The overall protective plastic sheath (Polyethylene)
- The steel armour for submarine cables to improve the mechanical performance

Example of MI HVDC cable:

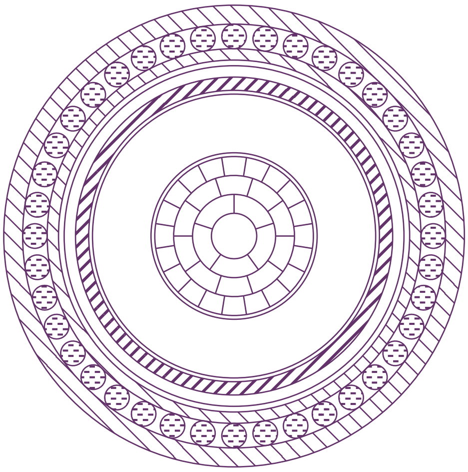


Typical Weight
30–60 kg/m

Typical Diameter
110–140 mm

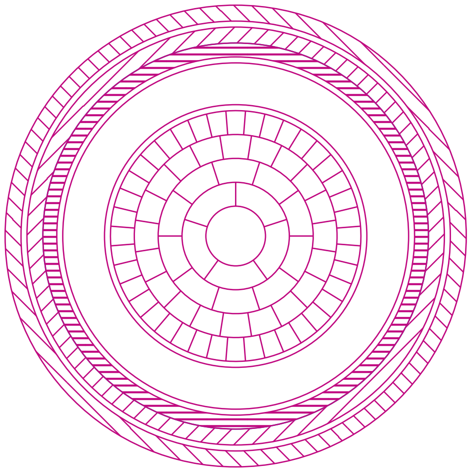
Components & Enablers (cont.)

Cable system – HVDC 400 KV MI Cables:



SUBMARINE HVDC Cable

Cu Conductor	1,500 mm²
Insulation	Mass impregnated paper
Armour	Galvanized steel
Overall diameter	121 mm
Weight of cable	43 kg/m



LAND HVDC Cable

Cu Conductor	2,000 mm²
Insulation	Mass impregnated paper
Armour	Galvanized steel
Overall diameter	121 mm
Weight of cable	38.5 kg/m

Mass impregnated cables are compatible for the HVDC conversion systems available today, i.e. CSC and VSC.

Technology Readiness Level

TRL 9

For on-shore (underground – corresponding to 5% of applications above 110 kV) and off-shore applications (submarine), **a TRL 9** has been reached (System ready for full scale deployment at the current performance).

Best Practice Performance

For on-shore (underground) and off shore (submarine):

Maximum Installed Rating: 2,200 MW bi-pole (±600 kV and 1,800 A)

Longest distance: no limitation, example of North Sea Link of 720 km (submarine, planned completion 2021)

Maximum sea depth (off-shore only): 1,000 m

Research & Development

Current fields of research: Increase in power; reduction of losses; increase in water depth for submarine installations; alternatives for use of lead in sheath; ageing of mass impregnated insulation systems; increase the speed and manufacturing quality of the on-shore cable joints.

Innovation Priority: Voltage (up to 800 kV), maximum sea depth (over 2,500 m by 2050).

Selected Best Practice Application

Location: Norway, the Netherlands

Year of commissioning: 2008

Description: The NorNed HVDC MI sea cable interconnection between Norway and the Netherlands was completed in 2008. The rated DC voltage is ± 450 kV DC and the transmission capacity is 700 MW. The entire link has a length of 580 km.

Design: Impregnated non-draining, paper insulated HVDC cable. Two different designs are used: twin-core and single-core cable. Both cables consist of copper conductor(s) and a layer of semi-conducting carbon paper.

Results: This link enables power trading and increases energy supply reliability.

Location: Denmark – Norway

Year in service: As of end 2014

Description: The Denmark–Norway Interconnector (SKAGERRAK 4) is a joint project between Statnett and Energinet.dk. It is the first VSC connection at a voltage of ± 525 kV with a monopole MI cable of 700 MW. The transmission capacity is 715 MW and the water depth is 550 m.

Design: The submarine part of the cable is 137 km long and the underground directly buried portions in Denmark and Norway are 92 and 13 km respectively.

Results: The interconnector facilitates more renewable energy production in both countries and benefits consumers and the industry amongst others through more stable power prices and increased security of power supply.

Location: North Sea – between Norway and UK

Year of commissioning: 2021

Description: North Sea Link will be operational in 2021 and will be the longest subsea interconnector in the world. The capacity is 1.4 GW and length is 720 km at a voltage of ±515 kV.

Design: The major part will consist of two parallel HVDC submarine cables, buried 1 to 3 m into the seabed. On both sides, a short distance of underground cable will also be constructed from the landfall to the converter station.

Results: Linking the two countries will provide opportunities to share renewable energy to meet new targets, increase supply security and provide additional capacity.

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Partial Undergrounding

Partial undergrounding with cables can be a solution when public acceptance or environmental impact does not allow for the installation of OHL. Compared to well-known conventional point-to-point cable connections, the consideration of further aspects is necessary, for example the design of cable-to-line transition, concepts for compensation of reactive power, special switching requirements to circuit breakers (CBs) and deriving maximal length of cable section.

Technology Types

For partial undergrounding, typical AC cables can be used. The choice of cable type depends mainly on required ampacity, installation time and required cable reliability.

The cables can be directly buried or placed in protective pipes. The latter can be laid conventionally in trench or in drilled mini tunnels.

At the transition point between cable and overhead line substations are required. They are typically equipped with current transformers and surge arresters only. Therefore, air and gas insulated solutions are available.

Components & Enablers

- EHV AC cables (in majority XLPE type)
- Cable joints and terminals
- Transition stations
- Reactive power compensators

Advantages & Field of Application

The concept of the partial undergrounding of HVAC transmission lines has become one of the solutions for achieving public acceptance and obtaining building permits, even when direct financial costs are significant.

The decisions regarding the use of partial underground section should be taken in conjunction with the investment costs, obstacles (roads, water pipes etc.) in the cable route and different environmental impacts during the construction phase. Moreover, further specific system aspects such as a shift of the network resonance frequencies or dynamic stability and the special switching requirements for CBs (energising resistance, missing zero crossings) should to be considered.

Technology Readiness Level

TRL 8

TRL 8 – EHV Pilot Projects

Research & Development

Current fields of research:

Deriving the maximal cable length that can be integrated into a specific system, increasing the reliability of cables and joints, improving cable laying technology (in trench and tunnel).

Best Practice Performance

Maximum capacity: 1,700 MW – 2,500 MW

Current rating: 1.8 (single) – 3.6 kA (double cable per phase)

Voltage rating: 380 kV

Selected Best Practice Application

Location: Wesel – Dörpen, Germany

Year of commissioning: 2023 (commissioning planed)

Description: Part of a planned 150 km 380 kV AC-EHV transmission line will be underground. The commissioning of the complete link is planned for 2022. Some parts of the transmission line (Raesfeld / Münsterland and Borken / Münsterland) are in pilot operation as a junction of two busbars.

Design:

- 380 kV, 3600 A, 2.6 GW cross-linked polyethylene
- Length of partial underground cables ~ 3.4 km

Results: The pilot project shows that it is possible to lay cables in open trench considering the environment friendly soil treatment.

Location: Delft, Netherlands

Year of commissioning: 2012

Description: The project 'Randstad Ring' connects the four largest cities in the Netherlands with two 380 kV lines. Approximately 11 km of the 132 km cable connection is installed as underground cable. The TSO completed it in November 2012.

Design:

- XLPE cable, conductor size 2,500 mm²
- 132 joints with screen separating insulations
- 24 outdoor terminations with composite insulators
- 68 link boxes for earthing and cross-bonding of cable screens
- High-voltage surge arresters, current transformers, fixing material and supporting structures

Results: Overcoming different obstacles along the transmission distance between Wateringen and Bleiswijk through partial undergrounding along 11 km of the distance.

Selected Best Practice Application (cont.)

Location: Beznau-Birr, Switzerland

Year of commissioning: 2020

Description: The project 'Gäbihübel', a 380 kV AC line from Beznau to Birr in Switzerland, will be performed by Swissgrid. The construction was planned to start in 2017 and be realised around 2020. Also, a distribution grid 110/16 kV will be laid underground.

Design:

- Length of underground cabling 1.3 km
- 2 m depth
- 380 kV AC, XLPE
- 2 × 150 mm² Cu
- max. short-circuit current 63 kA

Results: Forest obstacles in the area are overcome and the views are preserved in the area.

Location: Pogliano, Italy

Year: 2006

Description: The project 'Turbigo-Rho' connects the north sub-urban area of Milan. The total length of this meshed line is approximately 28 km and consists of a 380 kV overhead line single circuit at both ends with a double underground cable circuit of 8.4 km (16 km in total) in the middle, between the transition stations of Pogliano and Ospiate. The operator Terna completed it at the end of 2005.

Design:

- 8 km of 380 kV double circuit XLPE cable, conductor size 2,000 mm² Cu-Milliken
- Power capacity: 2,100 MVA
- Nominal current: 1,600 A
- Distance between the circuits: 6 m
- In operation since beginning 2006
- PD and DTS monitoring systems installed

Results: The main design criteria adopted for the choice of the route for the OHL is to avoid or minimise the crossings of protected areas (environmental constraints, landscape issues, etc.), urbanised areas (even where residential buildings are planned for the near future), and those zones presenting soil instabilities (flooding mud, erosion, overflowing).

Due to the necessity to cross a highly urbanised area and fulfil the stringent requirements in terms of environmental impact (electric and magnetic field limitation, visual impact, etc.), it was decided to install an underground XLPE cable system throughout the whole sensitive area.

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New Tower Concepts

The main components of OHLs are towers, tower foundation, conductors and insulators. The task of the tower is to carry the conductors that span two towers on insulators. In HV and EHV applications, mostly lattice towers are used because of their high efficiency, security in operation and cost effectiveness. Nevertheless, the conventional lattice tower concepts are understood as old and receive little acceptance by the public. Hence, the new tower concepts aim to minimise visual impact and optimise both the emissions and public support.

Technology Types

In HV and EHV, the following types can be differentiated:

- By tower body
  - ↳ Lattice towers
  - ↳ Full wall pylon (concrete or steel)
- By cross arm type
  - ↳ Lattice
  - ↳ Full wall
  - ↳ Insulated
- By number of earthing wires
- By number of circuits
- By arrangement of circuit phases
  - ↳ delta
  - ↳ one horizontal plane
  - ↳ one vertical plane

Advantages & Field of Application

The target of new tower concepts is to create a compact, environment friendly and affordable tower design that potentially increases public acceptance.

Moreover, the compact design can allow the capacity to be increased in right of way if the latter cannot be extended (e.g. 2 x 380 kV circuits in previous 2 × 220 kV right of way), or allow a reduction in the height of the towers by reducing the conductor sag (e.g. 50 Hz example).

Research & Development

Current fields of research:

Different approaches for full wall tower designs; insulated cross arms; compactness; reduction of air clearances by application of surge arresters.

Challenges are the design of a new compact tower while maintaining the current investment and maintenance costs, degrees of freedom for maintenance and repair works, and also reducing the electro-magnetic and noise emissions.

Technology Readiness Level

EHV

TRL 9

TRL 9 – Lattice towers

TRL 7

TRL 7 – New designs in pilot stage (e.g. full wall)

TRL 4

TRL 4 – Ideas and studies

Best Practice Performance

Typical EHV lattice tower

Number of circuits: 2 × 380 kV

Power rating: 2 × 2,600 MW

Voltage rating: 420 kV

Nominal current: 4,000 A

Conductor: Quad-bundled Al / ACS 550 / 70

Tower height: Approximately 60 m

Selected Best Practice Application

Location: The Netherlands to the border with Germany

Year of commissioning: 2018

Description: Given the densely populated area of Randstad in the Netherlands, conventional steel lattice pylons could no longer be installed to expand the grid as it would restrict building construction on a 300 m radius along the power line. The circuits are attached to two full wall steel pylons by insulated cross arms. The circuits are placed close to each other in two horizontal planes and phase twisted correspondingly in other to reduce total magnetic fields.

Results: The building restriction was reduced to a 200 m radius, and the tower design is visually less disrupting.

Location: Germany to the border with the Netherlands

Year of commissioning: 2018

Description: To increase local public acceptance and gain experience with innovative tower designs, the German part of the OHL to the Netherlands has been realised with full wall steel pylons and full wall steal cross arms. The two 380 kV circuits, consisting of three phase quad-bundled aluminium-steel 550 / 70 conductors (1,050 A per conductor), are arranged on both tower sides in a delta arrangement on two cross arms.

Results: The building of full wall steel pylon towers is more expensive comparing to the conventional one, mostly due to transportation requirements / limitations and foundation works. Moreover, for many components the standards are not available.

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Voltage Uprating

An increase of the voltage level allows for a significant increase of the transmission capacity in the existing right of way. The feasibility of voltage upgrade depends on the detailed assessment of the air clearances, required tower adaptation, the further use of existing conductors and also permissible electromagnetic emissions (E- and H-Feld and audible noise).

Technology Types

Essentially, there are two methods for voltage uprated in the existing right of way:

- Use of the existing towers with smaller adaptation of the tower layout and insulators.
- Removal of old towers (e.g. 220 kV) and the erection of new towers for a higher voltage level (e.g. 380 kV). Thereby, the 220 kV right of way is kept.

Components & Enablers

- New insulators
- Conductor bundles
- Tower reconstruction or new tower
- Transmission line surge arresters (TLAs)
  - ↳ Non-gapped line arresters (NGLA)
  - ↳ Externally gapped line arresters (EGLA)

Advantages & Field of Application

A voltage uprating of the existing OHL is an efficient way to increase the capacity. In particular, the use of existing towers and conductors minimises investment costs. Although the larger required air clearances can be solved by some technical adaptations, the increase of electromagnetic fields and noise emissions is a much more challenging issue. For this reason, this option is particularly suitable up to 220 kV and in areas with low population density.

The second option is to use the existing right of way, remove old towers and replace them point-on-point with new towers that are suitable for higher voltages. To fulfil the requirements related to the air clearance, audible noise and electromagnetic fields, the new tower designs (typically higher compared to the old line) and arrangements of the conductors must be used. For this option, many technical solutions exist. Some examples are:

- Use of V-Insulation string for the reduction of conductor swing out
- Single level arrangement of pure aluminium conductors that hang on low sag steel wires
- Application of surge arresters

Technology Readiness Level

TRL 9

TRL 9 up to 170 kV

TRL 7

TRL 7 ≥ 245 kV

Research & Development

Current fields of research:

New tower designs and conductor arrangements, that allow boundary conditions to be fulfilled.

Best Practice Performance

Depends on specific grid configurations.

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Digital Fault Recorders

A digital fault recorder (DFR) is an intelligent electronic device (IED)[1] that samples binary data during power system transients, using communications to retrieve fault, disturbance and sequence of event records, captured by protection relays. It stores data in a digital format when triggered by conditions detected on the power system. Harmonics, frequency and voltage levels are some examples of data captured by DFRs. They enable local substation troubleshooting and data archiving for permanent storage and analysis.

Technology Types

DFRs have generally three types of recording mechanism:

- High-speed disturbance recording of the instantaneous waveform signals of both current and voltages.
- Low-speed disturbance recording that is used to capture both long-term and short-term disturbances. In this recording type, the DFR records calculated parameters at a relative high sampling rate (1 – 10 waveform cycles).
- Steady-state recording that is used to capture min, max and average values of calculated parameters such harmonics at relatively low time resolution.

Two recording triggering methods are commonly used:

- Events that the DFR calculates from its input signals.
- Digital signals triggered by the protection equipment.

A DFR with a continuous waveform recording simplifies the installation process and ensures data availability for any event in the grid.

Modern digital relays often include the DFR function. The main differences between a relay with the DFR function and a separate DFR device are as follows:

- Sampling rate, which is usually higher for the DFR device.
- The amount of local storage and thus the recording duration is usually higher for the DFR devices.
- DFR devices can provide additional functions (such as power quality monitoring and others).
- Protection relays do not need additional binary signals like pickup and trip, because they are already generated internally and can be directly adjusted to the fault recorder.

Components & Enablers

This is usually part of a dynamic monitoring system that includes:

- Dynamic System Monitor (DSM)
- Power Quality Monitor (PQM)
- Phasor Measurement Unit (PMU)
- Fault Locator
- Circuit Breaker Monitor (CBM)
- Sequence of Events (SER) Display

Technology Readiness Level

TRL 9

TRL 9 – System ready for full scale deployment

Research & Development

Current fields of research: Since their introduction in the 1980s, DFRs have had an important role in monitoring the bulk electric power system. As digital monitoring technology continues to evolve, DFR capabilities are being incorporated into devices that have historically performed other functions.

Innovation priority: There is a trend towards more compact designs.

1 IEDs are devices built using microprocessors i. e. single chip computers that allow the devices into which they are integrated to process data, accept commands and communicate information.

Advantages & Field of Application

Proper interpretation of fault and disturbance data is critical for the reliability and continuous operation of the power system.

In short, DFRs:

- Provide a permanent detailed record of all substation activity
- Record Transfer Trip & Block Signals and other messages
- Provide secure data collection while also isolating the IED network
- Permanent recording of internal protection relay operands and calculations in Sequence of Events (SOE) and Fault records
- Have a fairly long lifetime and simplified maintenance

DFRs have been extensively used:

- For substation distributed digital fault recording
- For monitoring of system protection performance
- As components in larger enterprise wide fault and disturbance recording systems
- Monitoring of transient events, e.g. in the case of field experiments, connecting new assets to the grid

The growing need for reliable power system operation, along with the growing demand for digital substation, are expected to drive the digital fault recorder market in the future. Asia Pacific accounted for the largest share of the global DFR Market in 2017.

Best Practice Performance

DFR performance varies with the type of recorder. The characteristics of a multi-functional, state of the art, DFR can be found below:

- 24-Bit Continuous acquisition at 1,024 sample per cycle [50/60 Hz] (ability to record and store all electrical waveform for more than a year with no gaps in data)
- Modular Design
- Centralised and decentralised architecture
- Supreme synchronisation
- Compliance with IEC 61850 MMS, GOOSE messaging and sample value
- Comprehensive web interface
- 7" touch LCD
- Scalable architecture.

Selected Best Practice Application

Location: North of UK

Year of Commissioning: 2010

Description: The Utility has made a strategic decision to invest in monitoring equipment and use the resultant data to evaluate plant and network performance, and identify defects and weaknesses in the system to allow early remedial actions to be taken.

Design: Recorders are present in nearly all 400 kV, 275 kV and 132 kV substations monitoring lines, transformers and CBs. Protection and plant maintenance engineers mainly use fault records; the system operators use the triggered and continuous slow scan data to study low frequency oscillations, the effects of frequency disturbances and power swings; and the system planners use the power quality data for harmonic surveys and load flow analysis to review system performance and assess the impact of new embedded generation.

Results: The versatility of the multi-function devices and the ability to collect and analyse different types of data with one software package fully justifies the use of standalone systems as opposed to the reliance on protection relays. Future developments will include the introduction of enhanced data processing software to automatically analyse fault records and minimise the need for manual intervention.

Location: France

Year of Commissioning: 2019

Description: RTE has made a strategic decision to invest in centralising the reception of all Fault Recordings Files issued on protection arming signals by its various already installed DFRs and in a centralised software to automatically compute fault locations distance based on signal processing, in order to diminish the restoration service delay.

Design: Centralised software that computes fault location distance automatically using signal processing.

Results: The project is currently under deployment.

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Fault Current Limiter

Fault Current Limiters (FCLs) act as an additional high impedance to limit high fault currents to an acceptable level. In normal operation, FCLs have almost no impedance and are 'invisible' to the system. Unlike fuses or disconnectors, FCLs do not completely disconnect in a fault case. After the fault current disappears, they can return to normal operation. Due to their very short reaction time, FCLs can act and reduce the short circuit current so the CB can act in its nominal performance range if required. Typically, FCLs are used in low and medium voltage levels.

Technology Types

FCL can be classified into two major types, which can be further subcategorised per technology

Non-superconducting FCL

- Saturable core FCL – they exploit the non-linear characteristics of ferromagnetic materials to realise a high inductance.
- Solid state FCL – they use the high-power semiconductor device to realise a FCL and can be classified as either serial, bridge or resonance type.

Super conducting FCL (SFCLs)

- Resistive type of SFCLs – uses the capability of the superconductor to change state from superconducting into a resistive state known as the 'superconductor quench'.
- Inductive type of SFCLs – works like a transformer with short superconducting secondary winding. The resistance of the secondary winding is the superconductor quench.
- Bridge type of SFCLs – uses power thyristors and power diodes to block fault currents if a fault occurs.

Components & Enablers

Non-superconducting FCL

- Saturable core FCL – windings of conventional conductors, iron core, air-core reactor.
- Solid state FCL – solid state switch consisting of a configuration of semiconductor devices e.g. SCR[1], GTO[2], IGBT[3], IGCT[4].

Super conducting FCL (SFCLs)

- Resistive type of SFCLs – air-core superconductor transformer and PWM[5] converter.
- Inductive type of SFCLs – power semiconductors devices in parallel with a resistor or inductor.
- Bridge type of SFCLs – diodes and thysistor, DC reactor.

Advantages & Field of Application

By installing FCLs, system operators or commercial customers can optimise the system via the application of standard solutions with specific (low) nominal short circuit currents. Major advantages include:

- Reduction of the short-circuit current of the system, allowing the CBs to act in their nominal performance range
- Reduction of voltage sags and flicker due to the lower total source impedance
- Reduction of harmonics due to the lower total source impedance

1 Silicon Controlled Rectifier
2 Gate turn-off thyristor
3 Insulated Gate Bipolar Transistor
4 Integrated Gate-Commutated Thyristors
5 Pulse-width modulation

Technology Readiness Level

HV (≤ 145 kV)

TRL 9

Non-superconducting FCL: TRL 9

TRL 7

Super conducting FCL (SFCLs): TRL 3 – TRL 7 depending on technology types and voltage level

TRL 3

EHV (≥ 245): TRL 3

Research & Development

Current fields of research: Superconducting materials, compactness, self-triggering, increasing maximum voltage level, time to return to normal operation, cost reduction

Best Practice Performance

Voltage rating: up to 138 kV

Current rating: up to 6.3 kA

Limiting capability: 210 kA (RMS)

Selected Best Practice Application

Location: USA, Ohio

Year of commissioning: 2011

Description: Designing, building and testing of an FCL prototype in Tidd substation of American Electric Power.

Design: A three phase 138 kV, 1300 A saturable iron-core type 2G HTS FCL unit that reduces a 20 kA fault current by 43 % and instantaneously recovers under load was installed on the LV side of a 345 kV / 138 kV transformer to protect the feeder.

Results: By employing fault current limiters, the electrical installed equipment is protected.

Location: UK, Newhaven, East Sussex

Year of commissioning: 2013

Description: The Energy Technologies Institute worked on implementing an FCL in a main substation of UK Power Networks to supress damaging currents and provide network capability and reliability.

Design: A novel design was demonstrated that provides a simple, reliable and low maintenance solution and is fully scalable to other voltage levels. The concept of magnetic flux alteration for the iron core saturation is used. Instant, self-triggering response to new faults and quick recovery after clearance without interruption in the network, as well as being able to cope with multiple consecutive faults, are all benefits of the chosen design.

Results: Shorter connection times and reduced costs of connection with increasing shares of embedded generation. Increased efficiency and flexibility and resilience of the electric network is achieved.

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Gas Insulated Substation

Gas insulated substation (GIS) consist of components where active parts on high voltage potential are located in the middle of the aluminium alloy pipes and held in this location by epoxide resin insulators. The pipes are filled in with insulating gas and have earth potential. The GIS consists of typical HV components such as disconnectors, CBs, busbars, voltage and current transducers. GIS can save up to 90% of space compared with air insulated substation. It is particularly suitable for indoor and outdoor applications.

Technology Types

The technology type of GIS is defined by

- The insulation gas:
  - ↳ SF6
  - ↳ SF6 mixture with N2
  - ↳ SF6 free
- The phase arrangement:
  - ↳ one phase per pipe
  - ↳ three phases per pipe
- The voltage level
- Application type:
  - ↳ indoor
  - ↳ outdoor

Advantages & Field of Application

The GIS is applied in cases where the available space is very limited or the substations require complex connections. The single bays and busbars can be arranged very tightly because they are on earth potential. The GIS can be connected to overhead lines by bushings and to cables by special cable connectors.

The indoor GIS are mostly maintenance-free components that have higher reliability compared to air-insulated substations (AIS). Nevertheless, the total availability of GIS is comparable to AIS because of significantly longer (many weeks) repair times after a failure.

The GIS with non SF6 gas appeared recently on the market. The major advantage of non-SF6 gases is their very small or non-existing global warming potential. Therefore, two different applications need to be considered:

- non-SF6 gas is used for insulation only (up to 420 kV)
- non-SF6 gas is used for insulation and arc quenching (up to 170 kV)

Technology Readiness Level

TRL depends on the insulation gas used

TRL 3 – 6

SF6-free:
HV: TRL 6 (insulation purpose and switchgear)
EHV: TRL 3 (switchgear)
EHV: TRL 6 (insulation purpose)

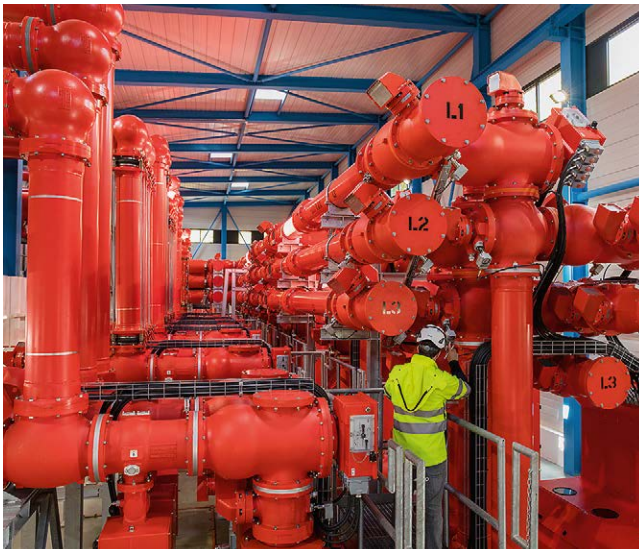
TRL 9

SF6:
HV / EHV / UHV: TRL 9

Research & Development

Current fields of research

1. The deployment of new insulation gas mixture as an alternative to SF6 to reduce the carbon footprint
2. Alternative compact design configurations that limit required space, cost and construction time
3. Fibre optics sensors and current measurement technologies that limit recalibration needs



Best Practice Performance

With SF6 gas

Rated voltage range: 52 kV to 1,200 kV

Rated current range: 2.5 kA to 8 kA

Standard definition: IEC 60517, IEC 62271

Expected lifetime: 50 years

Selected Best Practice Application

Location: Bergen, Norway

Year of commissioning: 2013

Description: Norwegian seaports have set themselves the goal of reducing harmful emissions during ship lay times. One measure is to supply increasing numbers of ships with shoreside electricity from hydroelectric power. To provide the necessary grid infrastructure to handle higher volt-ages, the Norwegian energy provider BKK Nett is upgrading its transformer substation in Bergen from a 45 kV to a 132 kV operating level using 'clean air' vacuum circuit-breaker and 'clean air' instrument transformer, making it a state-of-the-art GIS.

Design: GIS features a rated voltage of 145 kV, a rated short-circuit breaking current of 40 kA and a rated current of 3,150 A. The non-conventional low power instrument transformers (LPITs) used ensure an especially compact design.

Results: The switchgear's size and weight are up to 20 % less than in a system with conventional current and voltage transformers. The GIS will be climate neutral as the switching and insultation technology are based on clean air technology with no global warming potential.

Location: Etzel substation near Zurich, Switzerland

Year of commissioning: 2017

Description: pilot high voltage, 123 kV GIS installation using a new eco-efficient gas mixture as an alternative to SF6

Design: 123 kV, high voltage switchgear, rated voltage 145 kV, operating voltage 123 kV, rated short-time withstand current 40 kA during 3 s; Gas mixture SF6-free Fluoronitrile / CO_2 / O2-based on a chemical compound developed for switchgear applications in collaboration with 3M

Results: The project has been energised since 2018.

Location: Grimaud substation near St Tropez, France.

Year of commissioning: 2019

Description: Pilot high voltage, 63 kV GIS installation using a new eco-efficient gas mixture as an alternative to SF6

Design: High voltage switchgear, rated voltage 145 kV, operating voltage 63 kV; Gas mixture SF6-free Fluoronitrile / CO_2 / O_2-based on a chemical compound developed for switchgear applications in collaboration with 3M

Results: The project has been energised since 2019.

Selected Best Practice Application (cont.)

Location: Oerlikon, Switzerland

Year of commissioning: 2015

Description: Pilot high voltage, medium-voltage GIS installation using a new eco-efficient gas mixture as an alternative to SF6 which leads to low CO_2 equivalent emissions.

Design: 170/24 kV, high voltage switchgear, rated voltage 170 kV, operating voltage 150 kV, rated short-time withstand current 40 kA; medium voltage switchgear, rated voltage 24 kV, operating voltage 22 kV, rated short time withstand current 25 kA. Gas mixture SF6-free Fluoroketone-based on a chemical compound developed for switchgear applications.

Results: The project is forecast to save 50% of CO_2 emissions throughout the lifecycle of the equipment. These stems from a 50% reduction in raw materials, manufacturing, thermal losses and a 50% reduction in SF6 emissions based on a 30-year service life.

Location: Sweden

Year of commissioning: 1986

Description: 30 MW and 150 kV Gotland HVDC line featured the first fully redundant digital control and protection system and GIS for HVDC.

Design: The voltage was increased to 150 kV using a thyristor module. The line includes a submarine section that is 93 km long.

Results: The gas insulated switchgear for HVDC has allowed the better use of available space because of its compact size and high reliability.

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Mixed Technology Substations

Mixed technology substations (MTS) incorporate the use of air-insulated and gas insulated components and switchgear. In a substation, some or all of the switching bays consist of compact GIS modules with CBs, instrument transformers, disconnectors and grounding switches. The busbars, bay connections and often complete switching bays originate in conventional AIS technology.

Technology Types

The main focus when discussing MTS originates in compact GIS modules with bushings and with special requirements resulting of interac-tion with larger AIS substation parts. MTS can differ in their engineering design depending on the required configuration. Three combinations are possible:

- AIS in compact and / or combined design
- GIS in combined design
- Hybrid IS in compact and / or combined design assembled together and using a common structure to minimise the installation time

Components & Enablers

- Encapsulation
- Insulation gas (commonly SF6)
- Bushings
- Circuit-breakers
- Combined disconnector and earthing switch for cables and busbars
- Current and voltage transformer
- Earthing switch

Advantages & Field of Application

The first MTS modules were developed in the 1990s. They are compact switchgear applications mainly used in the refurbishment and expansion of substations with air-insulated outdoor and indoor switchgear. The application of MTS allows the bay footprint to be reduced by up to 50 %.

Depending on the national regulation, this can result in a lower cost of ownership for the technology compared to AIS.

Technology advancements in hybrid insulated substations (HIS) follow the same trends of GIS and AIS installations. MTS modules are com-mercially available for all voltage levels up to 420 kV.

Technology Readiness Level

The TRL depends on the gas mixture used in the GIS technology-based components.

TRL 5

SF6 free:
2020: TRL 5
2025: TRL 7
2030: TRL 9

TRL 9

For **SF6 based MTS,** the TRL is 9.

Research & Development

Current fields of research: The research on MTS focuses on requirements resulting from the interface between different insulating media and equipment stresses (e.g. switching of loop currents).

Power system technologies' manufacturers focuses their effort on the transportability of large assembled MTS modules. Key innovation is the rotating bushing concept, which takes less than 30 seconds per bushing from the in-service position to the transport position and back again at the installation site.

Innovation priority to increase overall TRL: N/A

Best Practice Performance

Maximum continuous current: 63 kA

Maximum voltage rating: 420 kV

Standard definition: IEC 62271 – 205

Expected lifetime: 50 years

Selected Best Practice Application

Location: Sicily, Italy

Year of commissioning: 2015

Description: A 420 kV MTS was commissioned in 2015 to help ensure the reliability of a new high voltage 2 GW power link between Sicily and the Italian mainland.

Design: With very limited space on the island substation and the need to perform maintenance on the modules while in service, conventional solutions were ruled out. The 420 kV MTS arrived on site factory assembled and tested, ready for rapid installation and energisation.

Results: Ensuring the reliability of the 2,000 MW power transmission capacity between Sicily and the Italian mainland while abiding to the limited available space.

Location: Wilster, Germany

Year of commissioning: 2016

Description: Construction of a substation for the link between two network levels in the region of Schleswig Holstein.

Design: Two transformers connect the 380 kV level with a 110 kV network with a capacity of 300 MVA.

Results: Onshore generated wind-electricity will be easily integrated and transmitted from the north to the south in the future.

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AC Power Transformers (with Tap Changer)

AC EHV power transformers are an essential component of the power system, enabling a change in AC voltage and thus allowing operators to interconnect AC networks of different voltage levels with each other. Power transformers must be built to withstand severe electrical stress from fault currents and transients. Their availability and longevity have a major impact on grid reliability and profitability.

Key functions of power transformers with tap changers are:

1. Voltage step-up and -down: As increasing voltage will reduce the currents required to distribute the same electrical power, step-up transformers are used to minimise transmission line losses. Step-down power transformers are used to bring down transmission volt-ages to usable voltage level for end-customer connections.
2. Slow dynamic regulation to adjust to changing network conditions supporting the voltage stability of the AC-grid.

Integrating a tap changer with the transformer allows for the regulation of the output voltage by adjusting the number of transformer windings (the transformation ratio). Although the effects on the network depend on the network itself, this nonetheless enables more flexibility to the operator compared to a fixed voltage step up or down ratio.

Technology Types

The main technologies of power transformers highlighting some specificities are reminded below:

- **Transformers per cooling types:**
  - Oil Direct Air Forced (ODAF)
  - Oil Direct Air Natural (ODAN)
  - Oil Direct Water forced (ODWF)
- **Power Transformers:** This transformer is used to transfer the energy to the substation or the public electricity supply.
- **Generator transformer:** This transformer, located on a power station, is used to connect the generator output to the grid.

Components & Enablers

The exact components depend on the specific transformer. Typical components of an AC power transformers are:

- Laminated core
- Windings
- Insulating materials
- Transformer oil
- Tap changer
- Bushings
- Oil conservator
- Cooling units

Advantages & Field of Application

The transformers constitute an integrated cornerstone in the power systems. The acceptance of these devices from a public acceptance and environmental impact is assessed by the audible footprint and the loss levels. The actual physical footprint is essential since the ‘not in my backyard’ discussions are expected to increase in intensity and frequency.

Technology Readiness Level

TRL 9

It is a mature technology **– TRL 9 –** System ready for full scale deployment (for standard components). However, a lower TRL prevails for some components’ development, which could lead to a change in the TRL once these components are ready to be commercialised (e.g. development aiming at better performance of the transformers in terms of losses and environmental impacts: cooling system, mechanical design, core and magnetics, insulation system, acoustic/noise, use of ester oil).

Research & Development

The coming generations of transformers will be characterised by a shift in environmental focus. The responsibility of reaching a lower impact on the environment will be shared between producers and users. This includes all steps from production to operation over the lifetime of the equipment and decommissioning/recycling. This shift will impact the following areas:

- Design and manufacturing: the design of the transformers is key to optimise their impact in terms of weights and losses results, more specifically the use of materials (steel, copper) will be carefully considered at that stage. The type of oil will be also part of the discussion, ester oil having a lower risk impact for the surrounding areas. Manufacturers will be required to produce equipment with a minimum impact on the environment during their production.

A key design feature for the installation of large power transformers (LPTs) is the transportability constraints due to their dimensions and heavy weight that could require specialised railroad freight infrastructure with high costs.

- Operation: Life-time assessment will become more important.
- Importance of losses: optimise losses for the operation.
- An increased utilisation, which improves return on investment for the users (higher focus on the actual hot spot). Incorrect or sub-optimised design can lead to a temperature rise by 6–8 degrees on the actual hot spot, which significantly decreases the lifetime of the equipment.

Best Practice Performance

LPTs refer to units with a power rating higher than 200 MVA or with voltage ratings higher than 275 kV for the three-phase units [4].

The United States Department of Energy defines the estimated magnitude of LPTs [23]. Typical characteristics for one-phase transmission transformers: 765–345 kV transformers with 500 MVA capability rating and a weight of 235 tons. The three-phase transmission transformers encompass several classes:

- 230–115 kV transformers with a 300 MVA capability rating and a weight of 170 tons
- 345–138 kV transformers with a 500 MVA capability rating and a weight of 335 tons
- 765–138 kV transformers with a 750 MVA capability rating and a weight of 410 tons.

On high and extra high voltage, commercial catalogue of manufacturers detail LTP equipment with similar performances: three-phase units up to 1,100 MVA and single-phase units up to 500 MVA, or extra high voltage transformers of 1,000 MVA, 500/275/63 kV 3 phase [25]; transformers well above 1,300 MVA [16], up to 1,200 MVA, and voltages up to 765 kV [24].

Selected Best Practice Application

Location: Germany

Year of commissioning: 2014

Description: 420 kV power transformer (rated power of 400 MVA) for a substation for TransnetBW (TSO state of Baden-Württemberg) to link the 380 kV voltage level with the 110 kV grid.

Design: Power transformer with ester oil as insulation. All permissible (over)temperatures have been rated according to IEC 60076-2.

Results: 420 kV extra-high voltage level using natural ester. Due to the lower flammability, the transformer also has a higher fire protection class (K instead of O) enabling the equipment to be used in densely populated areas.

Location: Russia

Year of commissioning: 2017

Description: The Siberian Generating Company has commissioned a new 125 MVA transformer at the Tom-Usinsk Power Plant as part of the project to improve the reliability of the largest power plant in Kuzbass.

Design: Siemens, 125-MVA autotransformer.

Results: The extreme temperatures in Siberia place special demands on transformers. The autotransformer fulfils these requirements, and losses are below the value stipulated in the Russian Governmental standard.

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Circuit Breakers – AC

A CB refers to a mechanical switching device, capable of making, carrying and breaking currents under normal circuit conditions as well as making, carrying for a specified time and breaking currents under specified abnormal circuit conditions, such as those of short-circuit.

Technology Types

The technology types of common new CBs can be defined as follows:

- The arc-quenching medium
  - ↳ for EHV – SF6, Oil
  - ↳ for HV – SF6, SF6-free, Oil, vacuum
- Arc-quenching principle
  - ↳ blast
  - ↳ Self-blast
  - ↳ Double motion self-blast
- Drive type
- Hydraulic
- Spring
- Number of series breaking units (1,2 or 4), grading capacitors or energisation resistors
- Design
  - ↳ Life tank (Interrupter is inside an enclosure that is insulated from ground potential.)
  - ↳ Dead tank (Interrupter is situated inside a grounded metallic enclosure filled with insulation gas. The Interrupter is connected via bushings to the AIS busbar. Typically, the current transformer is also attached to this module.)
  - ↳ GIS circuit breaker – Interrupter is located in a grounded pipe filled in with insulating gas. CB is connected with other GIS components such as disconnectors, voltage transformers and earthing switches in GIS technology.

Advantages & Field of Application

The CBs enable the power flow to be controlled by connecting or disconnecting components from HV grid and switching off the disturbances. Hence, they are essential for a reliable operation transmission system.

The choice of circuit breaker technology for specific application depends on required switching capabilities (e.g. 63 kA or 80 kA) and available space (e.g. life tank or dead tank). For special application (e.g. switching of currents without zero crossings) old technologies (hydraulic drive, blast principle, 4 interrupting chambers with grading capacitors) are still in use.

Due to very high switching performance requirements in the EHV grid, only SF6 gas is used. The latter has very high global warming potential. Hence, many new developments of SF6 free CB in HV networks have recently been observed. Nevertheless, there are no examples in EHV yet.

Technology Readiness Level

TRL 9

HV/EHV SF6 2020: TRL 9 – AIS & GIS circuit breaker

TRL 7

HV SF6-free 2020: TRL 7 – AIS & GIS circuit breaker

TRL 3

EHV SF6-free 2020: TRL 3 – AIS & GIS circuit breaker

Research & Development

Current fields of research: Higher switching performance (e.g. 80 kA in GIS); models and diagnosis methods for end of life prediction; increasing the reliability of devices, replacement of SF6

Selected Best Practice Performance in EHV

Rated nominal current: 4,000 A

Rated short circuit current: 80 kA

Maximum operating Voltage: 420 kV

Insulating medium: SF6

Number of breaking units per pole: 4

Speciality: very high arc resistance required for the switching of currents without zero crossing

Expected lifetime: > 50 years

Best Practice Application

Location: Oerlikon, Switzerland

Year of commissioning: 2015

Description: The first pilot project of a distribution system operator using non SF6 gasses for HV circuit breakers was initiated in Oerlikon, Switzerland.

Design: 3 × 50-MVA transformer station with 170 kV and 24 kV switching panels using non SF6 gas.

Results: Fault-free operation since August 2015. No measurable decomposition of fluorine ketones to date.

Location: Obermooweiler, Germany

Year of commissioning: Expected 2021 for new construction; 2026 for modification.

Description: The world's first 380 kV gas-insulated switchgear (GIS) will be installed which uses SF6 alternative gas mix (fluorine ketones).

Design: Detailed planning in process for a new construction as well as an extension/modification of an existing switchgear.

Results: No results yet – gain experience and reduce greenhouse effect by 99 %.

Location: Nördlingen, Germany

Year of commissioning: 2018

Description: First installation of a GIS using a vacuum-interruption technology in circuit breakers with a rating of up to 145 kV.

Design: The vacuum-interruption and clean-air insulation technology for a rated voltage of 145 kV, a rated short circuit-breaking current of up to 40 kiloamperes (kA), a rated current up to 3,150 A, and operating temperatures between – 55° Celsius and + 55° Celsius.

Results: No published results yet – expected to provide same performance and reliability while avoiding greenhouse gases such as SF6 or other fluorids.

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HVDC Circuit Breakers

The HVDC circuit breaker is a switching device that interrupts the flow of normal and abnormal direct current. The challenge in breaking direct current is the absence of zero current crossings. An additional component must be used that either generates zero-crossings by application of special oscillating circuit and mechanical circuit breakers or power electronics to break the current. The HVDC circuit breakers are required for meshed DC-grids and multi-terminal DC links.

Technology Types

An HVDC circuit breaker can be classified into four topologies:

- Mechanical circuit breaker with passive resonance circuit: old technology, typically an air blast circuit breaker with several interrupter units
- Mechanical breaker with active current injection
- Solid-state: fastest topology, many semiconductor-based switches are connected in series
- Hybrid DC breakers: controllable solid-state devices are used to break the current until a mechanical breaker or disconnector opens the circuit

Advantages & Field of Application

Multi-terminal HVDC systems are emerging to integrate bulk renewable energy, e.g. wind offshore, over long distances, or in a next stage could also be used for DC overlay grids. Such a system requires HVDC circuit breakers. Various protection strategies exist to clear a fault on a DC cable with different requirements for DC breakers (speed/rating). These strategies vary from direct line protection, to regional splitting, to wide area converter blocking with residual DC current breaking.

Technology Readiness Level

TRL 6

HV – High Voltage: TRL 6

TRL 3

EHV – Extra High Voltage: TRL 3

Research & Development

Current fields of research: scaling hybrid and mechanical circuit breaker to EHV DC voltage, increasing response time and improving stability, reduction of space required for hybrid dc breaker.

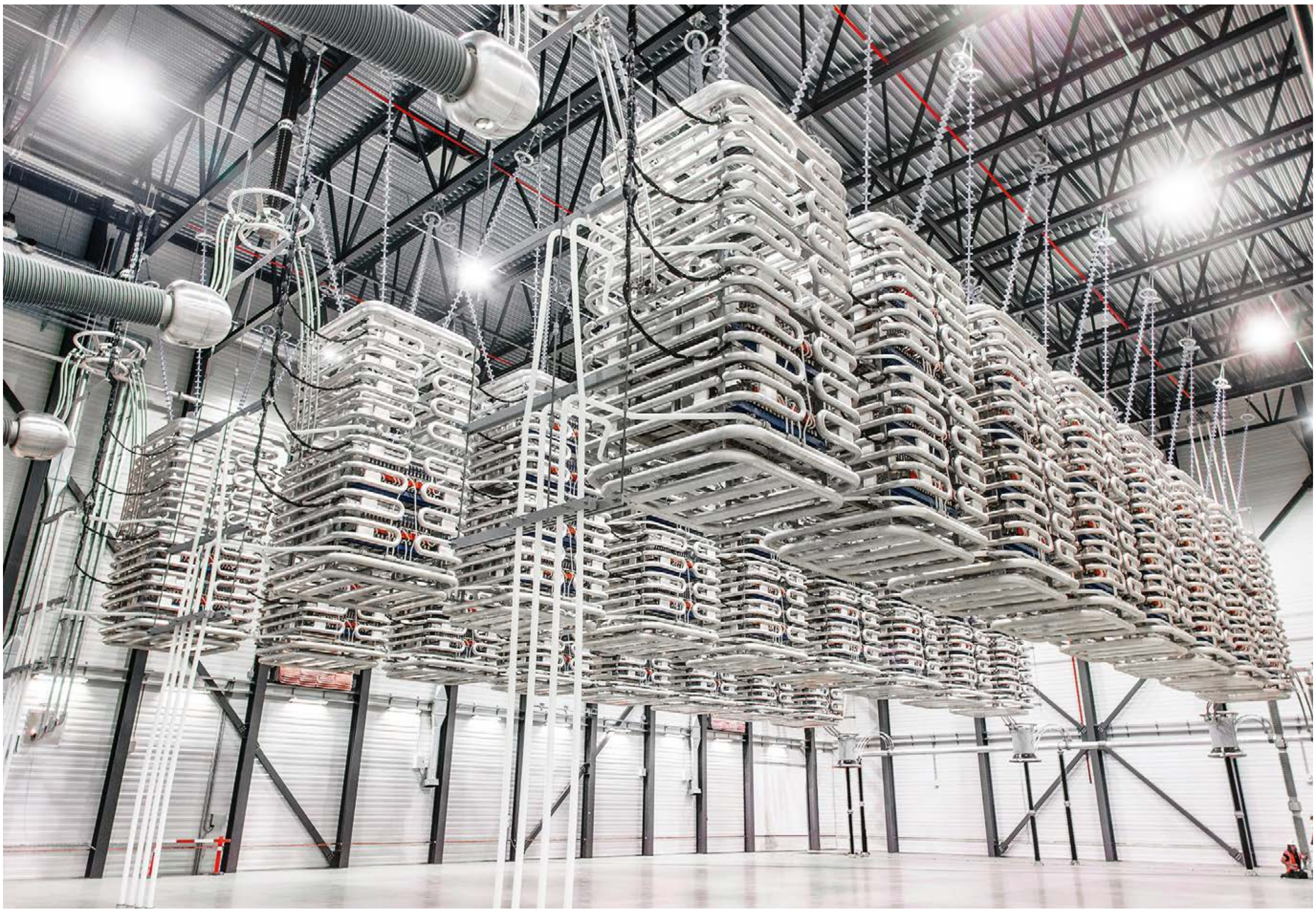
Best Practice Performance

Current rating: 8 kA (mechanical circuit breaker), 9 kA (hybrid circuit breaker– anticipated to reach 16 kA), 5 kA (pure semiconductor – anticipated to reach 800 kV)

Voltage rating: 120 kV (hybrid circuit breaker – anticipated to reach 320 kV), < 70 kV (pure semiconductor – anticipated to reach 800 kV)

Standard definition: Currently no standardisation exists

Expected lifetime: > 25 years



Selected Best Practice Application

Location: EU

Year of commissioning: Several projects 2016 – 2018

Description: Project 'PROgress on Meshed HVDC Offshore Transmission Networks' (PROMOTioN) under the EU Horizon 2020 programme to accelerate meshed HVDC grid development; work packages on 'WP5: Test environment for HVDC CB', 'WP6: HVDC circuit breaker performance char-acterization', 'WP10: HVDC circuit breaker performance demonstration'

Design: WP5 – Mitsubishi mechanical circuit breaker with active current injection, WP6 – hybrid and mechanical circuit breaker

Results: WP5 – successful demonstration of a DC fault current interruption

Location: Zhoushan, China

Year of commissioning: 2016

Description: World's first set of 200 kV DC circuit breaker for 5-terminal VSC-HVDC

Design: Combination of a high-speed mechanical switch and a hybrid cascaded full bridge module

Results: Circuit breaker design has greatly improved the reliability of the HVDC project; the circuit breaker successfully interrupted a short circuit current up to 15.6 KA

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Phase Shifting Transformers

A phase shifting transformer (PST) is a specialised type of transformer, typically used to control the flow of active power on three-phase electric transmission networks. It does so by regulating the voltage phase angle difference between two nodes of the system. The principle relies on a phase shifted voltage source injection into the line by a series connected transformer, which is fed by a shunt transformer. The configuration of the shunt and series transformer unit induces the phase shift.

It is a simple, robust and reliable technology. Preventive and curative control strategies are implemented for power flow controllability. In the preventive mode, the permanent phase shift allows redistributing the power flows and relieves network stresses in the event of line outage. In the curative mode, the phase shift is small (sometimes down to zero) in normal operation, but it is automatically controlled to reduce the power flow on the overloaded lines and to avoid a tripping out. The active redirection of power flows allows exploiting lines closer to their thermal limits.

Technology Types

PSTs can be classified based on the following characteristics:

- **Direct PSTs** are based on one 3-phase core. The phase shift is obtained by connecting the windings in an appropriate manner.
- **Indirect PSTs** are based on a construction with two separate transformers: one variable tap exciter to regulate the amplitude of the quadrature voltage and one series transformer to inject the quadrature voltage in the right phase.
- **Asymmetrical PSTs** create an output voltage with an altered phase angle and amplitude compared to the input voltage.
- **Symmetrical PSTs** create an output voltage with an altered phase angle compared to the input voltage, but with the same amplitude.

Components & Enablers

The components are comparable to traditional transformers:

- Laminated core
- Windings
- Insulating materials
- Transformer oil
- Tap changer
- Bushings

Advantages & Field of Application

The liberalisation of the European electricity market and the ever-increasing penetration of variable renewable generation have increased the need for this mature technology. Hence, the number of PSTs in the transmission grid is expected to rise. PSTs enable the grid operator to control unexpected loop flows, thus allowing the existing system to be used more efficiently. PSTs are used for congestion relief.

The PST system provides a means to control power flow between two grids. PSTs do not increase the capacity of the lines themselves, but if some lines are overloaded while capacity is still available on others parallel to them, optimising the power flows with PSTs can increase the overall grid capacity.

Provided that there is free capacity on parallel paths that can be used, these slow devices are better suited for power flow control in the event of no continuous congestion and low congestion volatility.

PSTs are often the most economic and reliable approach to power flow management and system design, enabling TSOs to get more out of their existing assets. Existing transmission lines can be loaded up to the thermal limit without being overloaded. The investment in new lines can be postponed or even avoided.

A strong need for coordination emerges among the TSOs operating PSTs which are placed at the extremities of congested cross-border -tie-lines.

The following are key applications of the PST technology:

Preventive/curative power flow control in transmission lines

PSTs are used in electrical power systems to control the active power flow between two points by regulating the corresponding voltage phase angle difference. The phase angle shift is obtained by opportunely placing the PST transformer in a shunt mode in respect to line terminals so that, by combining the voltages, the output voltage phase is shifted by an angle difference respect to the one as input in the PST. PSTs can thus be used to take advantage of an existing capacity margin on the network or to make an interconnection more secure.

Handle market flows in a physical meshed grid

As a consequence of the power flow controllability, PSTs can also be used to match contract obligations from trading activities at wide regional level with laws of physics. They provide for crucial tools to address non-anticipated flows and lower the need for countertrading or redispatch.

Other innovative applications

Innovative PST applications are enabled by adding series reactive elements aiming for substation uprating, substation reserve sharing, network decoupling, line power flow control using assisted PSTs (APSTs) and HV transmission lines deicing. All these applications rely on the connection of conventional PSTs and reactive elements to meet unusual objectives for PSTs.

Technology Readiness Level

TRL 9

TRL 9 – System ready for full scale deployment

Best Practice Performance

Rated through put power: up to 1,630 MVA

Rated voltage levels: up to 420 kV

Maximum phase angle: <±85o

Research & Development

Current fields of research:

For this mature technology, research efforts focus more on enabling issues than on technological ones: the development of standards, common PST models and protocols for the inter-TSO coordinated control of PSTs.

Innovation Priority:

Speed of switching, tap changer design, insulation fluid, reduction of losses, new materials

Selected Best Practice Application

Location: Border Germany / Poland / Czech Republic

Year of commissioning: 2016 – 2018

Description: Strongly increased wind power capacity in Northern Germany led to stress on the Polish and Czech transmission system and loop flows. PSTs were installed for the better control of cross-border exchanges. Thus, the required reserve capacity of the interconnectors can be reduced, and more interconnector capacity is available for the market.

Design:

- CZ-DE: four PSTs (380 kV) in Hradec (CZ), two PSTs in Röhrsdorf (DE)
- PL-DE: four PSTs in Mikułowa (PL), four PSTs in Vierraden (DE) (two commissioned, two planned

Results: Increasing power system efficiency and reliability at the German – Polish border.

Location: Border Spain / France

Year of commissioning: 2017

Description: Commissioned on 30 June 2017, the PST helps to reinforce international electricity exchanges in South-West Europe at a boundary with a limited number of interconnection links

Design: 220 kV and 550 MVA PST.

Results: Increase the security of supply and reinforcement of international exchanges power flows

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(Variable) Shunt Reactor

Shunt reactors (SRs) are used in high voltage energy transmission systems to control the voltage during load variations. Depending on the voltage requirement needs, shunt reactors are switched on or off to provide reactive power compensation. With increasing load variations in today's system, variable shunt reactors (VSR) are developed as a means to provide more controllability for grid operators in reactive power management by continuously adjusting the compensation according to the load variation. This technology uses a tap changer, of the same type used in power transformers, to vary the inductance by changing the number of electrical turns in the reactor windings. It is now possible to finetune the system voltage and provide regulation capability. The transmission system benefits from improved power quality, optimised grid operation and the possibility of interaction with other regulation devices, such as SVCs (Static Var Compensators).

Technology Types

Shunt reactors can be classified into two types according to the fixed or variable nature of the rating:

- Fixed rating SRs, either dry or oil-filled, and variable shunt reactors (oil-filled).
- Fixed rating SRs is a traditional technology with no means of regulation. Controllability is ensured by a switched in and out to follow the load variations, which can result in step changes in the system voltage level and induce more stress on system components. This drawback can be mitigated either by the combined use of several smaller SRs, smoothing these step variations and facilitating controllability, or by the use of VSRs that enable a continuous compensation of reactive power through the use of a tap changer to change the inductance of the power line or cable it is connected to.

The regulation of a variable reactor is accomplished by a separate regulating winding, or windings, located outside the main winding. The regulating range is limited by the maximum step voltage and voltage range of the tap changer in combination with the specific design concept used. The regulation range typically varies between 50 – 100 % of rated reactive power, e. g. a VSR with a rating of 150 MVAr at 300 kV can today be regulated between 80 MVAr and 150 MVAr.

Components & Enablers

Typical components of a VSR are:

- One or three phase, iron-core with fixed air gap
- Tap changer
- Windings
- Insulation material
- Insulating oil
- Bushing
- Cooling system

Advantages & Field of Application

VSRs combine the proven design of SRs and tap changers that have been used successfully for decades in power transformers.

They are used in high voltage transmission to compensate reactive power and thereby secure voltage stability according to the load variations: VSR enable grid operators to optimise reactive power compensation and benefit from improved voltage control. Main technical benefits of variability compared to a fixed reactor include the smoothing of the voltage jumps, the flexibility to the load, the ability to interact with a SVC, the possibility of relocation to another part of the grid, and the footprint reduction of a VSR replacing several fixed rating shunt reactors and circuit breakers.

Typical network conditions which favour the application of VSRs are:

- Networks with distributed generation (e.g. solar, wind, etc.) may not always provide full control over their electrical output which may create problems of increased flow of reactive power due to the varying reactive power of both generation and consumption.
- Strongly varying loads powered through relatively long overhead lines or underground cables. The application of a VSR will relieve the source line from reactive current and thereby mitigate the line losses and improve the voltage quality.
- Changing networks as additional transmission infrastructure is being installed to improve overall system reliability and support the loss of base load generating facilities (e.g. coal, nuclear).
- Grids where in- and out- switching of a fixed shunt reactor will lead to power quality problems in terms of voltage steps.

Technology Readiness Level

TRL 9

TRL 9 – System ready for full scale deployment

Research & Development

Current fields of research: Analysis and studies on the dynamic behaviour of the shunt reactor are being performed as well as on the 'ageing' of such equipment. Moreover, tests on geomagnetically induced currents (GICs) are being done to compensate reactive power and control the voltage level.

Innovation Priority: Manufacturers are seeking improvements in their production processes to address the challenge of the general layout of the winding arrangement, the lead concept to the tap changer and the huge shunt reactor dimensions.

Best Practice Performance

Three-phase VSRs:

- They include the 550 kV range and commercial products which are available at ratings up to 300 MVAr
- Large regulation ranges from 20 % to 100 %

For the sake of comparison, SRs are able to compensate reactive power up to 300 MVAr and be operated at voltage levels up to 765 kV, whereas reactive power compensation for single-phase shunt reactors reaches up to 320 MVAr and maximum voltage levels of 1,000 kV.

Selected Best Practice Application

Location: Slovenia

Year of commissioning: 2020

Description: The objective of the SINCRO.GRID – Phase 1 project is to provide for the more efficient use of the existing electricity grid in Slovenia and Croatia, which will enable the existing infrastructure to accept larger quantities of electricity from renewable sources and ensure a more reliable electricity supply. In June 2020, the ELES substation in Divača, equipped with a VSR, successfully made a trial connection of the VSR to the electricity grid in the substation.

Design: VSR manufactured by Siemens in Austria.

Results: This will solve problems of overloads in the long-term and with a positive effect on grid stability and security of supply for customers.

Location: United Kingdom

Year of commissioning: 2020

Description: Located off the Yorkshire coast, the Hornsea One project will span a huge area of approximately 407 square kilometres. The offshore wind farm will use 7 MW wind turbines, each one 190 m tall.

Design: The powerful shunt reactor used within the project features a rating of 120 – 300 MVAr and a rated voltage of 220 kV. The relatively low sound emissions of less than 84 dB(A) at 300 MVAr also add to the environmental compatibility of the units.

Results: VSR will cater for the fluctuating demand of reactive power compensation resulting from the volatile nature of wind power and improve environment compatibility (low sound emission).

Location: Norway

Years of commissioning: 2013 and 2018

Description: An extensive programme aimed at investing in the deployment of VSRs (as well as SVCs) in the grid to compensate for the loss of reactive power compensation resulting from the capacitive generation at low power flow from the installed power lines (Mid-Norway grid rein-forcement).

Design: Of the VSRs in operation, 10 are of voltage class 420 kV, 90 / 120 – 200 MVAr and two are of voltage class 300 kV, 80 – 150 MVAr with the goal of reactive power compensation.

Results: A lower voltage drop / rise with low short circuit capacity and slow tuning of the reactor guarantees that reactive reserves in SVC and the rotating synchronous compensator are secured and given optimal headroom.

Location: Germany

Year of commissioning: 2016

Description: A large VSR has been developed and applied with a regulation range of 80 % at a 400 kV Germany transmission grid.

Design: Tap changer is designed with 33 tappings to cover a rating from 50 to 250 MVAr for a 400 kV three-phase unit.

Results: Improved control of voltage, reduced reactive power loading of the grid, which results in decreased losses in the lines and in the VSR itself compared to a fixed shunt reactor. Expensive SVC equipment is also reduced.

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Static Synchronous Compensator (STATCOM)

A STATic synchronous COMpensator (STATCOM) is a fast-acting device capable of providing or absorbing reactive current and thereby regulating the voltage at the point of connection to a power grid. It is categorised under Flexible AC transmission system (FACTS) devices. The technology is based on VSCs with semiconductor valves in a modular multi-level configuration.

The dynamic reactive current output range is symmetrical (during normal disturbed network conditions); however, non-symmetrical designs are possible by introducing mechanically or thyristor switched shunt elements with unified control systems to cover most conventional applications. The STATCOM design and fast response makes the technology very convenient for maintaining voltage during network faults (as STATCOMs are capable of providing fast fault current injection limited to the rated current), enhancing short term voltage stability. In addition, STATCOMs can provide power factor correction, reactive power control, damping of low-frequency power oscillations (usually by means of reactive power modulation), active harmonic filtering, flicker mitigation and power quality improvements. Typical applications are in the electric power transmission, electric power distribution, electrical networks of heavy industrial plants, arc furnaces, high-speed railway systems and other electric systems, where voltage stability and power quality are of the utmost importance.

Technology Types

A typical STATCOM configuration consists of multi-level VSCs based on IGBTs, phase reactors and step-up transformer. It is shunt-connected to the grid. The reactive current is provided or absorbed by producing a controlled internal voltage waveform. Most STATCOMs available in the market today operate as GFCs and require a grid voltage reference to operate (with a defined level of grid strength). The voltage waveform is adjusted in its response with reference to the grid connection point voltage. In general, the STATCOMs operate as AC current controlled device, although the control of the output current is achieved via the regulation of the STATCOM internal voltage (behind the phase reactor) in amplitude, whereas the angle is close to 90 degrees with respect to the grid connection point voltage. If the STATCOM voltage amplitude is higher than the system voltage amplitude, capacitive reactive power is provided to the grid. If, vice versa, current flows from the system to the STATCOM and inductive reactive power is provided. The amount of reactive current depends on the transformer short circuit reactance and the voltage difference and is limited to the thermal limits of the IGBTs. In normal operation, i. e. the system voltage is within certain limits, both voltage amplitudes are equal and no reactive power is exchanged with the grid. An established control is if the grid voltage is above the threshold value, STATCOM control will decrease the amplitude of the STATCOM voltage waveform, making the STATCOM act as an inductive element and absorb reactive power from the grid. When the grid voltage is above the threshold value, the magnitude of the voltage waveform will be increased, making the STATCOM act as a capacitive element and providing reactive current to the grid.

Advantages & Field of Application

Modern designs are modular and allow for a high level of scalability and flexibility, ensuring the total required dynamic and steady state rating. Via the addition of shunt elements, the symmetrical output range of the pure STATCOM device can be adjusted to also meet non-symmetrical performance requirements. For conditions where a fast non-symmetrical dynamic range is required, on the one hand, thyristor-switched reactors and capacitors can be operated in parallel to form hybrid solutions. On the other hand, mechanically switched reactors and capacitors can be added to optimise slow response performance and provide additional steady-state capacity as required by e. g. typical intra-day load flow changes.

Components & Enablers

Typical components of a STATCOM installation are:

- High-voltage AC circuit breaker
- Step-down transformer
- Coupling reactors
- 3 converter branches connected in delta
- Converter-branch sub-modules, consisting of H-bridge installation of DC capacitor, IGBT and diode
- Control and protection
- Auxiliary system
- Cooling system
- High-frequency filters
- Additional capacitive or inductive shunt elements for asymmetrical control range (MSC, MSR, TSC, TSR)

Performance characteristics

The major characteristics of STATCOM are – assuming grid following control – fast response time (less than 2 cycles), high operational flexibility, superior under-voltage performance, excellent over-voltage performance, configuration with typically no harmonics filters, low noise emissions, low space requirements, high availability, hybrid design to cater to non-symmetric grid requirements and others.

Technology Readiness Level

TRL 8

TRL 8 – System ready for full-scale deployment if classical design and control is used.

Selected Best Practice Performance

Voltage rating: up to ~ 400 kV

Reactive power range: up to ±600 MVAr

Continuous rated capacitive current generation at grid voltage lower than 0.2 per unit.

Voltage measurement and control at reference high-voltage nodes more than 160 km away from the facility.

Research & Development

Current fields of research and development: mitigation of commutation failures; novel reactive power control strategies based on machine learning techniques; power quality im-provement by selective compensation of voltage harmonics (active filtering); challenges of applications in distribution grids (D-STATCOM); use of solar PV inverters as STATCOM (PV-STATCOM); enhancement in power oscillation damping; coordinated use of multiple devices and area voltage regulation and others, change of STATCOM control from normal classical current control to an even more grid convenient grid forming control (GFC) to enable STATCOMs to provide more ancillary grid services such as inherent current response to changes in grid voltage or/and amplitude; change in configuration from delta to star connection to integrate energy storage devices (i.e. supercaps), es-sential to provide instantaneous power reserve (inertia) in a relevant dimension.

Innovation priority: GFC with energy storage devices to enable inherent response and to improve dynamic performance, stable steady-state and dynamic behavior, semiconductor performance, reactive power output increase, cost reduction, facility footprint minimisation, noise reduction and hybrid solutions.

Number of IEEE publications since 2000, more than 3,000.

Best Practice Application

Location: Borken, Hesse, Germany

Year of commissioning: 2018

Description: The first German hybrid STATCOM facility has been in operation since 2018 to dynamically support the voltage and enhance the power quality at the 380 kV level.

Design: Hybrid construction of the reactive power compensation system, with two STATCOM branches and a mechanical switched Capacitor with Damping Network (MSCDN) providing reactive power compensation within the range of –250 MVAr to +400 MVAr. The MSCDN is used to provide the capacitive base load.

Results: Provides wide reactive control range and enhances power quality.

Location: Texas, United States

Year of commissioning: 2005

Description: In 2005, a STATCOM was installed in Austin to replace the reactive power capabilities of a closed down power plant. Due to noise and EMF emission as well as land use constraints, a STATCOM was chosen instead a SVC.

Design: A ±100 MVAr system was installed at a 138 kV bus along with three 31 MVAr capacitor banks, controlled by the STATCOM. Due to the IGBT converters being housed in a two-floor building, land use and noise emissions could be reduced. The STATCOM is designed for continuous operation at 46 °C.

Results: Provides high-speed control and decreases costs compared to other equipment improvements in the transmission infrastructure.

Location: Virginia, United States

Year of commissioning: 2018

Description: World's first mobile STATCOM to compensate for the load when plants are shut down, which can occur within months of announcement in the US.

Design: The design and substation infrastructure corresponds to that of a typical facility, however it has been customised to fit into three trailers. The rated power output is ±50 MVAr.

Results: The mobile solution gives a high level of flexibility. Instead of several years of planning and execution for a permanently installed substation, the mobile technology can be installed and commissioned within days anywhere, providing the required reactive power output to stabilise the grid.

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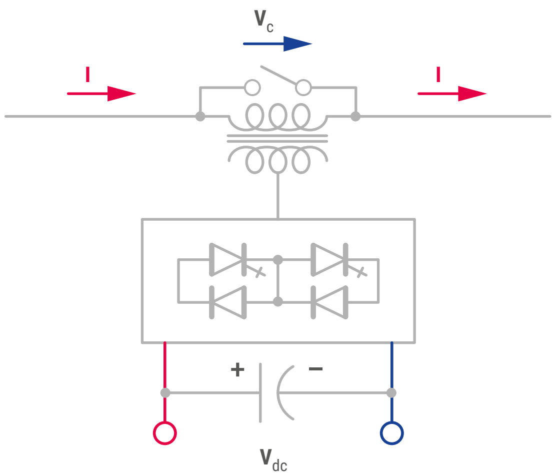
Static Synchronous Series Compensator

The static synchronous series compensator (SSSC) is a power quality FACTS device that employs a VSC connected in series to a transmission line through a transformer or multi-level inverters. The SSSC works like the STATCOM, except that it is serially connected instead of a shunt. Its output is a series injected voltage, which leads or lags the line current by 90°, thus emulating a controllable inductive or capacitive reactance. The SSSC can be used to reduce or increase the equivalent line impedance and enhance the active power transfer capability of the line. Moreover, the SSSCs are highly controllable devices and can provide further functionalities and services to the energy system.

Technology Types

SSCCs are part of the family of series controllers within FACTS devices. Two variants are possible:

- The conventional SSSC, connected to the transmission line through a transformer
- The transformerless SSSC, connected to the transmission line through multilevel inverters (such as modular transformerless SSSCs).



STATIC SYNCHRONOUS SERIES COMPENSATOR

Schematic diagram of SSSC [16]

Components & Enablers

Conventional SSSCs are also known as advanced series compensators (ASCs) or GTO-CSC, being the evolution of controlled series compensation (SC) devices. The SSSC consists of a coupling transformer, a GTO VSC and a DC circuit. They act as a controllable voltage source whose voltage magnitude can be in an operating area controlled independently of the line current. The SSSC can be considered functionally as an ideal generator that can be operated with a relatively small DC storage capacitor in a self-sufficient manner to exchange reactive power with the AC system or, with an external DC power supply or energy storage, to also exchange independently controllable active power, analogously to a STATCOM.

Transformerless SSSC solutions typically comprise a single-phase, modular-SSSC injecting a leading or lagging voltage in quadrature with the line current, but include a built-in-bypass to avoid damage of the power electronics resulting from high currents e.g. during a network fault. It can increase or decrease power flows on a circuit and perform dynamic services.

Advantages & Field of Application

The use of SSSCs provides the typical advantages of load flow control that can also be realised by other technologies such as PST, TCSC and partly by a series reactor.

However, both conventional and transformerless SSSCs also offer additional special functions such as:

- **Better controllability of power flow,** as SSSCs possess the inherent capability to decrease as well as to increase (real) power flow almost linearly in the circuit.
- **Receiving end voltage regulation of a radial line:** In short circuit weak networks by controlling the degree of series compensation to keep the end-voltage constant in the face of changing load and load power factor.
- **Power oscillation damping:** the SSSC is a controlled device and can be used to damp wide area low frequency power oscillations.
- **Regional network voltage regulation** by the inherent networking of devices applied at different locations in a grid.
- **Phase balancing:** Modular SSSC as a single phase device can independently alter the effective phase impedance of a circuit[s] to rebalance power flows.

In addition to these range of applications, the modular SSSC are designed to be easily relocated if needed. Moreover, the amount of load flow shift can be adjusted by adding or removing modules, depending on the network needs. A little effort redeployability for is expected.

Research & Development

Current fields of research: Generic research related to FACTS includes a variety of domains, from power electronics to applications. Of note are: power electronic topologies and control; exploration of new type of semiconductors replacing silicon; mitigation of power quality impacts of large scale power electronics application; more user-friendly interfaces; standardisation; evaluation of cost and benefits through demonstrations; coordinated control of multiple FACTS devices and relocatable FACTS.

In addition to these generic topics, when focusing more particularly on SSSC, research is conducted to detect in advance the interactions such as sub synchronous resonance (SSR) events with other network components. Some research is focusing on enhancing the low voltage ride through the capability of wind turbines using a combination of SSSC and controllable series braking resistor.

Focusing specifically on modular transformerless SSSC, real time congestion management, power quality management, offshore network control, phase angle correction and ancillary services from short term active power provision / management are the fields to be further developed in the future.

Technology Readiness Level

TRL 7

Conventional SSSC: TRL 7 – System prototype demonstration in operational environments

TRL 9

Transformerless SSSC up to 110 kV: TRL 9 – System prototype demonstration in operational environments

TRL 7

Transformerless SSSC above 110 kV: TRL 7 – System prototype demonstration in operational environments

Best Practice Performance

Conventional SSSC:

- **Rated system voltage:** 220 kV
- **Rated Reactive power:** 100 – 400 MVAR

Transformerless SSSC:

- **Rated system voltage:** up to 550 kV
- **Rated Reactive power:** modular units are designed to be operated in combination, allowing any reactive power rating to be possible, i. e. 1 – 10 MVAr in size for each module.

Selected Best Practice Application

Location: Spain

Year of commissioning: 2010

Description: The application foresees the SSSC functionalities validation, the case study definition enabling the equipment behaviour validation (in normal operation and during contingencies in the grid) by using a power flow simulation software. It is complemented by a simplified case study to analyse the behaviour of the SSSC in electromagnetic short-circuit simulations.

Design: The validation of the SSSC solutions behaviour used a reference grid including two transmission lines representing the 400 kV Transmission System with two parallel lines representing the 220 kV lines. A need was identified in the 220 kV lines, due to the differences in impedance and the transmission capacity of the 220 kV lines.

The short circuit behavior of the network and its impact on the SSSC was evaluated, to ensure the SSSC could withstand 40 kA of short circuit current across the coupling transformer.

Results: the SSSC can solve some of the overload problems detected in the 220 kV grid of the Spanish Electrical System. It was proven to be particularly convenient in old lines (with low capacity), with a power flow very much influenced by wind power production.

Location: Ireland [18]

Year of commissioning: 2016 – 2017

Description: For the trial installation, three transformerless SSSC units were installed on the Cashla – Ennis 110 kV line. Once the trial validated the safety of the installation process, two transformerless SSSC units were installed on the first tower coming out of the Cashla substation in County Galway. The remaining unit was installed on the first tower coming out of the Ennis substation on the same circuit. This pilot lasted for a year, verifying that communications with the devices did not impact the systems used to report primary faults and can change reactance as specified. The full functionality of the devices was assessed, including switching units from full Capacitive Reactance Injection mode to full Inductive Reactance Injection mode.

Design: Use of modular transformerless SSSC to enable real-time power flow control on grids.

Results: During system faults, the devices performed as expected and entered a bypass mode under fault conditions, with no unexpected interactions with the normal protection system. During the testing, Ireland was hit by the tail end of Hurricane Ophelia on Monday 16 October 2017 (Status Red wind warning – the highest threat level possible). Despite strong gusts of up to 156 km an hour on land, there was no structural damage caused to the devices. The units did not cause any damage to the transmission infrastructure. All units remained fully operational through this period.

Location: Spain

Year of commissioning: 2015

Description: At times of high wind infeed and hydro production, 220 kV high voltage lines were overloaded in Torres del Segre in Spain. To relieve congestion, the system operator was obliged to reduce renewable production output at certain instances of time.

Design: A 50 MVAr conventional SSSC was installed including control equipment, magnetic elements for grid coupling, by-pass switch, thyristor and a local SCADA.

Results: Construction of a new 220 kV circuit has been avoided and the efficiency of the existing infrastructure has been improved, with enhanced dispatching of power flows and an increase in renewable energy integration.

Location: Nigeria

Year of commissioning: 2017 (modeling)

Description: Use of SSSC for solving problems associated with the Nigerian 330 kV longitudinal power network, using voltage magnitude as performance metrics.

Design: Modelling of power system and SSSC modelling producing two sets of non-linear algebraic equations solved simultaneously using the Newton–Raphson algorithm method and implemented using MATLAB.

Results: Results of power flow analysis of Nigerian 330 kV transmission network without SSSC showed that there was voltage limit violation of ±10 % at bus 16 Gombe (0.8973 p.u). The results with the incorporation of SSSC showed that the SSSC was effective in eliminating voltage limit violations and reduced network active power loss by more than 5 % of the base case (93.87 MW). Therefore, SSSC is effective in solving steady-state problems of longitudinal power systems.

Selected Best Practice Application (cont.)

Location: United Kingdom [19]

Year of commissioning: 2021

Description: NGET are proceeding with five installations in 2020, due for completion in 2021. These projects will contain a total of 375 MVAr of power flow control capability, located along the Fourstones to Harker to Stella West, Penwortham to Kirkby, and Lackenby to Norton circuits.

Design: Use of modular transformerless SSSC to enable real-time power flow control on grids.

Results: These projects are anticipated to increase boundary capabilities by 1.5 gigawatts in total across three transmission network boundaries. National Grid ESO has assessed similar projects at a number of further locations, and these are recommended for progression in the Network Options Assessments report for later years.

Location: New York, United States [21]

Year of commissioning: 2019

Description: Three transformerless SSSCs were installed on the 115 kV Sturgeon Pool – Ohioville line owned by Central Hudson in New York State. Central Hudson sought to gain experience with the technology in advance of a larger installation planned for 2021. This larger installation will add 21 % series compensation on a 345 kV line to enable full capacity deliverability of interconnecting generation. The Electric Power Research Institute (EPRI) observed the 2019 installation and evaluated the technology's functionality.

Design: Use of modular transformerless SSSC to enable real-time power flow control on grids.

Results: The installation process was smooth and without incident. The transformerless SSSC operated effectively in capacitive and inductive injection modes. The devices responded through control commands issued locally through the substation-based interface and remotely from the SCADA / EMS. During system faults, the devices performed as expected and entered a bypass mode under fault conditions. There were no unexpected interactions with the normal protection system.

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Synchronous Condenser

A synchronous condenser (also called a synchronous capacitor or synchronous compensator) is a DC-excited synchronous machine (large rotating generators) whose shaft is not attached to any driving equipment. This device provides improved voltage regulation and stability by continuously generating/absorbing adjustable reactive power as well as improved short-circuit strength and frequency stability by providing synchronous inertia. Its purpose is not to convert electric to mechanical power or vice versa, but to make use of the machine's reactive power control capabilities and the synchronous inertia. It constitutes an interesting alternative solution to capacitor banks in the power system due to the ability to continuously adjust the reactive power amount. Synchronous condensers are perfectly suited to controlling the voltage on long transmission lines or in networks with a high penetration of power electronic devices as well as in networks where there is a high risk of 'islanding' from the main network.

Technology Types

A synchronous condenser is a conventional solution that has been used for decades for regulating reactive power before there were any power electronics compensation systems.

A conventional synchronous condenser is an AC synchronous motor that is not attached to any driven equipment. The device can provide continuous reactive power control when used with the suitable automatic exciter. An increase of the device's field excitation results in providing magnetizing power (kVAr) to the system. Synchronous condensers have traditionally been used at both distribution and transmission voltage levels to improve stability and to maintain voltages within desired limits under changing load conditions and contingency situations. To do so, they use a small amount of active power from the power system to supply losses.

The development of high-temperature superconductivity enabled the development of a second type: HTS based machines which are smaller, lighter, more efficient and less expensive to manufacture and operate than conventional machines. Advancements in the HTS wire technology have resulted in superconducting electromagnets that can operate at higher temperatures than those made of low-temperature superconductor materials. Consequently, they utilise simpler, less costly and more efficient cooling systems. This makes HTS wires technically feasible and economically viable for condenser applications at power ratings lower than this can be achieved with the low-temperature superconductor wire.

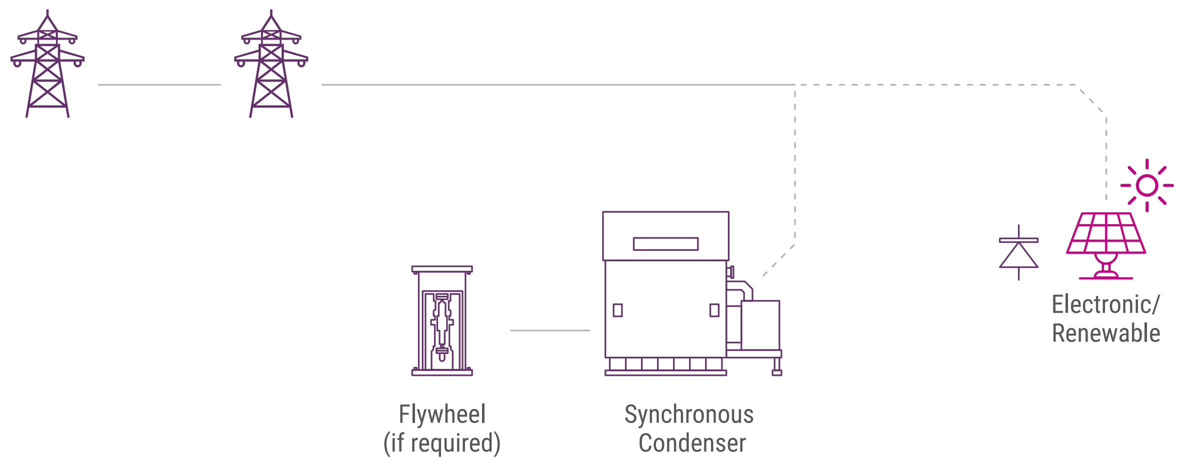
Components & Enablers

Typical components of a (complete solution) synchronous condenser are:

- Stator and rotor with solid integral pole tips
- Cooling system (hydrogen, air or water)
- Excitation system
- Lubrication oil supply
- Step-up transformer and auxiliary transformer.

High-inertia synchronous condensers are similar to traditional synchronous condensers but with additional inertia. A dedicated flywheel for better system inertia matching could complement a synchronous condenser if this is required by the inertia requirements of the TSO.

Components & Enablers (cont.)



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Advantages & Field of Application

A synchronous condenser is a long standing well-known technology that provides the following advantages:

- **System inertia:** Inertia is an inherent feature of a synchronous condenser as it is a rotating machine. The benefit of inertia is improved voltage 'stiffness', which improves the overall behaviour of the system.
- **Increased short-term overload capability:** Depending on the type, a synchronous condenser can provide more than two times its rating up to a few seconds, which enhances system support during emergency situations or contingencies.
- **Low-voltage ride through:** Even under extreme low voltage contingencies, it remains connected and provides smooth, reliable operation.
- **Fast response:** By using modern excitation and control systems, a synchronous condenser is fast enough to meet dynamic response requirements.
- **Additional short-circuit strength:** Another feature of a synchronous condenser is that it provides real short short-circuit strength to the grid, which improves system stability with weak interconnections and enhances system protection.
- **No harmonics:** A synchronous condenser is not a source of harmonics and can even absorb harmonic currents. This feature enables ease of integration into existing networks. Typical applications of a synchronous condenser include: HVDC (provides short-circuit strength and dynamic reactive power support); Wind/Solar (increases short-circuit ratio); Grid Support (improves weak AC grid performance, voltage support during faults and contingencies, limits ROCOF); and Regulation (can replace dynamic voltage regulation and inertia from retired units). Disadvantages include higher level of losses, mechanical wear and a slower response time compared to power electronic technologies. It should also be mentioned that over the last three decades, a preference for synchronous condensers was given to alternatives based on highly dynamic, low-loss and low-maintenance power electronics solutions. As of today, in a world with the massive penetration of renewable energies, they again constitute a robust solution to ensure system stability in a scenario of the high penetration of renewable generation, and thus they play a role in the planning of the future grid (see H2020 Migrate project results on the competition between grid forming and synchronous condensers).

Technology Readiness Level

TRL 9

Conventional systems are rated TRL 9 – System ready for full-scale deployment, whereas HTS-based devices are assumed to be at a lower TRL. However, publications claim that HTC-based devices have reached the market.

TRL 7–8

Maturity for high inertia synchronous condensers with flywheel reaches levels between TRL 7 – System prototype demonstration in op-erational environment – and TRL 8 – system complete and qualified (see application case in Italy announced in May 2020).

Best Practice Performance

Power range: Typical range of reactive power rating for synchronous condensers connected to the grid are in the range of 20 to 200 MVAr, but manufacturers can tailor synchronous condensers for power grid stability up to 350 MVAr.

Research & Development

Current fields of research: The increasing penetration of renewables in the energy mix fostered interest in synchronous condenser technology. Utilities are rediscovering the benefits of conventional synchronous condenser technology and are looking for ways to utilise them in their networks from a technical and economical perspective. From the technology standpoint, the HTS synchronous condenser capitalises on the progress in HTS research and innovation.

Innovation Priority: Grid forming, synchronisation of converters, virtual synchronous machines. Research is now focusing on analysing the application of synchronous condensers at different locations of the grid, their role in frequency response markets, and ways in which synchronous condensers could play a role in future system planning

Selected Best Practice Application

Location: Oberottmarshausen, Bavaria, Germany

Year of Commissioning: 2018

Description: The nuclear power plant in Gundremmingen with a 1.34 GW capacity was shut down to enforce the Atomic Energy Act. Therefore, measures to ensure grid stability with respect to inertia and reactive power compensation were required.

Design: A synchronous condenser offered a wide reactive power +340 to –170 MVAr with loss optimised and life-time optimised operation. The solution ensured grid stability during voltage fluctuations.

Result: A synchronous condenser was incorporated to provide a wide range of reactive power capability for operating under ambient temperature conditions in Oberottmarshausen.

Location: Scotland, United Kingdom

Year of commissioning: 2017

Description: Partnership between the UK Utility, the System Operator and academic institutions to demonstrate a sustainable design and operational control of a synchronous condenser with an innovative co-ordinated control system combined with a STATCOM flexible AC transmission system device. The project was awarded a budget of £ 17.64 m through the UK's Network Innovation Competition (NIC) in 2016.

Design: Synchronous condenser with innovative co-ordinated control system combined with a STATCOM flexible AC transmission system device.

Results: Provision of an efficient and composite solution that will enhance system stability and security while maintaining power quality, resulting in minimising risks of power outages and delivering significant benefits to UK customers.

Selected Best Practice Application (cont.)

Location: Bjæverskov, Fraugde and Herslev substations (Denmark)

Year of commissioning: 2015

Description: Denmark is one of the few countries to include a large share of wind energy in its energy mix, which is why the country requires synchronous condenser solutions to help stabilise its electricity transmission system and support higher wind power generation.

Design: The scope of delivery for the synchronous condenser solutions included a synchronous generator with brushless excitation, a generator step-up transformer and the electrical auxiliary systems, such as control and safety systems, voltage regulators and startup systems. Each synchronous condenser solution can deliver more than 900 MVA of short-circuit power and +215/–150 MVAr of reactive power. The startup time is designed so that the generators can reach up to 3,000 rpm within 10 minutes and be synchronised with the transmission grid. There is a minimum availability of 98%. They feature high efficiency, low noise emissions, and low installation and commissioning costs.

Results:

- Bjæverskov substation 250 MVAr synchronous condenser solution started operation in 2013.
- The Fraugde and Herslev substations synchronous condenser solution is capable of delivering more than 900 MVA of short-circuit power and +150/–75 MVAr of reactive power; trial operation as of August 2014.

Location: Granite Substation, Vermont, USA

Year of commissioning: Nov. 2008

Description: As part of the Northwest Vermont Reliability Project, a number of upgrades were investigated to provide for the reactive power needs at the Granite substation. Simulations indicated that the power system is very near to a point of voltage instability. In the case of an outage of the Vermont Yankee – Coolidge 345 kV line, a continuous reactive power control device is critical to prevent voltage collapse.

Design: Selection of synchronous condenser over static devices due to the low voltage ride through capability and the high short time overload characteristics.

Results:

- Four +25/–12.5 MVAr sync condensers
- Four 25 MVAr shunt banks (MSC)
- Two phase-shifting transformers
- Integrated control system

The overload capability of the condensers provides sufficient time for the mechanically switched 115 kV shunt capacitors to be placed into service.

Location: Hesse, Germany

Year of Commissioning: 2013

Description: After the governmental decision to shut down nuclear power plants in Germany following the Fukushima incident, one of the generating units of the 2.5 GW Biblis nuclear power plant was converted into a rotating synchronous condenser.

Design: A 14 MW medium-voltage startup converter was set up for generator startup. This was connected to a new 18.3 MVA transformer, which subsequently transforms its output voltage to the generator terminal voltage of 27 kV via a further 17 MVA transformer. With a gas-insulated 30 kV medium voltage switchgear, the new system was connected to the generator via the generator terminal lead.

Result: The newly converted condenser regulates the reactive power from –400 to +900 MVAr, which is made available to grid operator Amprion in situations of low or high voltage.

Location: Codrongianos, Italy

Year of Commissioning: 2014 (units connected to grid

Description: 2 × 250 MVAr synchronous condensers for stabilising the Sardinian grid. Speed: 3000 rpm. Voltage: 19 kV

Description: SCs aim to allow a safer and enhanced utilisation of the Sardinian HVDC links. The two SC present innovative differences with respect to traditional ones: round rotor design (better cost/Mvar ratio), two poles design to reduce weight and cost, Air-to-water cooling to simplify maintenance, fast static starting system (<15 mn.), adiabatic cooling system for the primary water circuit, 200% overload capability (10 s), completely unmanned operation from remote control centre. Total losses are estimated at 1.15%.

Selected Best Practice Application (cont.)

Location: Blackwater station, New Mexico, US

Year of Commissioning: 2019

Description: Transmission lines (216 miles) between 362 kV Station (north of Albuquerque) to Blackwater 362 kV Station (near Clovis) enables the exchange of power generated from wind farms between New Mexico and Texas. Consequently, the transmission lines of this length resulted in low short-circuit conditions that were challenging the control and operation of power electronic systems for the high-voltage direct current convertor and wind farms located at or near the Blackwater station. Studies revealed that the installation of a synchronous condenser provides the required short circuit capability to facilitate transmission services in Blackwater 362 kV station.

Design: The synchronous condenser was selected to provide 959 MVA short circuit power at the 362 kV Blackwater station.

Result: The installation of the synchronous condenser maintains acceptable system performance by increasing the short-circuit ratio and providing voltage support during faults and contingencies, thereby enabling the transmission of power in New Mexico.

Location: Brindisi, Italy

Year of Commissioning: (announced in May 2020)

Description: Two synchronous condensers and flywheel will be provided to Terna for the Brindisi substation in southern Italy. Each synchronous condenser unit will supply reactive power of up to +250/–125 MVAr and 1750 MWs inertia to support the stability of Italy's grid.

Design: These synchronous condensers will complement the park of synchronous condensers operated by the Italian TSO. The offer from the manufacturer includes the design, civil works, supply, installation and commissioning of the 2 electrical two-pole generators and related equipment (step-up transformers, circuit breakers, auxiliaries and balance of plant, protection and controls systems) as well as the monitoring and diagnostic systems and 20 years of planned maintenance. Each of the generators will be equipped with a flywheel to respond to the inertia requirements from Terna.

Results: Both pieces of equipment are expected to supply a combined 500 MVAr reactive power and 3,500 MWs inertia to help stabilise the grid and support the integration of more renewable energy.

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Line-Commutated Converters – Current Source Converters

Line-commutated converters (LCCs) are the conventional, mature and well-established technology used to convert electric power from AC to DC or vice versa. The term line-commutated indicates that the conversion process relies on a stable line voltage, with clear zero-crossings of the AC system to which the converter is connected in order to have a flow commutation from one switching element to another.

In a current source converter (CSC), the DC current is kept constant with a small ripple using a large inductor. In practice, for most applications an LCC equals an CSC. The direction of power flow through a CSC is determined by the polarity of the DC voltage, whereas the direction of current flow remains the same. A LCC requires connection to a strong grid with sufficient short circuit power to avoid commutation faults and a synchronous voltage source in order to operate. In comparison to a VSC, it still allows for much higher power conversion capacities with lower losses, but would require converter stations with a larger ground footprint than the equivalent capacity VSC sites.

Technology Types

LCCs are differentiated in two technology types: Mercury-arc valves based LCC and Thyristor based LCC.

- Mercury-arc valves based LCCs is a technology that was used until the 1970s. It is a type of cold cathode gas-filled tube made from a pool of liquid mercury. It was therefore self-restoring and long-lasting, capable of carrying high currents up to 1.8 kA at 450 kV but with high maintenance time and serious environmental hazard risks. The last operating mercury arc system was shut down in 2012.
- Thyristors-based LCCs were first used in HVDC systems in the early 1970s while widely implemented since the 1960s, for both OHL and cable applications. A thyristor is a solid-state semiconductor device similar to the diode, but with an extra control terminal that is used to switch the device on at a defined instant. Additional passive components (e.g. grading capacitors and resistors), need to be connected in parallel with each thyristor to ensure a uniform share of the voltage between the thyristors across the valve. Initial designs used six pulse converters. Most modern designs apply twelve pulse converters.

Advantages & Field of Application

Thyristors based LCCs are widely used for bulk power point-to-point (with overhead lines and or subsea cables), for back-to-back links between different synchronous networks and as an embedded link within a synchronous network.

Applications for CSC will most likely be outside Europe. In Europe, VSCs are expected to be the predominant technology for most applications.

This thyristor-based technology is characterised by its short time overload capability and its high efficiency, with a total operating power loss in a converter station of typically 0.7 – 0.8 % of the scheme rating.

Components & Enablers

- Converter transformer
- AC passive filters and possible additional reactive power compensation at point of connection
- Current source converter (6/12 pulse)
- DC smoothing reactors
- VAR compensator
- DC filters
- Control and Telecommunications

Components & Enablers (cont.)

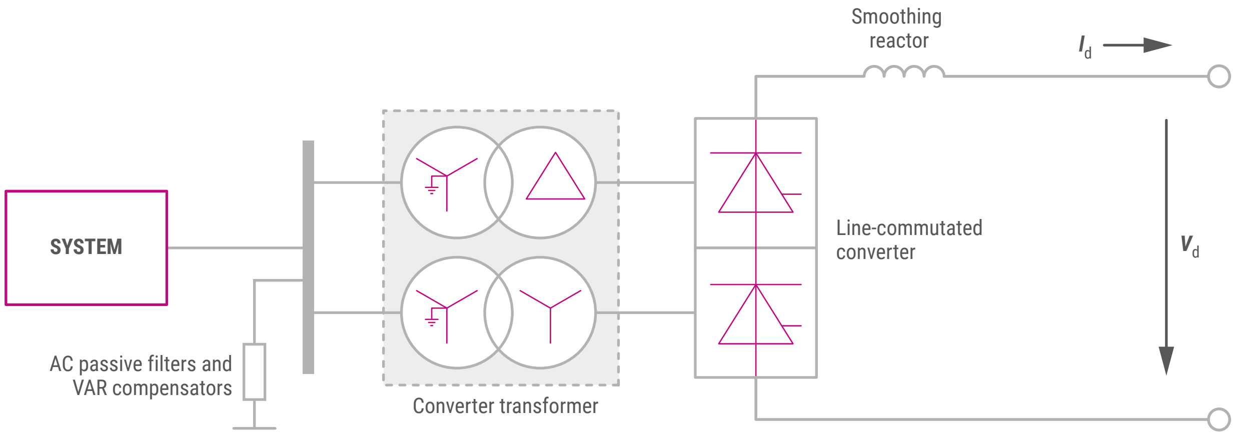

Fig. 1: Conventional HVDC with Current Source Converters (CSC-HVDC)

Technology Readiness Level

TRL 9

TRL 9 – System ready for full scale deployment

Best Practice Performance

Following many years of development, thyristor devices are able to operate at blocking voltages up to 8.5 kV and switch DC currents of up to 6.25 kA, which allowed LCC schemes to be installed up to 10 GW and ±800 kV[1] (7.2 GW already in operation in China), with a current rating amounting 5 kA.

In Europe, the largest LCC scheme is rated at 2,200 MW at ±600 kV (Western Link in the UK, commissioned in 2018).

The maximum length for a line is 2,000 km, whereas for a cable this maximum length is 600 km.

Research & Development

Current fields of research: Virtual impedance control; Reduction of common-mode voltage, AC-side compensation; control algorithms in unbalanced grid voltages; natural sampling based space vector modulation; development of new types of semiconductors (SiC, diamond, etc.) which will allow the development of new thyristors; eco-conception of CSC (CO_2 impact, noise, lifetime).

Variable for improvement: In the context of the Ultra-High HVDC (UHHVDC), development of air insulation of water cooled thyristor valves, transformer oil / paper insulation, development of modular design of UHHVDC converts (size and weight) to face transport constraints; shunt active power filter; operation in unbalanced grid conditions; synchronisation techniques; power density of converter; lower harmonics magnitudes.

1 Although, to date, such ratings are only considered in China, India and Brazil

Selected Best Practice Application

Location: Norway – Netherlands

Year of commissioning: 2008

Description: The HVDC submarine link came into operation in 2008 to connect the Norwegian and the Dutch grid.

Design: The HVDC system is bipolar, with a total cable length of 580 km, and is operated at ±450 kV.

Results: Transmission of 700 MW of active power across borders, facilitating cross border exchange.

Location: Belgium – Great Britain

Year of commissioning: 2019

Description: The Nemo Link consists of subsea and underground cables connected to a converter station and an electricity substation in each country, allowing electricity flows in either direction between the two countries for improved grid reliability, access to sustainable generation and electricity trading.

Design: The HVDC Nemo Link has a total cable length of 140 km (of which 10 km is underground and 130 km submarine) and is operated at ±400 kV.

Results: Commercial operations began on 31 January 2019 and it is able to transmit 1,000 MW of active power. Jon Butterworth, President of National Grid Ventures, explains that 'By enabling the market to react immediately to rapid changes in supply and demand, Nemo helps to better balance an energy system that is more reliant on intermittent wind and solar energy'.

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Voltage Source Converters

VSCs are self-commutated converters to connect HVAC and HVDC systems using devices suitable for high power electronic applications, such as IGBTs. VSCs are capable of self-commutation, being able to generate AC voltages without the need to rely on an AC system. This allows for independent rapid control of both active and reactive power and black start capability. VSCs maintain a constant polarity of the DC voltage for their building blocks, such as the 2-level or 3-level converter as well as the so-called 'modules' in an MMC. The change of power flow direction is achieved by reversing the direction of the current. Thereby, VSCs are more easily integrated in multi-terminal DC systems. VSC-based HVDC systems offer a faster active power flow control with respect to the more mature CSC-HVDC, while also ensuring flexible and extended reactive power controllability at the two converter terminals.

Technology Types

VSC can be classified with respect to the converter technology types used, which have evolved over time:

- **Two-Level VSC –** earliest technology used
- **Three Level Diode Neutral Point Clamped** (NPC) or **Three Level Active NPC**
- **Two Level with Optimum Pulse-Width Modulation** (OPWM)
- **Cascaded-two Level Converter** (CTL)
- **Modular Multi-Level Converter** (MMC), which is the latest and most advanced technology used for HVDC transmission. MMC differentiates further into the so-called Half Bridge type and Full Bridge type MMC.

In offshore HVDC grids, MMC is becoming the preferred power electronic converter for converting between AC and DC as it presents several benefits: (i) the ability to reverse the power flow without reversing the polarity of the DC voltages by DC current reversal; (ii) modularity and scalability features, making it advantageous compared to other VSC topologies; (iii) its inherent capability of storing energy internally in the converter. This can benefit the system in which it is connected and enables the drastic reduction of operating losses of the converter stations by avoiding the need for high frequency switching of the semi-conductor devices.

Components & Enablers

- DC / DC converter
- Transformer (Optional Tapping in series / parallel)
- DC-link capacitors
- Passive high-pass filters
- Phase reactors
- DC cables
- DC breaker (Optional)

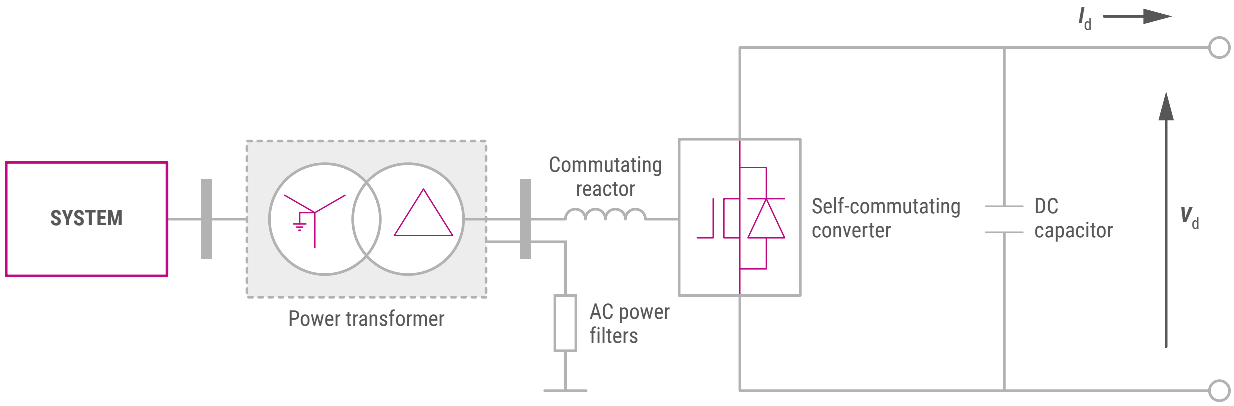

Fig. 1: VSC main components

Advantages & Field of Application

The VSC technology provides several technical advantages, such as resilience to commutation failure, ancillary services and reactive power control (and consequently voltage control).

In comparison to the LCC technology, VSC has a shorter history[1], less operating experience and, so far, lower maximum voltages and power transfer capability. Although power and voltage ratings have risen dramatically in recent years, the overload capability of VSC technology remains low, limited by the capability of the IGBT devices.

VSC-HVDC is best suited to interconnecting remote generation facilities (e. g. offshore wind far away from shore, typically > 80 km) to the main power grid; performing a black start to start-up connected offshore wind farms or re-energising network sections; and contributing to power system and voltage stability thanks to its fast reactive power flow and voltage control at its terminals.

It is expected to support Multi-Terminal HVDC (MTDC) applications, which form the backbone of potential offshore grids (such as the one in the North Sea) implementation.

To date, most VSC applications[2] have used submarine or underground cables. The first multi-terminal systems are in operation (in China) and others are under construction (in Europe), and the number of commercial applications is rapidly growing.

The technology uses IGBT devices rated up to 6.5 kV and 2,000 A. The largest scheme in service is the 2 × 1,000 MW ± 320 kV INELFE project (France – Spain) and the highest voltage is on the 700 MW Skagerrak Pole 4 project at 500 kV (Norway – Denmark).

The under construction North Sea Link (NSL) project[3] between the UK and Norway will operate as a bi-pole at 1,400 MW and ± 525 kV. Further development involves a 'full bridge' solution for more flexible operation of the VSC technology for OHL links. The current 'half bridge' solution cannot block DC fault currents and requires combination to a DC circuit breaker in series with the DC line.

1 HVDC stations using VSC technology have been in service since 1997.
2 except the back to back links
3 scheduled to be online in 2021

Technology Readiness Level

TRL 9

Monopole and Bipole VSC
TRL 9 – Ready for full scale deployment

TRL 4

DC/DC Converter
TRL 4 – Technology validated in lab

TRL 9

VSC half bridge
TRL 9 – Ready for full scale deployment (INELFE Project)

TRL 8

VSC full bridge
TRL 8 – Incorporated in commercial design (ULTRANET project)

Research & Development

Current fields of research: Virtual impedance control, Grid-Current-Feedback Damping, advanced vector control, availability; improved efficiency of VSC converter based on new switching typologies; development of transformerless VSC converters; development of novel multilevel switching typologies (architecture and switching modes) to enhance transmission capacity; DC circuit breakers development for selective fault clearance; development of multiterminal VSC transmission.

Innovation priority: IGBTs, control algorithms, filters, overload capability

Other: Future developments foresee an extended domain of use of HVDC technologies, such as far offshore and ultra-deep submarine connections (2,000 m+), ultra-high voltage and higher transmission distance, and combining HVDC and HVAC networks and the related impact on reliability.

Best Practice Performance

Maximum capacity: 2,000 MW per substation (bipole)

Voltage rating: 525 kV

Current rating: 2 kA

Longest distance: max. length of cable: 623 Km (NORD Link); expected to be more than 700 km in 2021 (North Sea Link)

Best Practice Application

Location: Kristiansand (Norway) – Tjele (Denmark)

Year of commissioning: 2014

Description: The Skagerrak (SK) HVDC transmission system has been in operation since the 1970s and now comprises four HVDC links which together provide a total of 1,700 MW transmission capacity.

Design: Of the 4 HVDC links, one is equipped with a VSC: the Skagerrak 4 link for which the capacity of the VSC is 700 MW with a rated voltage of 500 kV.

Results: Successful demonstration of the black-start capabilities of the system as well as the energising of isolated AC grids.

Location: Belgium and Germany

Year of commissioning: 2020

Description: The 'Aachen Liege Electricity Grid Overlay' project should provide a transmission power capacity of 1,000 MW. It will use an HVDC transmission technology as an underground cable: the AC Grid together with the DC transmission line will increase cross-border electricity flows.

Design: The HVDC link requires a converter station positioned at each end of the line providing the switch from AC to DC, for which a VSC is implemented. The link will be positioned between the already existing 380 kV stations in Oberzier Germany and Lixhe Belgium, and it will extend over a length of 90 km.

Results: Increased security of supply and increased flexibility in cross-border load flow exchange.

Location: Denmark (Endrup) – The Netherlands (Eemshaven)

Year of commissioning: 2019

Description: The COBRA cable consists of two parallel, approx. 300 km long, DC submarine cables linking western Denmark and the Netherlands together. The project also comprises approx. 20 km of onshore cable. The cables are connected to converter stations built in Endrup, east of Esbjerg, Denmark and Eemshaven in the Netherlands, respectively. The VSC converter stations in Endrup and Eemshaven connect the 400-kV AC grid to the DC COBRA cable.

Design: The system has a power transfer capacity of 700 MW and is operated at a voltage of ±320 kV. The total HVDC cable route is 329 km, of which 307 km are offshore and 22 km are onshore. Two cables are installed in parallel, making the total length of cables 658 km.

Results: The COBRA connection contributes to the introduction of renewable power production in that both countries are able to manage much more sustainable production, i.e. buy and sell wind power and solar power across borders whenever there is a surplus situation in either country. At the same time, the connection ensures a high level of security of electricity supply, as an increasing amount of wind energy flows into the systems 'as the wind blows'. The connection is designed to meet future requirements by presenting the opportunity for future offshore wind farms in the North Sea to be connected to the COBRA cable. Furthermore, the cable can be part of a future interconnected offshore electricity grid between the countries bordering the North Sea, capable of unpinning the expansion of wind power and strengthening the European electricity transmission grids.

Location: Baixas (France) – Santa Llogaia (Spain)

Year of commissioning: 2015

Description: The INELFE underground electrical interconnection is a joint project that came into operation in 2015. It enabled double electricity capacity between France and Spain.

Design: The system has a total power transfer capacity of 2,800 MW and is operated at a voltage of ±320 kV. The entire 64.5 km link is undergrounded which includes 8.5 km tunnel connection through the Pyrenees.

Results: Increased transmission capacity between Spain and France with flexible reactive power control, black-start capabilities and local power quality management. Prior to the construction of the new connection, surplus wind production generated in Spain could not be exported to the rest of the continent due to the limitations of cross-border capacity. The new infrastructure facilitates the incorporation of clean weather dependent energy without putting the supply at risk.

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Adaptive Protection Technology

A conventional protection system has relays with fixed setting parameters. With the growing complexity in operating power systems, the increasing shares of power electronic connected generating units, a lack of short circuit current injection to correctly detect faults, and increased harmonics that can falsely trigger protection relays, various challenges arise to fulfil the protection requirements in variable operation conditions. Adaptive protection schemes result from the application of microprocessors in the area of protective relays and are growing in importance in the electrical power systems. They enable grid operators to have flexible protection schemes in response to changes in the power system.

Technology Types

Protection relays are devices deployed in the field that trip off under certain conditions. They can be categorised as:

- **Analogue relays:** the conventional electromechanical or static relays operating offline, with low maintenance, reliable but unable to determine the exact location of the fault. They establish a zone of protection in which the relay will operate or trip if they measure an overcurrent. They have high maturity but allow only for a fixed protection scheme.
- **Digital relays:** recent microprocessor / numerical relays which operate online and can adapt their settings in real time in response to power system conditions.

Adaptive protection schemes can be categorised by the adaptive protection device and adaptive protection system. Developed since the 1980s, they are based on the underlying idea of the ability of the protection system to adapt to the current operating condition of the power system.

Various **definitions of the adaptative protection** function can be found in the literature, such as the one proposed by the IEEE Power System Relaying Committee: 'automatically adjusts the operating characteristics of the relay system in response the changing power system conditions'. This definition clearly reflects the two main features of an adaptative protection scheme: (i) the adjustment of the protection functions or configurations, and (ii) the automatic nature of this adjustment.

Protection functions deployed in transmission and distribution systems differ. This results mainly from the more stringent stability requirements for transmission with more complex schemes in addition to the necessary redundancy. Distribution networks require more cost-effective protection solutions due to the volume of assets that require protection.

Protection principles include generally unit-based protection, for which the zone of the protection boundary is limited, and the non-unit protection, which relies on local measurements to inform about protection features (e.g. overcurrent, distance protection):

- **unit-based protections** are mostly applied to transmission networks where the cost of required communications is justified, such schemes are highly selective in their operation
- **non-unit protection schemes** can be found in both transmission and distribution.

Due to its simplicity, overcurrent protection is mostly applied in distribution, but also in transmission as a backup protection function.

Distance protection is a mature protection mainly used in transmission systems[1]. It is based on the observation that the protected line impedance is proportional to its length: monitoring changes in the impedance (e.g. by measuring locally voltage and current) thus enables the identification of a fault without any communication device.

System integrity protection schemes (SIPS) are used to protect the overall integrity of the power system against events leading potentially to unstable transients, overloads or blackouts. The advent of wide area measurements promises more flexibility in available protection actions.

1 It is applied, to a lesser extent, in meshed distribution systems to improve selectivity with a faster operating time

Components & Enablers

When studying adaptative protection literature over the last three decades and the applications in system operators, a progression is thus observed from basic concepts such as subsystems (e. g. adaptive distance relay), and localisation studies or rapid coordination calculation, to technologies and experiments of wide geographic area protection that could be considered as extensions of the protection system.

Consequently, the adaptive protection scheme aims to monitor the power system to determine its state and adjust its configuration accordingly. In particular, adaptive relaying means changing relay settings and picking up relay currents in online mode as the operating conditions of the system changes.

Adaptive protection schemes require typically the following components: hardware (referring to the digital relay itself and intelligent electronic devices – IEDs), computational and communication systems that model and monitor the relays and coordinate the adaptation of parameters, the communication protocol for intelligent electronic devices at electrical substations and the algorithms ruling the settings, as well as the protocols to interface to human factors.

Wide Area Monitoring System (WAMS) is an enabling technology based on an information facility with monitoring purposes to improve situational awareness and visibility within power systems. Based on Phasor Measurements Units (PMUs), WAMS allow monitoring transmission system conditions over large areas in view of detecting and further counteracting grid instabilities. As mentioned above, such an early warning system contributes to increasing system reliability and can be considered as an extension and enabler of an adaptive protection system:

- PMUs sensors – measures bus angles and frequencies at a high sampling rate
- WAMS – monitoring device that time synchronise via geolocalised PMU measurements.

Advantages & Field of Application

An ex post study of the National Electric Reliability Council on black-outs in the US showed that the maloperation of relays has contributed to 70 % of US black-outs. Adaptive protection technologies therefore a potential facilitator of the reliability, resilience and security of the future power system. Indeed, real-time adaptation of the system protection actions to the true system state enable the prevention of cascade failures and wide area disturbances to power system blackouts, ensure the security of back-up relays and limit the impact of hidden failures that are revealed under stressed conditions.

In addition, the increasing use of grid assets constitutes a considerable benefit: as protection setting and thermal limits are calculated for worst case conditions, power system assets are under-utilised throughout most of their lifetimes.

Technology Readiness Level

TRL 2–9

Wide area, adaptative protection addresses a large variety of technologies of various levels of maturity and TRL ranges from **TRL 2 –** Technology formulation (concept and application) to **TRL 9 –** System ready for full scale deployment.

Best Practice Performance

Performance improvements are very case-specific and are subject to a pattern of changes: distance wise, from local measurement-based to remote measurement while, function wise, adaptation algorithms will combine advanced techniques such as multi-variable, multi-objectives or adaptative algorithms, able to operate stand-alone, even in cases of the loss of communication of any other unexpected event.

Research & Development

Current fields of research include topics that could be grouped.

Multi-agent coordination:

- Multi-agent system based protection
- Distributed adaptive protection schemes
- Resilience to system splits
- Smart coordination of overall protection devices, improved speed for detection and clearing
- Algorithms for robust operation to all network configurations and network conditions and wide area backup protection scheme, possibly based on machine learning techniques, fuzzy logic (-neuro, -wavelet based)
- Blockchain technology for protection relay configuration

HVDC protection and web architecture:

- Hybrid HVDC / HVAC fault clearing
- HVDC protection devices / breakers
- Numerical directional overcurrent relays

Protection relays and new equipment:

- Adaptation of protection components and systems to new market requirements, development of new material (e. g. fault current limiters with superconductive materials).

WAMS / PMUS:

- PMU-based concepts for transmission line protection
- Signal accuracy and reliability, communication architectures and data processing, as well as on standards for data processing and large-scale demonstrations, possibly in combination with other active equipment.
- Regional WAMS and PMUs applications operational in TSOs to enable the operation of the transmission system closer to its physical limits with high reliability
- Distributed observability of the transmission system through steady state and dynamic state estimation of transmission systems, using intelligent monitoring devices such as PMUs.

Selected Best Practice Application

Location: Brauweiler, Germany

Year of Commissioning: 2013

Description: One of the four German TSOs upgraded the main control centre using a new state of the art grid system. This TSO monitors an approximately 11,000 km HV grid in Germany.

Design: A new adaptive protection function will be integrated into the control system.

Results: Combined with overhead line monitoring, this function is used to dynamically adapt the system limits to climatic conditions and to adapt protection device settings respective to the varying short-circuit level.

Location: EU wide

Year of Commissioning: 2017

Description: The ELECTRA Integrated Research Program on Smart Grids envisions for the future power system a novel grid architecture, called the Web-of-Cells, with a wholescale deployment of distributed energy resources. The adaptive scheme has been applied to a representative cell grid and it addresses appropriate actions by protection devices to cope with the flexibility required by the Web-of-Cells concept.

Design: The arrangement of this concept includes power system cells bounded to a geographical area which are interconnected via tie lines and where each of these cells is managed by a Cell Control Operator (CCC). The feature of the Web-of-Cell concept combines flexible resources, the use of advanced information and communication technology as well as novel frequency and voltage control schemes.

Results: The case study simulation with the designed adaptive functionality for IED models showed that the proposed protection scheme responded appropriately at disturbed grid conditions, coping with different cell operating states. The results show that the CCC enables a proper automatic shifting of IED tripping curves according to the short-circuit level during the islanding condition of the cell.

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Asset Management, Tools and Procedures

Asset management (AM) is one of the most important chapters in the operation of the power system (and energy system). Power system operations and AM activities are not always strongly linked. Operational decisions are mostly based on operational grid parameters such as voltages, currents and power flows at operational time horizon, whereas AM decisions condition the reliability of supply for several decades: AM decisions support tools and methodologies and support transmission and distribution grid operators to integrate the condition of their assets in their optimisation process to reduce capital and operational costs. Examples of asset conditions that can be monitored are temperature, moisture, dielectric strength, corrosion, gas mixture, oil health, dust, shadow, age, spare parts and maintenance availability, etc. From the perspective of the TSO, two central questions are how to make the best use of the assets over the asset lifetime and how to schedule the various asset management operations, especially for assets re-quiring outage for the duration of the operation.

Technology Types

A classification of AM distinguishes at first time-based and activity-based AM.

The further subdivision of time-based AM includes the:

- Long-term (one year and beyond, encompassing future planning and investment on new assets or their upgrading).
- Mid-term (ranging a few months and involving the optimal scheduling of equipment maintenance and allocation of available resources with the aim of expanding the life span of existing facilities through proper maintenance), and short-term (categorised into operational asset management (daily and weekly).
- Real-time asset management (outage management). Operational asset management aims to minimise risks involved with assets, both physical and financial, due to load demand and hourly prices. Real-time asset management is also called the asset outage management and is based on contingency analysis which assesses the effect of unexpected outages.

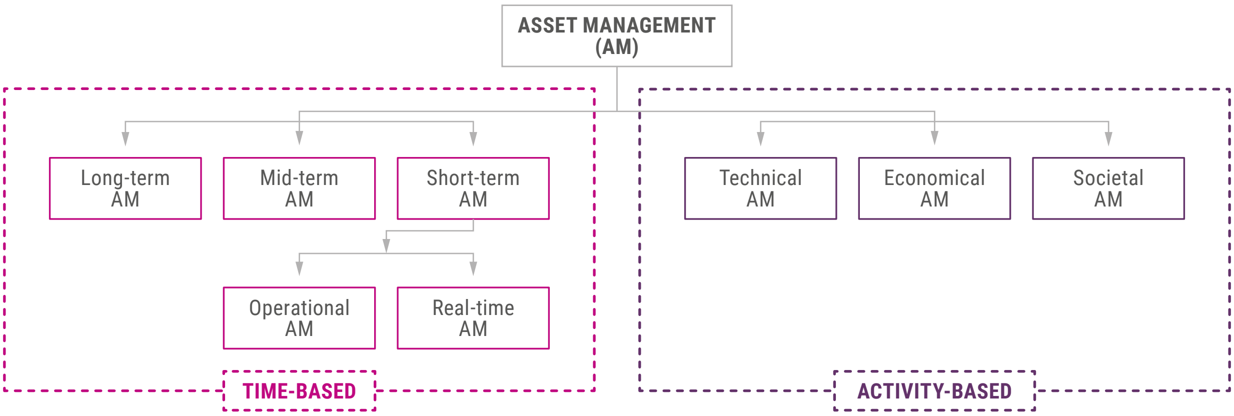
The second activity-based category is split into technical-, economic- and societal-asset management. Technical AM deals with ageing, insulation and other physical conditions of assets. Socioeconomic analysis consider economic features (how AM would be influenced by financial constraints) and assesses the impact on society (that could be considered at large including environmental impacts: e.g. the impact of a failure and leak of SF6).

The distinction between maintenance and renewal action induces the difference between the corrective (carried out after failures occur) and preventive maintenance (carried out before failures occur).

Consequently, five types of AM emerge when considering the nature and maturity of the monitoring:

- Reactive monitoring analysis
- Time-based monitoring and analysis
- Reliability-based monitoring and analysis
- Condition-based monitoring and analysis
- Predictive monitoring and analysis.

Technology Types (cont.)



Components & Enablers

AM covers a wide range of domains including: maintenance strategies, determination of component condition, asset simulation and life assessment. Founding components are thus data and methods, complemented with sensor and monitoring equipment:

- The framework of data management upon which AM and maintenance strategies is built is an essential component.
- Methodologies to tackle the risk associated with AM include several approaches such as Value at Risk (VaR), Life Cycle Cost (LCC), Run–Refurbish–Replacement (3R's), and various probabilistic approaches. In this category should be included all type of degradation and end-of-life mathematical models that support the AM policy.
- From the equipment standpoint can be mentioned all device, components, systems dealing with the data collection, management and processing chain and the knowledge management tool: asset health centre for the critical assets (transformer monitors, feeder monitors, circuit breaker monitors, power quality monitors); Instrumentation / sensors (moisture, temperature dielectric strength); Digitised protection and control relays; IoT and 5G for gathering and transmitting data from the sensors; Drones for advanced inspection; Big data analytics platform; Predictive analytics (AI) for distribution automation and transmission automation applications; AM decision software tools, including predictive analytics (AI) for equipment replacement and maintenance scheduling.

Advantages & Field of Application

Based on the data of monitored assets, AM methods simulate and detect asset degradation, allowing for adapted and optimised asset replacement. For example, AM systems may use correlation processing for AI to detect predictive asset degradation. The idea is to analyse real-time operational data from an active T&D grid device and compare the data to a library database of healthy similar devices, identifying any developing changes from normality that could become failures. This process allows comprehensive diagnostic systems to detect early failure patterns and prevent breakdowns before they occur. It has proven to be valuable in identifying operating conditions causing long-term performance issues.

Best Practice Performance

When considering AM for TSOs, it remains very dependent on each TSO's internal maintenance strategies and data framework. From the point of view of offer, providing a benchmark is complex due to the wide range of offers and their deployment to each particular context.

Technology Readiness Level

There is a consensus that there is a strong need to develop and validate tools which address the lifecycle management of power (resp. energy) systems components, the scope includes ageing and degradation study to system diagnosis as it impacts both the CAPEX and OPEX of power (resp. energy) systems.

TRL 7+

Deployment of IoT sensors, communication, data management & analysis and feedback to control systems: High TRL actions (**TRL 7+**) are expected in the next 2–3 coming years including large demonstration actions aiming at reduced OPEX and optimised costs for AM.

TRL 3–4

Probabilistic AM methodologies based on risk evaluation are expected to have a longer term impact: AM policy assessment and outage scheduling are at a proof of concept stage **(TRL 3) – laboratory testing (TRL 4)** with a time to exploitation in the 2020–2025 time horizon.

TRL 4–5

TRL 8–9

Alternatives to human interventions will be studied and deployed: in the short term with the data acquisition of power lines with drones that are fully competitive (**TRL 8–9**) and at a longer-time horizon with actions to validate the robotic replacement of live line working activities (**TRL 4–5).**

Research & Development

AM and maintenance is identified as Research Sub Areas 4.3 in the ETIP SNET R&I Roadmap 2020–2030 and in the ETIP SNET R&I Implementation Plan 2021–2024, and part of Research Area 4. Planning – holistic architectures and assets.

Current fields of research: Include the Integrated AM Approach; Augmented Reality; AI, Big data, Image recognition; Risk analysis in AM (Value at Risk), Life Cycle Cost, Run–Refurbish–Replacement (3Rs); Probabilistic methods for TSOs Reliability Management, mid-term and long-term asset management for TSOs (see GARPUR results on maintenance policy assessment, outage schedule assessment, modelling of the shorter-term reliability management).

Innovation priority to increase overall TRL: Expand enterprise asset managing performance programs to include greater connectivity between work processes and operation management tools.

The ETIP SNET R&I Implementation Plan 2021–2024 for transmission foresees the following R&I priority in relation to Asset Management: 'Development of models for State-of-Health estimates of transmission system components (e.g., components wear, oil level in transformer oil pits, SF6 level in swithgear and probabilities of failure)'.

Selected Best Practice Application

Location: Norway

Year of commissioning: 2017–2019

Description: Smarter Asset Management using Big dAta (SAMBA) is a 3-year industry innovation project headed by Statnett and supported by the Norwegian Research Council. The project has been researching the methods and methodology required to enable a transfer from asset management based on intervals to asset management based on the actual state of components in the power system.

Design: A variety of sensors were deployed, from sensors to measure SF6 gas density, voltage transformer surveillance, cable temperature/pressure/moisture, oil health, transformer temperature, sensor motion in circuit breaker, dynamic line ratings sensors etc. In addition, PMUs were deployed to measure frequency, current, voltage and phasors across the grid. A Wide Area Monitoring, Protection and Control System (WAMPACS) to integrate and analyse the PMU-data was implemented into the SCADA-system to get real feedback and experience. Dynamic models were developed to calculate the asset health probability of failures, criticality and risk indexes.

Results: A wide ranges of use cases were identified to improve the monitoring and visualisation of results, analysis of incidents and protection and control. In addition, the operator saved an operational cost ~30–40% by going from preventative to predictive maintenance and an annual capital cost of € ~50 k by deferring replacement of transformers. Overall, the operator was able to set up an ICT architecture suitable for AM, demonstrate the need for sensors, measurements and data quality and built in-house expertise for condition monitoring models for power components.

Selected Best Practice Application (cont.)

Location: Spain

Year of commissioning: 2020

Description: The MANINT programme 2017 – 2020, developed by Red Eléctrica de España. The project aims to develop optimised maintenance techniques for the HV assets to increase the grid availability and reduce costs.

Design: By applying digital technologies, data analytics and proper user interfaces, the reactive and preventive maintenance turns into predictive and cognitive maintenance. Key elements to achieve this transformation and transit to a fully optimised maintenance schedule is the data monitoring, the use of the asset health index and asset risk index.

Results: Benefits are expected in several domains: technical, management, economic and environmental. It is a conceptually natural extension of this system to become a predictive maintenance, which further improves efficiency and reliability. This will reduce maintenance costs and extend asset lives.

Location: United States

Year of commissioning: Research started in 2012

Description: Public Service Electric and Gas Company (PSE&G) employs advanced analytics on real-time sensors to track various operational metrics.

Design: PSE&G uses analytics to generate a condition score for transformers based on multiple factors, such as moisture, dielectric strength, combustible gas rate of change and cooling performance. An asset replacement (predictive) algorithm uses this condition score and other factors (chronological age, spare availability) to determine the appropriate time to replace transformers.

Results: Usage of analytics has helped the company identify problems and remediate issues before a failure, saving millions of dollars in equipment failure avoidance. The company has also determined that by replacing some transformers proactively (by using an analytics models), rather than reactively, it will save over $ 100 m over a 25-year period.

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Drones and Robotics

Power grid inspection and AM are an integral part of power grid maintenance. Drones and robotic technology can be used with the goal of improving the quality and productivity of the power grid maintenance, which will ultimately support reliability and cost-effectiveness. Automated data acquisition and management will play a larger role for predictive maintenance and will leverage drones and robotics for data collection and analysis.

Technology Types

- Piloted drones (Unmanned aerial vehicles [UAVs])
- Autonomously flying drones (Unmanned aerial vehicles [UAVs])
- Robotic inspection
  - ↳ Rolling Robots
  - ↳ Climbing robots
  - ↳ Brachiating robots
  - ↳ Unmanned Ground Vehicles (UGVs)
- Robotic maintenance
- Robotic arms with different equipment

Components & Enablers

- Self-positioning (GPS and image processing)
- FPV control
- Unmanned Traffic Management (UTM)
- Live line equipment used by robots (hot sticks, insulated jibs, insulated boom trucks, stripping machine, electric wrench, wire breaking pliers etc.)
- Sensors for navigation as well as detecting steel corrosion and gathering visual, thermal, UV and audible information
- Robot/drone power supply

Advantages & Field of Application

Today, power grid inspections are mainly done manually with the help of power line engineers, which often requires laborious work and power transmission interruptions. The introduction of drones and robotics in power system maintenance brings several advantages to the power industry:

- Increase safety and decrease risks to maintenance technicians
- Decrease maintenance equipment downtime
- Enhance accuracy in data collection of an asset's condition
- Reduce staffing need and associated employment cost
- Repurpose maintenance inspection of truck rolls for other uses

Drones are currently piloted but have a potential to fly autonomously through GPS self-positioning. When using GPS, flying near high voltage lines could lead to drone flight errors. Self-position estimation through image processing could solve this issue when the GPS is not available. Drones as well as robots installed for line inspection and maintenance will be supported with sensors, power supply and various maintenance equipment to perform or assist in maintenance work, depending on the nature of the task.

Technology Readiness Level

TRL 7

TRL Score 7 – system prototype demonstration in operational environment.

Research & Development

Current fields of research: autonomous flight control, longer ranges, smarter navigation, UTM.

Innovation priority: automation, image processing, improved robotic movement over obstacles.

Best Practice Performance

Very application specific, hence complex to give performance benchmarks.

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Best Practice Application

Location: Canada

Description: The LineScout Robot was developed for live transmission line inspection and maintenance.

Design: LineScout, designed by Hydro Quebec is built to clear different obstacles such as dampers, corona rings etc. while moving along the transmission line and is able to reach and function in places that are otherwise limited for line workers. Highly precise inspections are possible through infrared, high-quality visual inspection and electrical resistance measurement. LineScout is also able to perform different maintenance tasks such as tightening and loosening bolted assemblies and the temporary repair of broken conductor strands.

Results: Main savings are achieved through a decrease in the shutdown time of lines and an increase in flexibility and efficiency during inspection.

Location: Spain

Description: The ROBTET telerobotic system has been designed for automated maintenance tasks on the Spanish power network.

Design: The system works semi automatically, controlled by an operator in the truck cabin. A telescopic boom carries telemanipulators and tools to perform different maintenance tasks such as insulator set change, attaching a jumper cable between two points of the line, opening switching units and replacing fuse elements.

Result: Live line maintenance is enabled through the telerobotic system without cutting supply.

Location: France

Description: RTE has launched several experiments with drones: drone in a substation or drone around a tower operated by an RTE crewman with live video or picture camera for diagnostic maintenance, drone pulling a bout cable to initiate the leverage of the main aerial cable, long distance drone (over 50 km), a remotely operated drone to survey a 400 kV line.

Design: The long distance drone weights 2 kg, has a 50 km 50 minutes range flight at 150 m height at 50 km/h speed.

Result: Since 2016, RTE has been an official aeronautic drone operator. Drones simplify maintenance diagnostic in live line conditions. They provide a flexible alternative to helicopters in some specific use cases. 500 line crewmen will be trained to be fully operational in 2021.

Large-Scale DC Overlay Grid Concepts

DC overlay systems are quite radical evolutions of the legacy of AC interconnected systems developed over the past few decades. Due to a strong shift in the type and location of power generation as well as a shift towards a digitalised energy sector, continuing incremental AC interconnection upgrades will not neces-sarily lead to the most cost-effective and timely solutions to cope with the energy transition.

DC overlay systems can be designed as radial multi-terminal systems or in a meshed way, providing the characteristics of a grid. Two-terminal long-distance DC corridors emerged in the 1960s and, with the rapid advancements in power electronics and control systems, the first multi-terminal, non-meshed, HVDC system was commissioned in the 1990s. Meshed Multi-Terminal DC grids (MTDC), in which more than one power-flow path between two grid terminals will exist, is still being examined at the research level to solve the challenges of integration with the AC meshed grid. Once that stage is passed, this will create a so-called DC overlay grid. The concept of DC overlay grids may one day also allow the various large electricity networks to be interconnected on a global level. Furthermore, a DC overlay grid system is able to enhance the flexibility of the entire transmission grid, being able to cope with the characteristics of renewable power infeed in a more effective manner.

Technology Types

Radial DC overlay systems:

Interconnection of N terminals with one power-flow path between two terminals of the DC grid.

Meshed DC overlay systems:

Interconnection of N terminals with more than one power-flow path between two terminals of the DC grid.

Components & Enablers

- Transmission corridor technologies (CSCs, LCCs) with capacities of approx. 4 – 8 GW per circuit, and continuing developments towards 2050
- VSCs with ratings in the range of 1 – 3 GW per circuit, and continuing developments towards 2050
- Advanced operational coordination
- Advanced grid planning technique
- Tailored fault clearing strategies to the specific HVDC / HVAC grid characteristics
- HVDC Circuit breakers
- HVDC Gas insulated switchgears
- Flexible DC Transmission devices

Advantages & Field of Application

The choice between an extension of a grid in AC or DC depends on a variety of technical, economic, environmental and technical factors, the profitability threshold between the two types of current systems has varied over time depending on the use cases. The first resurgence of a DC system was registered in 1954 in Sweden when the island of Gotland was connected back to the mainland.

With the increasing need to integrate remote large-scale renewables and the growing share of distributed DC connected energy resources, DC transmission will become more relevant, and its integration within the current AC system will contribute in several ways to achieving a cost-efficient energy transition.

Advantages & Field of Application (cont.)

Major advantages of the integration of DC systems will be:

- An increase of transmission capacity by leveraging existing AC corridors to create new higher capacity DC corridors, boosting transmission capacity with limited additional environmental and social impact.
- An enhancement of power flow control which enables a better utilisation of the lines closer to thermal limits.
- An increase in ancillary services provision such as voltage / frequency regulation or power oscillations damping.
- Enhancement of flexibility in the overall transmission grid, being able to cope with the characteristics of renewable power infeed. To date, there exist more than 180 HVDC operational projects worldwide. A few non-meshed multi-terminal systems are in operation in Europe, North America and Asia. In the next ten years, over 25,000 km of HVDC transmission lines will be built and operated in parallel with over 300,000 km HVAC transmission lines according to the TYNDP estimates, yet most of these are case-by-case, point-to-point connections.

Research and development is being accelerated in this field to overcome the technical and regulatory barriers to operate and control MTDC system and integrate them in meshed AC systems. Such integration will combine the benefits of AC and DC technologies and open the door to new devices and systems, such as HVDC circuit breakers, HVDC gas insulated switchgears and flexible DC transmission system devices that can bring benefits to the security, reliability, performance and economics of a DC overlay grid.

Concepts such as the North Sea Wind Power Hub already show advanced DC grid layouts complementing the AC onshore system. The Med Grid idea is already linking European, North African and Middle Eastern areas around the Mediterranean area.

More visionary approaches such as a global grid based on DC backbones may allow high levels of renewable energy supply to be exchanged in a cost-effective and secure manner.

Technology Readiness Level

For the estimation of the TRL[1] of DC grid systems, the following must be distinguished:

TRL 9

TRL 9 for radial multi-terminal systems;[2]

TRL 4

TRL 4 for meshed multi-terminal systems.[3]

Research & Development

Current fields of research: DC Voltage control in a multi terminal set up; protection types for VSC HVDC, Static and Dynamic stability of hybrid AC / DC systems; sizing and location of converters, protections and HVDC breakers; flexible DC transmission systems (FDCTS); probabilistic grid planning.

Innovation priority: Currently, point-to-point systems have one converter controlling the DC voltage at its bus and the other converter controlling the active power. In a multi terminal set up, this should be ideally spread out over multiple converters, allowing them to collectively stabilise the voltage after a fault or converter outage, e. g. through droop control. With multiple converters connected to the same synchronised system, there is a need to find appropriate power set points depending on the goal of optimisation of the whole system.

Other: The development of grid codes for MTDC systems and standardisation protocols are essential to inspire the confidence in different grid operators to interconnect each other through MTDC grids.

1 Indicated TRL is valid only for single vendor radial and meshed multi-terminal systems.
2 TRL can be assumed with 9, since actual systems with three to five terminals are already proven in operational environment. However, this estimation depends also on the involved components and therewith the degree of selectivity used in the actual system. Not all components required for fully selective fault clearing show a similar TRL. As an example DC circuit breaker can be mentioned (TRL 6 – 7, dependent on the circuit breaker concept and technology).
3 No operational project is currently available, only laboratory proof of concepts, resulting in a TRL of 4 of the overall system. Some components possess an even higher TRL (e. g. VSC). However the first industrial full-scale project can be expected in 2020 / 21 in the Chinese Zhangbei project operating a four-terminal meshed DC grid (TRL 7 – 8 after successful commissioning).

Selected Best Practice Application

Location: Sardinia-Corsica-Italy

Year of commissioning: 1967 – 1992

Description: The point-to-point 200 MW, 200 kV DC interconnection between Italy and Sardinia was extended in 1988 with an MTDC station of 50 MW at in Corsica.

Design: Using thyristor-based LCC converters, the station was equipped with high changeover switches to enable bidirectional flow. The two older existing mercury arc valves-based LCC stations were replaced in 1992 with two new thyristor-based LCC stations. The three MTDC stations form together the SACOI interconnection which operates as an MTDC system. The transmission system has three overhead line segments and two subsea cable sections. The line segments are 22 km long on Italy, 156 km on Corsica and 86 km over Sardinia, whereas the undersea cable is 105 km between Italy and Corsica and 16 km between Corsica and Sardinia.

Results: The bidirectional flow between Corsica, Sardinia and Italy's mainland was facilitated by the construction of the MTDC stations.

Location: North Sea Wind Power Hub

Year of commissioning: N / A

Description: Authorities, TSOs, wind industry and other stakeholders of countries around the North Sea have reviewed the potential large-scale coordinated infrastructure over the past decade. A recent example is the large-scale North Sea Wind Power Hub proposed by, among others, TenneT NL, TenneT DE and Energinet.

Design: The whole system is intended to function as a hub for wind energy transport and as an interconnection hub to connected countries and a location for possible Power to Gas solutions.

Results: The project will enable Europeans to extract the wind energy from the North Sea up to levels of 180 GW and transmit DC power far inland directly to commercial centres. Synergies with gas / H_2 are being pursued.

Location: Zhoushan 5-Terminal project

Year of commissioning: 2014

Description: The world's first five terminal DC project at high voltage level. The five-terminal system connects five islands with the main power grid, providing 400 MW at a voltage of ± 200 kV DC to stabilise the weak power grids on the islands.

Design: The system is designed as radial multi-terminal system in a non-fault selective way, which results in the disconnection of the five terminals in case of a DC fault. A refurbishment with DC circuit breakers is intended to provide selectivity.

Results: The project will enhance the security of supply for the island's power grids.

Location: global view

Year of commissioning: N / A

Description: The concept of a global grid still sparks the imagination of many. The CIGRE WG C1.35 performed a recent feasibility study on this.

Design: The interconnection of 15 large electricity systems using DC corridors.

Results: Interconnecting 15 large electricity systems worldwide, mainly by DC corridors, would allow the integration of higher levels of RES at lower cost compared with 'isolated' areas. The interconnections give high flexibility benefits to accommodate flows from PV energy at any time of the day as well as wind energy from the globes' most resourceful areas.

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Enhanced Load Forecasting

Conventional load forecasting techniques have been widely used over the past 30 years. These forecasts have tied load demand to the economic activity of the country and temperature variations while assuming inelasticity of the load to price sensitivities. Based on time-scale, they can be classified into three groups:

- **Short-term load forecast (STLF):** the time-period of STLF lasts for a few minutes or hours to one-day ahead or a week. STLF aims at economic dispatch and optimal generator unit commitment while addressing real-time control and security assessment.
- **Medium-term load forecast (MTLF):** the time-period of MTLF is a week to one year (possibly two years). MTLF aims at maintenance scheduling, coordination of load dispatch and price settlement so that demand and generation is balanced.
- **Long-term load forecast (LTLF):** the time-period of LTLF ranges from a few years up to 10 – 20 years ahead. LTLF aims at system expansion planning, i.e. generation, transmission and distribution. In some cases, it also affects the investment in new generating units.

Different methods can be applied depending on the model identified. Short term load forecasting would require Similar Day Look up Approach, Regression based Approach, Time Series Analysis, Artificial Neural Networks, Expert Systems, Fuzzy Logic, Support Vector Machines, while Medium and Long-Term Load Forecasting will rely upon techniques such as Trend Analysis, End Use Analysis, Econometric Analysis, Neural Network Technique, Multiple Linear Regressions.

Enhanced load forecasting goes beyond the traditional linear regression method of forecasting load, which is based on economic activity and temperature forecast, considering the load inelastic to price sensitivities. It leverages the advancements in machine learning to predict the variability of the load at the customer level, this variability continuously increasing with the penetration of distributed energy resources, storage and electric vehicles. With the deployment of advanced metering infrastructures and variable tariffs offered on a retail level, new bottom-up methods are being tested that leverage the power of big data and predictive analytics to better understand customer decision-making mechanisms as well as its sensitivity to variable price signals for improved prediction of load demand.

Technology Types

In addition to the three main categories for load forecasting according to time horizon (see above: short, mid-, long- term), the literature proposes additional classifications to the mid and long-term load forecasting, more complex than the short-term, which concentrates most of the load forecasting techniques since the 60s.

Whereas the STLF rely on data modelling (fitting data to models, extrapolation) rather than on intimate information of how an electrical system works, the MTLF / LTLF require simultaneously the data analyst expertise and the expertise of how power system / markets behave. The manner in which all these impacting factors (such as temperature, weather, historical load, GDP forecast, demographic) are considered enables the classification of the MTLF / LTLF approaches:

- Either based on 'time series' (assuming that data have their internal structure and correlation), or on economic indicators affecting the load (the 'econometric approach'), or on the 'end-use approach' concatenating, in a bottom-up mode, information gathered from the individual end-uses (presenting several advantages but very data intensive), or
- Another classification is based on the extent of these impacting factors. The 'conditional modelling' approach encompasses all historical load and weather data, socioeconomic indicators and energy policies, whereas the so-called 'autonomous approach' depends only on historical load and weather data. Researchers have proven that the latter provides better forecasts for a time horizon below one year.

Enhanced load forecasting techniques use new data mining techniques based on machine learning to classify different types of load behaviour provided by a large volume of input data. These methods can be used to estimate approximate functions that depend on many inputs when there is no accurate mathematical model to describe the phenomenon. Their validity is currently being tested to forecast loads using aggregated load data points (transmission level).

In this new methodology, load can become segmented on clusters of customers based on structural, demographic and financial factors, and the forecast outcome becomes probabilistic based on the likelihood of customer adoption of a technology and their reaction to variable retail prices.

Components & Enablers

Mathematical techniques constitute the founding blocks for load forecasting. 'Parametric methods' should be distinguished from AI methods, or other 'hybrid methods'.

- In parametric methods, the model of the load is built upon the relationship between load and load-impacting factors, the adequacy of the model being assessed based on the forecast errors as model residuals. ARMA, ARIM, ARMAX or ARIMAX are widely used time series methods[1]. The Grey dynamic model is based upon three types of systems according to the degree of availability of the information (white system: all required information is available; black system: no information is available; grey system: partial information is available)
- AI methods are clearly part of the non-conventional, enhanced methods; they mostly include fuzzy logic, artificial neural network (ANN) and support vector regression (SVR).
- The hybrid category, also clearly non-conventional, includes heuristic optimisation algorithms such as genetic algorithms, expert systems or evolutionary computation algorithms.

Deploying a model for load forecasting (based on relevant data inputs) requires a series of generic steps, given below:

1. Collection of historical load data
2. Preparation of the load data, collection of historical weather data and historical event data
3. Analysis of the data
4. Preparation of the model input and test the data
5. Select a model, fit the data and run the model
6. Select the best model and implement it
7. Run and refine the model.

Focusing on enablers, they include data from smart meters and home energy management systems, retail electricity prices (variable), demand response subscribed customers, DERs owned by customers, data mining tools, etc.

1 autoregressive moving average (ARMA), autoregressive integrated moving average (ARIMA), autoregressive moving average with exogenous variables (ARMAX), and autoregressive integrated moving average with exogenous variables (ARIMAX)

Advantages & Field of Application

Relative load forecasting errors using conventional statistic methods seen at the level of transmission substations have been quite low (from [3], many large and medium utilities operate their systems with one day ahead load forecast error at 3 % or lower) as aggregation reduces the inherent variability in electricity consumption, resulting in increasingly smooth load shapes.

By leveraging the data of smart meters and customer sensors, enhanced load forecasting can play a major role in optimising grid investments and grid operations as machine learning techniques become more advanced and efficient in predicting customers' behavior[2]. Similarly, it is expected that market operations will become more efficient as aggregators will need fewer unbalancing reserves with re-duced load forecast errors.

Best Practice Performance

Depending on the choice of forecasting method/ strategy and the parameter configuration, the forecasting accuracy can be subject to significant variations.

Typical examples of best practice performance can be mentioned from the literature:

- Study on 'Neural Network Model for Short-Term Load Forecast Based on Long Short-Term Memory Network (LSTMN) and Convolutional Neural Network (CNN)'. A combined CNN / LSTM model was proposed to improve forecasting accuracy for the prediction of the next 24 h load forecast. The forecasting performance was based on evaluation indexes (Mean Absolute Error [MAE], Mean Absolute Percentage Error [MAPE] and Root Mean Square Error [RMSE]). The combined model can improve performance by at least 9 % compared to the DeepEnergy, 12 % compared to the CNN module and 14 % compared to the LSTM module. The combined CNN–LSTM model can achieve the best performance in STLF.

Technology Readiness Level

TRL 9

TRL 5

Although traditional linear regression method of forecasting load based on activity and temperature are mature **(TRL 9)**, enhanced load forecasting techniques remain at lower TRLs, such as **TRL 5** for Machine Learning Technology validated in the relevant environment[3].

Research & Development

Current fields of research: The ETIP SNET R&I Implementation Plan 2021 – 2024 includes a specific topic on 'Medium and long-term control (Forecasting (Load, RES), secondary & tertiary control: LFC, operational planning: scheduling / optimisation of active / reactive power, voltage control)'. The topic addresses the solutions for operational planning of the energy systems, with special reference, among others, to resources scheduling (through adequate generation and load forecasting).

Research on enhanced load forecasting includes:

a) the design of machine learning algorithms with improved forecasting performance, lower memory requirements and scalable architecture

b) the development of novel data-aware resource management systems that can provide powerful data processing in distributed parallel computing systems and clusters for real-time processing

c) featuring engineering to select the most relevant information to feed the machines, for each specific case to increase accuracy while decreasing the risk of overfitting.

Improvement foreseen: Effective data sampling, improved categorisation of the information and extraction of load patterns. In addition, given the different regulatory regimes worldwide on data privacy, the technical full potential of data analytics in predicting residential load forecast will be likely more restrained in Europe as a result of the more stringent citizen's data privacy protection framework.

2 In [11] the authors presented an approach to forecast electricity loads on the individual household level using CART, support vector machines (SVM) and MLP neural networks for 24 hour short-term load forecasts. The study concluded that a combination of historical usage data and household behavioral data could greatly enhance the forecasting of individual consumer loads. The obtained Mean Absolute Percentage Error (MAPE) were 51 % for the neural networks and 48 % for the SVM.

3 Estimation based on Statnett experience in Norway and on Navigant experience in the US.

Selected Best Practice Application

Location: EU

Year of commissioning: 2017

Description: The EU funded GARPUR project worked on developing a novel long-term load forecasting technique (~3 years).

Design The outcome is a new applicable methodology that uses multiplicative error model which incorporates the volatility experienced in long-term forecasts and outputs load forecast predictions based on aggregated historical demand data.

Results: The results are supported by 95 % confidence intervals. The authors proved that, using a multiplicative error model, they were a) able to forecast with higher accuracy the peak loads of a transmission operator compared to the conventional linear regression method by a margin of 7 % b) improve the directional accuracy of the forecast considering unpredicted (historical) market movements (e.g. the 2008 financial crisis).

Other: The project focused on enhancing current conventional techniques of long-term load forecasting. No attempts were, however made to compare these results to load forecasting based on machine learning techniques.

Location: Norway

Year of commissioning: 2018

Description: development of machine learning models to make predictions for power consumption on different bidding zone.

Design: The rationale of the development was based on the observation that (i) load forecasts used for system operations result from using proprietary software, in the form of black box algorithms, and present the drawback of an in-depth understanding of the particular performance of the model in a particular time period, or in a specific area, (ii) there is a need for predictions for longer horizons than the current software is providing. Design features are founded on the willingness to use open data sources. Predictions are provided 48 hours ahead for each of the five bidding zones in Norway with a training/learning strategy adapted to each of these bidding zones.

Results: To evaluate the models, use of mean absolute percentage error (MAPE). The proof of concept models outperformed the current software with the use of one year of test data, reducing the MAPE by 28 % on average over all bidding zones in the forecasts.

Location: Poland

Year of commissioning: 2015

Description: Researchers investigated a two-stage approach to forecast short-term electricity loads in the Polish transmission power system considering predictions from demand peak classification models. The dataset comprised of hourly load values of the Polish power system from 1 January 2008 and 31 December 2015 and weather data, including temperature, humidity, sunrise and sunset. The analysis was enriched by transforming 19 additional variables that impact load fluctuations from standard dummy encoding to binary codes to transform the data into fewer dimensions.

Design: In the first stage, the models are trained to classify peak load levels, which are equal to or above the 99th, 95th or 90th percentiles for the respective load distribution when considering weekly horizons. In the second stage, the scores from the classification models are fed into the forecasting models, which use data mining techniques based on machine learning to identify patterns and underlying dependencies in the analysed data to predict the aggregated load 24 hours ahead.

Results: The results of the two steps approach (enhanced model) were compared to a basic forecasting model, which used the same data mining approaches but without including variables that came from the peak classification models for the different quantiles, i.e. without learning probability distribution of variables affecting peak load variations and their interdependencies. The results show that the ANN ML technique proved to be the best method to peak load forecasting and was able to reduce the MAPE error by 6 %, from 3.3 % (basic model) to 3.1 % (enhanced model). MAPE stands for the mean absolute percentage error between the measured load and forecasted load.

Selected Best Practice Application (cont.)

Location: US

Year of commissioning: 2014

Description: Researchers investigated different data mining techniques to forecast residential load. These techniques included basic techniques (ARIMA, basic regression) and machine learning techniques (ANN, support vector machine, random forest algorithm). The authors conducted two experiments. The first was on a single household in British Columbia Canada, consisting of two years of recorded energy consumption at one-minute intervals using 21 submeters covering 2012 – 2014. The second was on an aggregate of 46 households in Austin, Texas, with consumption measurements of one-hour interval from 24 circuits within each home.

Design: The machine learning techniques were in trained to detect household behavioural patterns by analysing appliances with similar switch ON probability distribution through the day or the week with the method of segmentation and sequence analysis.

Results: Results show that a) machine learning techniques had in general smaller errors and higher accuracy rates in forecasting load compared to basic techniques b) combining historical data usage and household behaviour data enhances the forecasting of consumer loads using machine learning techniques. With respect to a), the artificial neural network technique came out best in class in forecasting single household load with a MAPE of 23 % and accuracy of 54 % compared to basic techniques with an average MAPE of 41 % and accuracy of 30 %. With respect to b) enlarging the data set of the 46 households given to the machine showed that the ANN technique was able to reduce the MAPE by 8 % from 46 % (basic data set) to 41 % (richer data set). It is important to note that ANN was the only technique in which in an enlarged data set improved the forecast compared to the other machine learning techniques or basic techniques. The MAPE of other machine learning techniques or basic techniques with a basic data set ranged between 60 % to 120 % in the experiment with 46 households. The authors conclude that ANN could be the best method for solving short-term forecasting when dealing with a large amount of high volatility data.

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Enhanced RES Infeed Forecasting – Wind

The massive penetration of weather-dependent RES generation brings several challenges to power system operation. Short-term forecasting of RES generation, a few minutes up to days ahead, is a cornerstone prerequisite for the secure and economic operation of power systems with high RES penetration.

In the past two decades, considerable research has been conducted leading to several forecasting tools, most of them originating from the specific field of a particular RES. Wind power forecasting techniques were developed through several EC funded R&D projects (FP5 Anemos, FP6 Anemos. plus, FP7 SafeWind), whereas solar forecasting is being addressed through FP7 DNICast and FP7 Performance Plus projects. Spinoffs emerged providing forecasting services, and operational tools have been adopted by electricity value chain stakeholders (TSOs, DSOs, RES plant operators, aggregators and forecast service providers) in applications including power system scheduling, estimation of reserves, congestion management, coordination of renewables with storage or trading in electricity markets once the RES plants are commissioned and operational.

Originating from meteorology, and not initially oriented to the energy sector, numerical weather prediction (NWP) tools have been developed resulting from collaborations with energy and meteorology, with the aim of aligning NWP models to the expectations of the power and energy industry. These models are used to forecast wind, together with algorithms that provide the non-linear transformation of wind speed into power considering the other relevant meteorological and orographic effects, as well as the wind turbine type and/or wind farm layout, including shadow effects. Depending on the forecast time horizon, such forecasts are used by grid operators for intraday and near-to-real time grid operations (few hours ahead; 15 to 30 min), day-ahead market clearing check (24h) and operational planning (hundreds hours-ahead).

Technology Types

RES forecasting involves a model and value chain encompassing models for weather forecasting and for RES forecasting as well as models related to the applications the forecasts are used for (i.e. decision making for trading). Three types of methodologies exist to forecast wind output:

- The physical method/deterministic method that uses meteorological data to obtain wind speed forecast and convert it into wind power. Forecasts are based on numerical weather predictions (NWP) using weather data such as temperature, pressure, surface roughness and obstacles. NWP, satellite and sky image based methods generate forecasts of weather variables for horizons up to several days ahead with updates usually every 6 hours, and spatial resolution that can go down to 1 km and 1–3 hours temporal resolution
- The statistical method is based on a vast amount of historical data without considering present meteorological conditions. It usually involves advanced data science and time series analysis approaches (machine learning)
- The hybrid method combines physical methods and statistical methods using weather forecasts and time series analysis approaches (machine learning).

Components & Enablers

- Meteorological data (temperature, pressure, surface roughness and obstacles, wind speed and direction) and related satellite and sky image based methods
- Numerical weather prediction tools
- Drones and Lidar in data-spare areas (e.g. offshore for wind energy forecasting)
- Wind turbine parameters and characteristics
- Wind turbines' maintenance schedules and grid maintenance schedules
- Historical forecast and generation data.

Another classification of wind forecasting approach is also used by some authors and is based on the time horizon, namely immediate-short-term (8 hours-ahead) forecasting, short-term (day-ahead) forecasting, long-term (multiple-days-ahead) forecasting.

Advantages & Field of Application

Over 20 years of experience with different forecasting systems is capitalised in early wind-adopting utilities in Denmark, Germany, Spain, the Netherlands and Ireland.

Gaps and bottlenecks limiting the performance of the forecasting model chain include the intrinsic limitations of weather forecasting models, the dependability of RES/wind forecasting models on the type of input data, the constraints regarding confidentiality or privacy of data, the lack of standardisation of forecasting products and the under-usage of the collected data for improving wind forecasts. One more structural barrier is the necessity to connect research conducted in the respective fields of meteorology and wind forecasting.

Thus, room for improvement concerns, simultaneously, the weather prediction side and the usage of the forecast, as well as their interaction.

At the forecasting model chain end, an important room for improvement remains: the accuracy at levels which appear as adequate for current RES penetration, but are inadequate for systems with high penetration of renewables. Such levels result in the over-dimensioning of costly remedies, to potential financial penalties by grid operators for wind power plants participating in electricity markets, or to the difficulty of providing ancillary services with a high reliability.

Technology Readiness Level

TRL 9

A commercial offer is available **(TRL 9 –** System incorporated in commercial design, which do not preclude current development at lower maturity levels on next generation multi-source RES forecasting).

Research & Development

Current fields of research: A steady trend in research is confirmed **bridging statistical and meteorological models** and focusing on predicting the impact of weather events on the forecast.

In Europe, advanced modelling tools for modelling and forecasting energy production from variable renewables are expected in a short-term time horizon.

The ETIP SNET R&I Implementation Plan 2021 – 2024 for transmission foresees the following R&I priority in relation to RES Forecasting: 'Advanced RES forecasting considering weather forecasts, local ad-hoc models, historical data and on-line measurements'.

The 4-year H2020 Smart4RES collaborative R&D (begun in 2019) aims to substantially improve the entire model and value chain in renewable energy prediction by proposing the next generation of RES forecasting models, enabling an increase of at least 15% in RES forecasting performance. It is built on the vision of a holistic approach, covering the whole model and value chain related to RES forecasting from weather forecasting up to end-use applications.

Some of the **'advanced modelling tools'** outputs of the projects will include:

- improved forecasting of RES-oriented variables with NWP, satellite and ground-based all-sky images for weather modelling and forecasting
- data science tools for blending information from multiple sources and creating a seamless view of RES forecasting at various temporal and spatial granularity levels for RES power forecasts.
- new business models for RES forecasting, ensuring distributed and privacy-preserving forecasting and based on data marketplace for RES forecasting.
- risk-based decision-aid tools under risk for use cases including storage and RES joint optimisation; predictive dispatch of inertia and frequency containment reserve in isolated power systems with massive integration of non-synchronous generation; distributed voltage control and congestion management in distribution grids; data-driven RES trading in multiple markets.

Machine learning algorithms constitute a key domain of research, including the application of statistical learning, of machine learning (to locally approximate the atmospheric equations of motion and extrapolate the system's behaviour into the near future) and deep learning (convolutional neural networks, long short-term memory recurrent neural networks) models to combine multi-source data and improve forecasting skill up to several days-ahead.

Variable for improvement: The focus should be on improvements in the forecasting of high impact (meteorological) events, probabilistic methods for spatiotemporal forecasting, numerical weather prediction models that are specific to energy in general and to variable energy resources, and joint the forecasting of wind and solar power generation. The IEA Wind Task 36 aims to coordinate international efforts to improve methods and adoption in wind power forecasting. Survey results in 2016 from IEA Wind Task 36 shows large untapped potential in systems operators' and market actors' use of forecasting uncertainty in their business practice.

Other: A crucial effort is to be made on data management to address the further mentioned gaps: dependability of forecasting models on the type of input data, data privacy, harmonisation of data structure, and data processing protocols for quality and efficiency purposes.

Best Practice Performance

It was proved that the error of the prediction result will enlarge with a larger time horizon. Several benchmarking exercises on forecasting skill compared the performance of weather and power forecasting models for wind power. They showed that performance depends on several factors: weather conditions, time of the year, the terrain typology, the time horizon and the type of models, as well as the level of aggregation of RES plants, due to the smoothing effect that permits errors to compensate for geographical distributed RES plants.

For a typical single wind farm with a lead time of 24 hours ahead, the normalised mean absolute error (NMAE) can be up to 9 – 12% of installed capacity, levels considered too high by most users and urge for improvements. For shorter horizons (between a few minutes and up to 6 – 8 hours ahead), potential for improvement with spatial-temporal approaches and multi-sources combination can reach up to 15 – 20% for wind energy.

Selected Best Practice Application

Location: Europe

Year of commissioning: expected 2023 (project started in 2019)

Description: The Smart4RES project aims at the research, development, and validation of a next generation of tools for modelling and forecasting energy production from variable renewables and decision aid for a number of use cases.

Design: Smart4RES proposes disruptive research ideas for developing and validating the next generation tools ensuring jointly an increase of at least 15 % in RES forecasting performance and a leverage of the economic value of RES forecasting by considering the whole value chain from weather forecasting to end-use applications.

Results are expected based on the proposed project objectives which include (i) the definition of requirements for forecasting technologies to enable near 100 % RES penetration by 2030 and beyond, (ii) the development of a RES-dedicated view of weather forecasting, leading to improvements in forecasting of the relevant weather variables in the order of 10 – 15 % using various sources of data and the development of very high-resolution forecasting approaches, (iii) the development of a new generation of RES forecasting tools able to improve RES power production forecasting by at least 15 %, (iv) the development of new forecasting products, data marketplaces and novel business models to get optimal value from data and forecasts, and (v) new data-driven optimisation and decision-aid tools will enable the large-scale penetration of RES into the electricity market and the provision of system services towards TSOs and DSOs.

Location: Germany (ParkCast project)

Year of commissioning: expected Oct. 2021 (project started Nov. 2018)

Description: ParkCast project addresses the optimisation of minute-scale power forecasts of offshore wind farms using long-range lidar measurements and data assimilation. It aims to develop, optimise and evaluate new methods for short-term forecasts of the performance of offshore wind farms. The power forecasts focus on the time range up to 60 minutes with high temporal resolution. The aim is to significantly improve the temporal resolution and forecasting quality of the parking performance in the above-mentioned time period and thus make a contribution to grid stability and supply security.

Design: To this end, long-range lidar measurement data are assimilated into a high-resolution, local weather model using new methods based on machine learning. Physical and advanced machine learning-based prediction models are then used for the power prediction and validated in real time for the Alpha Ventus Offshore Wind Farm as part of an online test phase.

Results: A dedicated work package will focus on 'Wind Farm Power Forecast'. The assessment of different forecast methods for windfarm power will contribute to the minute-scale power forecast of an offshore wind farm.

Location: Norway

Year of commissioning: 2018

Description: A comparative study assessing the potential benefit of using a deterministic NWP model with 1-hour generation time compared to an NWP ensemble with 2.5 hours generation time.

Design: Nine months of data for the Norwegian wind farms Bessakerfjellet and Hitra were organised to evaluate several forecast models and based on various uses of the predictive information, sources hourly quantile wind power forecasts are made.

Results: In terms of mean absolute errors, the results were neutral, but in situations where moderate to large changes in wind speed were forecast, the scores where in favour of the deterministic NWP model with one hour generation time.

Location: France

Year of commissioning: 2014

Description: Researchers compared different forecasting methods. The data set was provided by the wind energy company operating the wind farm. Each wind turbine provides 10 min. interval measurements of electrical power, wind speed, wind direction and temperature, as well as an indicator of the working state of the turbine.

Design: The electrical power output of the whole farm is also provided on a 10 min. interval basis. All measures are recorded simultaneously. Data is available for 3 different farms made up of 4 to 6 turbines, in the North and East of France, from 2011 to 2014.

Results: The CART-Bagging algorithm (machine learning) outperforms other forecast methods for the case study evaluated. The RMSE of the forecast was as low as 1.65 % with CART-Bagging compared to 2.4 % which was, at that time, a state-of-the-art recorded by French industries, according to the renewable energy union.

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3

Digital

Digitalisation is central to TSOs as they have to manage a fast-evolving power system 24/7 while keeping the lights on. Today, they are required to overcome a variety of new challenges, such as the increased amount of variable generation, sector coupling, power and transport connected through e-mobility, increasing electrification and, in particular, heating and cooling, as well as the rise of the Energy IoT and the many flexibility opportunities and needs. Digitalisation not only contributes to these but also to further market facilitation and enables new actors and new roles.

A cyber-physical grid is in the making. This is composed of the physical part on the one hand – towers, cables, wires, substations etc. – and the increasing Digital Grid on the other. The Digital Grid will enable the integration of models, tools, platforms and information. It will enable not only automated and coordinated decision-making inside the business units of TSOs and between them, but also enable it in the future DSOs and all the other parties that constitute the electricity value chain.

The 8 digital factsheets listed here present the various technologies which will play a key role for TSOs in developing the cyber-physical grid, thus enabling possibilities which are merely visions today. These technologies are set to transform the whole energy system as we know it and elevate it to a new level. By adapting all these, the systems will provide an essential framework to reach Europe's carbon neutrality goal by 2050.

5G Digital Cellular Networks

5G is the 5th generation cellular network technology that provides broadband access. The 5G wireless devices also have 4G LTE capabilities, as the new networks use 4G for initially establishing the connection with the cell, as well as in locations where 5G access is not available. 5G can support up to a million devices per square kilometre, whereas 4G supports only 4,000 devices per square kilometre.

Technology Types

With no firm 5G technology standard truly in place at this time, the market is still figuring out the essential 5G features and functionalities. The primary 5G standards bodies involved in these processes are the 3rd Generation Partnership Project (3GPP), the Internet Engineering Task Force (IETF), and the International Telecommunication Union (ITU). 5G's main characteristics are large bandwidth (>1 Gb/s), high connection density, low latency (<5 ms) and high connection reliability (99.99%).

Technology Readiness Level

TRL 7

TRL Score 7 – Demonstration System Operating in Operational Environment

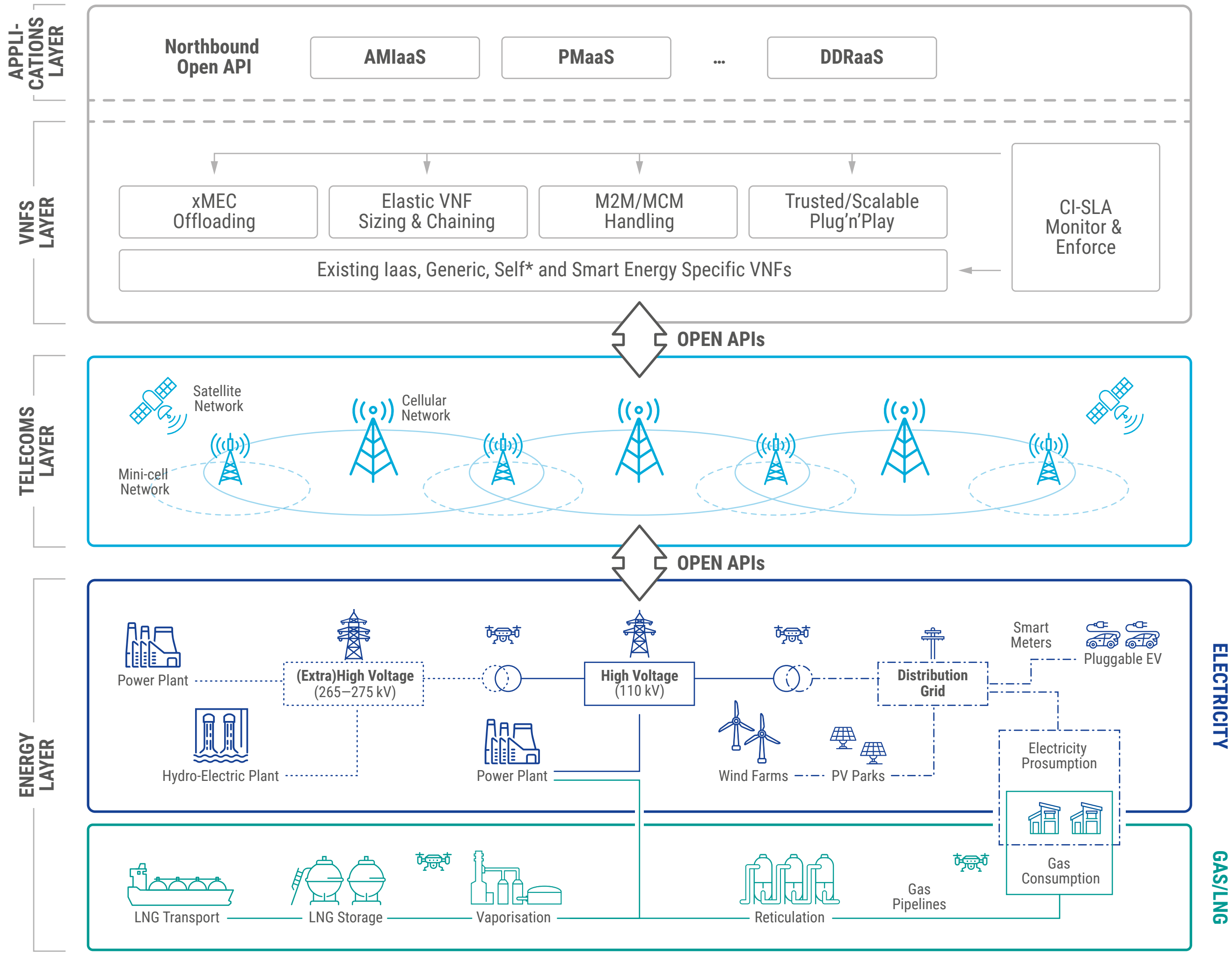
Advantages & field of application

5G technologies is a fundamental layer in electricity power systems (Figure 1) that will enable IT-AM, WAMS and WAMPAC systems. 5G technology and IoT devices, together with deep learning algorithms, will connect distribution electricity systems with transmission electricity systems at the highest performance resolution and computational level regarding Big Data and digitalisation.

Monitoring includes monitoring of grid equipment, including real-time situational awareness and supervision of capacitor bank controllers, fault detectors, re-closers, switches, and voltage regulators within substations. PMUs for wide area monitoring of the voltage and current in the grid are used to detect faults in the grid. In this scenario, the frequency of sending data in this scenario is less compared to protection and also the demand for low latency is less strict; however the need of time synchronisation, security and large-scale coverage becomes extremely important.

Other than the PMUs, there could be sensors installed on different points in the grid to monitor the temperature, vibration and other physical characteristics of the devices in the grid. Metering devices, which already today are commonly deployed using wireless technologies, can also be a data source for the evolved power grid. Video surveillance of remote substations represents another type of application, with a significantly higher bandwidth need.

5G Concepts for the Smart Energy Grid



Source: http://www.nrg5.eu

Research & Development

Emerging applications and services enabled by 5G:

Smart Grid:

- Drivers: Smart Meters deployment, Intelligent / Automated demand / supply control, Power line communication, AM, Predictive maintenance, WAMS and WAMPAC systems and analytics
- Enablers: IoT sensors and networks, AI

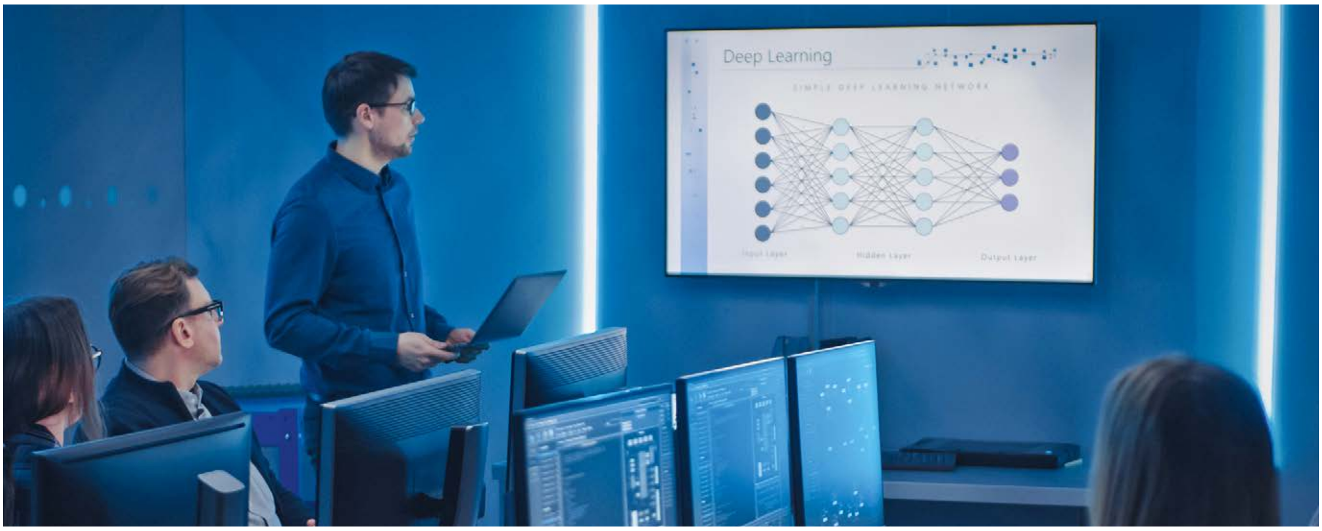
Automotive / Autonomous Cars:

- Drivers: Collision avoidance, intelligent navigation and transportation systems
- Enablers: V2V, Vehicle-to-Infrastructure (V2I) and other intelligent transport systems (ITS)

Smart Cities:

- Drivers: Connected utilities, Transportation, Healthcare, Education and all amenities
- Enablers: Massive IoT networks, Automation, Cloud infrastructure, AI

Artificial Intelligence



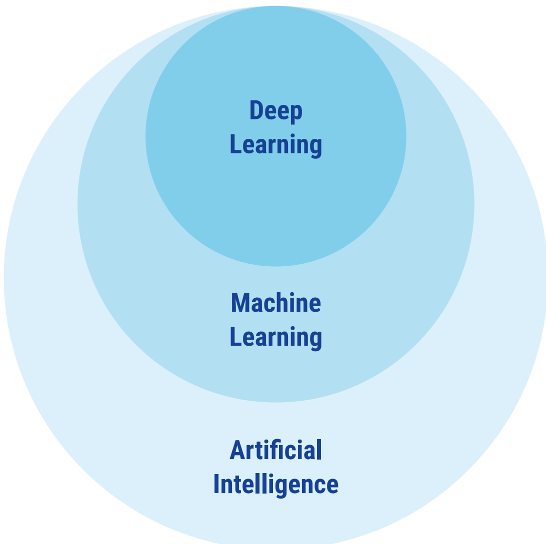
In modern life, Artificial Intelligence (AI) already plays a significant role in social media and streaming providers already, such as Instagram and Netflix. The AI can be used to place personalised advertisements due to the shared data of its users. Nonetheless, the AI approach can be implemented in vast swathes of TSOs' core business to adapt a large amount of data, providing support for decision making either from a system operation perspective or within corporate development and business administration.

Technology Approach

The AI approach is part of **computer science** that focuses on the simulation of human intelligence applied via machines and computer systems. One aspect of AI is the **machine learning (ML)** which is able to recognise a certain pattern (e.g. of a picture) in such a way as to memorise and identify a similar pattern. A more advanced aspect of ML is the **Deep Learning** Method **(DL).** A common approach to realise such a DL is to build a so-called **Artificial Neuronal Network,** which was inspired by the human brain. The main idea is that such an algorithm can process information out of a variety of input data to 'learn' a specific task's fulfilment.

Moreover, this can be distinguished between a **strong AI,** which is equal in the capability of a human mind and can be applied to a variety of areas, and a **weak AI,** which is just capable of fulfilling a specific task of a certain area.

All the existing AI implementations must be considered a weak AI.



Components & Enablers

Until now, the company that provides services within the new platform Economy own their AI algorithm. Therefore, the software code is operated on locally redundant Data Centres.

Advantages & Field of Application

In general, AI software solutions show high potential in improving an organisation's performance and can be implemented in both **technical and economic terms.** The main advantages and useful applications for a TSO's core business is still under discussion but might be established in one of the following:

- Using DLs in drones for maintaining the purposes of OHL.
- Applying digital twins of high-voltage equipment of high importance.
- Introducing software in controlling & accounting to improve administration performance within an organisation.
- Using optimisation code for automated energy trading.

To use these affects, TSOs must acquire evidence of certain advantages. It is necessary to identify specific potential in either grid opera-tion, market design or administration processes to accelerate the development of AI software solutions and to lead it into 'best practice' examples.

Technology Readiness Level

TRL 6

TRL Score 6 – Technology demonstration

Research & Development

For the time being, there are many methods and concepts developed for different ML purposes. A key to a useful implementation of AI software solutions in a TSO's core business is to launch external and internal projects to adapt those measures to experience best practices and lessons learned.

Best Practice Performance

Until now, there has bene no decent 'best practice' example from a TSO's perspective.

Distributed Ledger Technology/Blockchain

Distributed Ledger Technology (DLT) is an asset database that is shared and stored across a decentralised network of different and independent users, respectively nodes. All active network nodes guarantee that changes in the database (e.g. digital records or transactions) follow defined rules via a consensus mechanism, which makes the DLT tamper-proof. There are different forms of DLT designs, such as Blockchain (Bitcoin, Ethereum, EOS, etc.) or Direct Acyclic Graphs (DAG) (IOTA, Hashgraphs, etc.).

A Blockchain is a list of records, i.e. linked blocks that are cryptographically secured. Participants in a Blockchain network have access to the records of every transaction, which are securely stored in the ledger in a permanent manner. This technology, for the first time, allows online transactions between individuals without the need of a trusted middleman/platform.

On top of the DLT/Blockchain, a smart contract concept has been developed. This brings automation capabilities to the Blockchain technology, based on the principle 'If This Then That' (IFTTT), and enables new applications such as automatic payment after charging an EV. The data, the smart contract, while deployed on the Blockchain, is immutable.

Components & Enablers

The Blockchain technology dimensions:

- DLT design (Blockchain, DAG)
- Protocol definitions (e.g. speed, block size, etc.)
- Consensus algorithm (PoW, PoS, DPoS, PBFT, …)
- Governance principles (on-chain vs. off-chain)
- Public vs. private (i.e. permissionless vs. permissioned)
- Anonymity built-in (or not)
- Others components (tokens…)

Technology Types

- A **DLT-layer** (built from scratch, copy of an existing framework, or a public platform (e.g. Ethereum, EOS)
- **Application layer** (in the form of smart contracts)
- A so-called **'oracle'** has to be used to trustworthily link the DLT to the real world (human oracle, SW oracle, HW oracle, consensus-based oracle)

Advantages & Field of Application

A non-exhaustive list of TSO / electricity DLT use cases:

- Peer-to-peer flexibility trade for system purposes
- Peer-to-peer energy exchanges
- Peer-to-peer certificates trade (origin, CO_2 emissions)
- Cybersecurity improvement in settlement (time-stamp)
- Certification of data (fingerprint of a dataset on the Blockchain).

DLT has the potential to:

- Facilitate the efficient integration of smaller and decentralised production and flexibility units
- Lower entry barriers for participation to markets
- Improve transparency and trust among different players

Technology Readiness Level

TRL 7

No full-scale commercial projects in the electricity industry have been developed so far. Further improvements are required [4]. Limitations are e.g. low scalability and a lack of standardisation, but DLT is developing fast.

2020: TRL 7
2025: TRL 9

Best Practice Performance

Specific design requirements for good performance e.g.:

- Smart contract architecture: consider future needs (e.g. mother smart contract with immutable characteristics, linked to other smart contract which can be adapted)
- Limit the data to be put on-chain to those necessary: e.g. only a fingerprint of data (hash which is a crypted and unique representation of the data).

Research & Development

Research is required for mass adoption in the energy sector:

- Scalability problem (e.g. 2nd layer (off-chain) vs. 1st layer (on-chain) solution).
- Energy efficient, scalable, secure consensus mechanisms
- Confidentiality (for public Blockchain)
- Performance comparison: DLT v. other IT solutions
- Policy / regulation issues – technology / security standards
- Governance issues of Blockchain networks
- Potential security / safety risks

Best Practice Application

Examples of running pilots:

- LO3 (formerly 'Brooklyn microgrid') (US): peer-to-peer trading platform for local green energy use [1]
- Power Ledger (AU): P-2-P clean energy trading [2]
- TenneT (NL / DE): Ancillary services from decentralised flexibility resources (home batteries, EVs) [3]
- PJM (US) & Acciona (ES) track origin of energy [5], [6]
- 'Share & Charge' (MotionWerk's): P2P service for EV and charging point owners to rent their charging infrastructure to each other autonomously [7]

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Digital Twin

The new digital twin (DT) approach in production and AM claims to optimise the value chains in various industry sectors, such as in automotive manufacturing and energy products. It can be understood as a **digital representation of a physical asset,** e.g. a substation. This **digital picture of installed power equipment** may be used to operate complex grid infrastructure more accurately. There are quite a few products and services available, but proof is required of its trade-off for implementation in TSOs' core business.

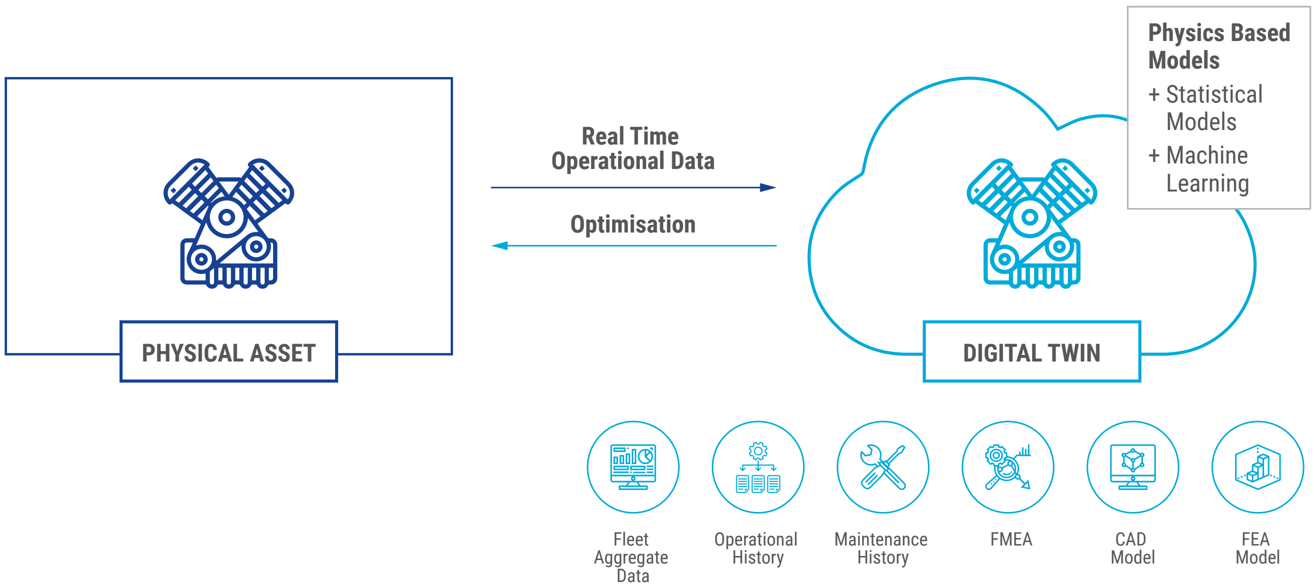
Technology approach

There are three main purposes of implementing a DT:

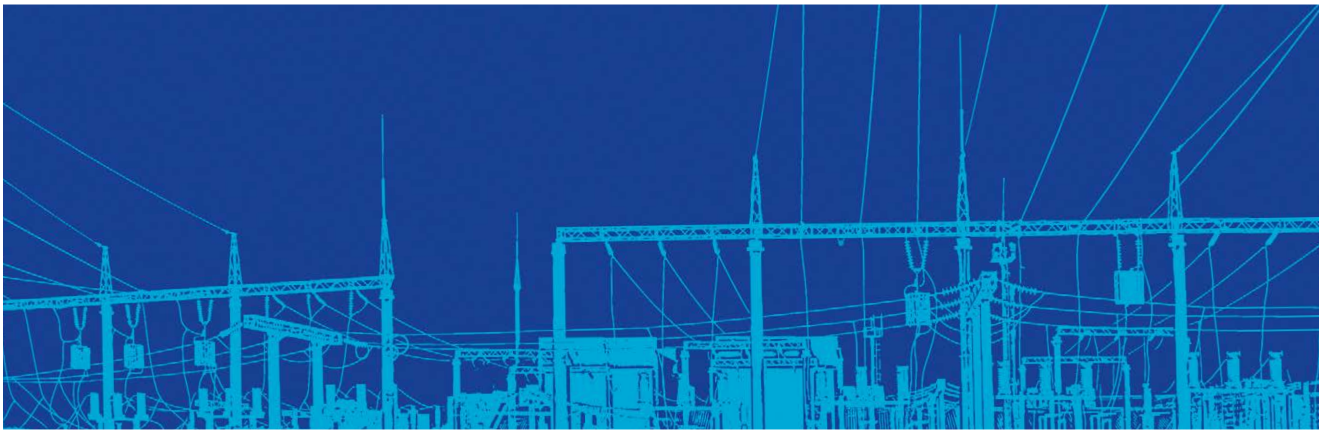
- A **Product Digital Twin** – to guarantee reliable design in product development and improvements.
- A **Production Digital Twin** – to improve production planning and manufacturing.
- A **Performance Digital Twin** – to capture, analyse and act on data while an asset is in operation.

From a TSO's perspective, the Performance DT is most relevant. Here, an Asset Owner gathers the necessary data to feed modelling and simulation software solutions to support decision making at several operational levels, e.g. system operation or maintenance activities.

Another argument for implementing such a DT for several purposes is to have **one** sophisticated method for stacking and using data from various sources – therefore ensuring **one** 'source of truth' is available.



Source: https://www.railwayage.com/analytics/siemens-bentley-strengthen-partnership/



Components & Enablers

The DT infrastructure consists essentially of 3 parts:

- The **Engine** is responsible for the operation of the central multi-user database as well as several data management functions.
- The installed **sensors and corresponding interfaces** are the components that obtain data and transfer within another.
- The implemented **User Interface** provides sufficient functionality, such as graphical data visualisation.

Advantages & Field of Application

The DT approach promises to improve the utilisation of data gathered from e.g. market participants and energy traders, generation units and power plants as well as the TSO's grid infrastructure. It can be discussed as a useful tool to affect data-driven performance in future power grids; appropriately in **Power System Operation** and its **grid planning** or in **Power System Economics** and its local **flexibility markets.**

Technology Readiness Level

TRL 6

TRL Score 6 – Technology demonstration

Research & Development

The main developments have been promoted not academically but in industry sectors. Therefore, leading companies as Siemens AG and General Electric Corp. offer different products and software solutions to Asset Owners and other stakeholders.

Best Practice Performance

Together with Siemens AG, **Fingrid** introduced an electrical DT model (ELVIS) to affect their **asset** and **operation management** as well as infrastructure investment planning. Meanwhile, the DT model is being used to develop several investment scenarios considering different policy frameworks. In conclusion, the data collection and verification process takes less than 20 % of the time that it used to take.

The **American Electric Power (AEP)** established a similar project to obtain a **reduction of the time and costs** associated with grid and market modelling efforts manually. Furthermore, an advanced **data governance foundation** to support its investment strategy was implemented.

Cloud and Edge Computing

Cloud computing is a type of computing that relies on shared computing resources rather than having local servers or personal devices to handle applications. The term is generally used to describe the large data centres available to many users over the Internet (public cloud) or on a private network (private cloud).

Edge computing [R1] is the delivery of computing capabilities to the logical extremes of a network to improve the performance, operating cost and reliability of applications and services. By shortening the distance between devices and the resources that serve them, and also reducing network hops, it mitigates the latency and bandwidth constraints of today's Internet, ushering in new classes of applications.

The combination of edge and cloud computing in a single continuum is part of the 'fog computing' paradigm [R2] and includes a common management of every computing resource. Computer and data storage resource, as well as applications and their data, are positioned in the most optimal place between the user and Cloud. In practical terms, this means distributing new resources and software stacks along the path between today's centralised datacentres and the increasingly large number of devices in the field, concentrated, in particular but not exclusively, in close proximity to the last mile network, on both the infrastructure and device sides.

Technology Types

Edge computing can either use existing devices (routers, servers, gateways, switches,…), telecom base stations or dedicated physical components known as cloudlets ('data centre in a box') with the extensive use of virtualisation techniques.

Advantages & Field of Application

Edge computing facilitates the processing of delay-sensitive and bandwidth-hungry applications near the data source by pre-processing data. Cloud computing provides scalable computing and storage resources. The right combination of cloud- and edge-based applications is key to maximum performance.

Components & enablers

A good infrastructure is required, such as high-bandwidth telecommunications, ICT infrastructure in the substation or existing telecom equipment (i.e. routers).

Digital substation automation maximises the capabilities of edge computing through direct connection.

Micro-services architectures, virtualisation, containerisation and orchestration tools are the key to achieving a smooth operation.

Technology Readiness Level (Edge Computing)

TRL 6 – 7

2020: TRL 6 – 7 (higher in Telcos)

Research & Development

Current fields of research:

Fault tolerant architectures; distributed storage; hierarchical data mining, seamless management and configuration of heterogeneous components; automatic resource allocation between cloud and edge

Innovation priority to increase overall TRL:

Adapt existing framework to TSO-specific protocols (61850, 60870-5-104, …) to implement demonstrators' experiment with a large-scale management system

Best Practice Application

Numerous TSO functions can benefit from edge/cloud computing:

- Data collection for **asset monitoring** (local treatment and high level indicators sent to cloud), especially from IoT captors.
- **Automatic flow control** for DER integration (in association with batteries or Dynamic Line Rating), **distributed voltage control,** faster automatic service restoration.
- HD **video surveillance** for intrusion detection.

For each function, real time data are treated at the edge and complex data such as topology, forecast are sent by the cloud.

Best Practice Performance

- Dedicated cloud operating system (potentially Open-Stack, EdgeXFoundry)
- Separation of control and data planes
- APIs to support interoperability

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https://github.com/lf-edge/glossary/blob/master/edge-glossary.md

[R2] Fog Computing Conceptual Model NIST Special Publication 500-325
https://doi.org/10.6028/NIST.SP.500-325

Internet of Things

The Internet was established to transfer files and share information between local area networks – therefore it can be understood as the Internet of People. Until now, vast groups of the world's citizens have had access to a more or less restricted World Wide Web. The IoT approach elaborates on the idea of connectivity not only for people but also technical devices and equipment. This kind of system allows data transfer and analysis without human-to-human and human-to-computer interactions. This approach has high potential for transportation, health care, manufacturing and smart buildings.

Technology Approach

Within IoT, a set of hardware is used to communicate and interact with other devices in a controlled network. Hence, the communication part is of high importance, which can be wire-based or wireless.

Several communication standards are available currently:

- LTE or 5G for real-time applications within factories or autonomous mobility
- Bluetooth for short length of transfer
- Ethernet, ModBus, etc. for industrial applications

Advantages & Field of Application

A system of interconnected physical objects and devices offers opportunities, e.g. to increase productivity in manufacturing or optimise power flow and consumption in heavy industries.

In power systems and grid infrastructure, a useful adaption must be discussed to evaluate best practices for a TSO's core business.

Components & Enablers

In general, the IoT architecture can be divided into three layers – the **perception layer, network layer and application layer.**

The major components in such a system are:

- **Smart devices** and **sensors** to gather data and transfer them
- **Gateways** to manage data traffic and adapt protocol
- **Cloud** storage to stack data
- **Software solutions** to analyse data and produce content out of derived information
- User **interfaces** to allow users to have access and control the network

Technology Readiness Level

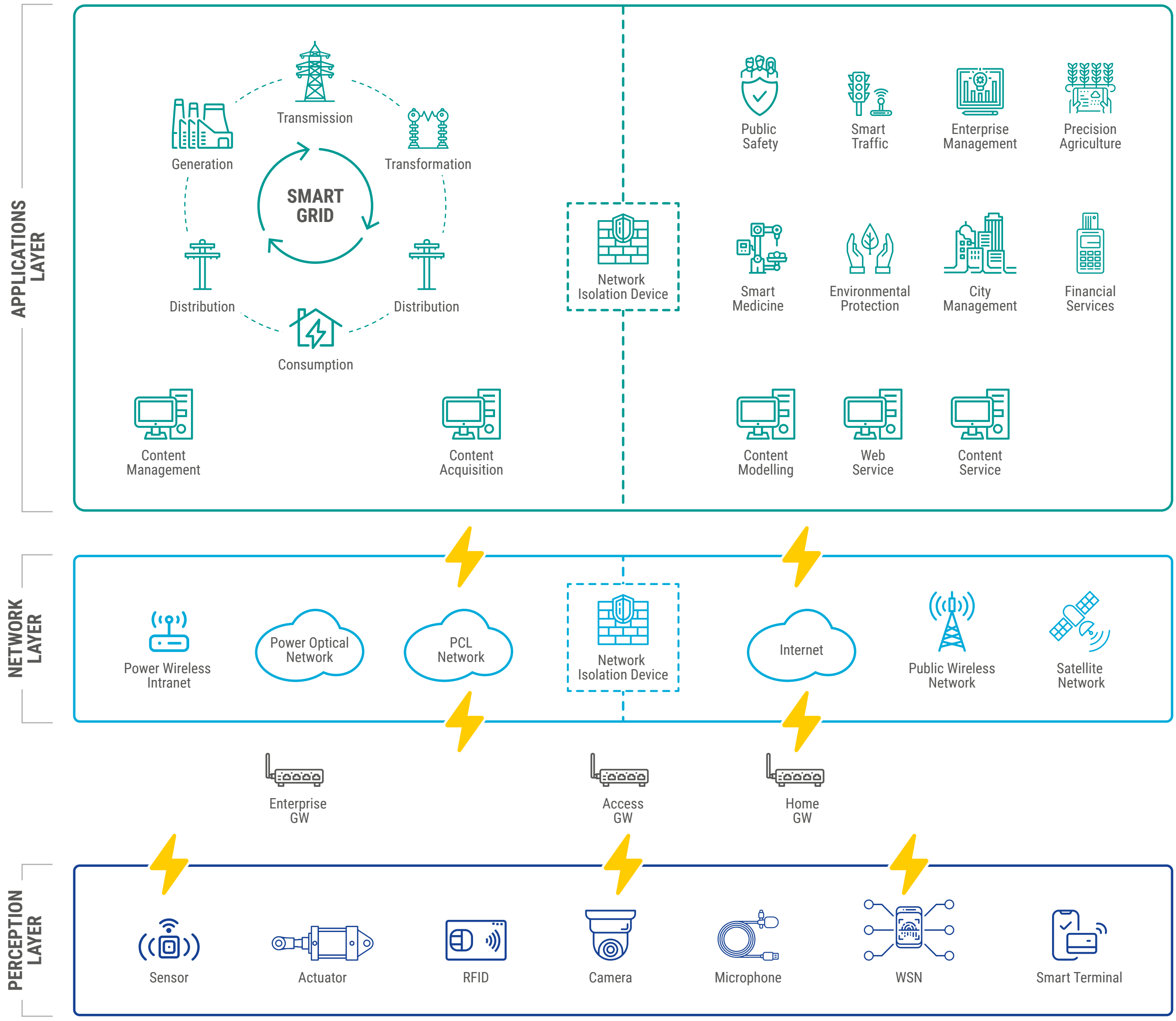
TRL 7

TRL Score 7 – Prototype in demonstration

Research & Development

Several IoT solutions have already been introduced to the markets, provided by big companies such as IT or energy, but multiple small companies and start-ups are also involved in offering products for Power System Operators.

IoT architecture



Source: 'Application of Internet of Things in Smart Grid Power Transmission.' 2012 Third FTRA International Conference on Mobile, Ubiquitous, and Intelligent Computing (2012): 96 – 100.

Best practice performance

Simple 'IoT systems' are already used in transmission systems nowadays to monitor and control their operation. More advanced IoT is now used in the Fingrid´s grid, where IBM´s IoT system Watson is used to increase the automation of the system. There are high expectations from application in distribution grids which have previously been passive, and IoT would allow them to implement distributed generation, DMS and other services, thereby increasing the efficiency, ecology and economy of such systems. This ranges from flow monitoring on the LV lines to consumption monitoring at the consumers´ side of the system. Such systems are already being researched by DSOs and other involved institutions.

Satellite Applications

Satellites can be used for many different applications such as communication, broadcasting, navigation, weather forecasting etc.

Technology Types

Modern communications satellites typically use geosynchronous orbits, Molniya orbits or Low Earth orbits.

Earth observation satellites are satellites intended for non-military uses such as environmental monitoring, meteorology, map making etc.

Navigational satellites (e.g. GPS) are satellites which use radio time signals transmitted to enable mobile receivers on the ground to determine their exact location. The relatively clear line of sight between the satellites and receivers on the ground, combined with ever-improving electronics, allows satellite navigation systems to measure location to accuracies on the order of a few meters in real time.

Weather satellites are primarily used to monitor Earth's weather and climate.

Reconnaissance satellites are Earth observation satellite or communications satellite deployed for military or intelligence applications.

Starlink (SpaceX) and OneWeb have projects to launch **constellations** of hundreds of satellites, which could provide a cheaper broadband service.

Components & Enablers

- Satellite transponder
- Antenna subsystem
- Solar cell and battery backup
- Ground stations / devices

Advantages & Field of Application

- Communications between substations and dispatch centres, especially for remote locations or backup links
- Communication with mobile assets (e.g. drones)
- Monitoring of power lines
- Monitoring of vegetation in corridors
- Positioning of assets (GPS)
- Synchronisation of electronic equipment (GPS)
- Weather forecast as input for planning operations

Technology Readiness Level

TRL 7 – TRL 9

TRL 7 – 8 for constellations, 9 otherwise.

Best Practice Performance

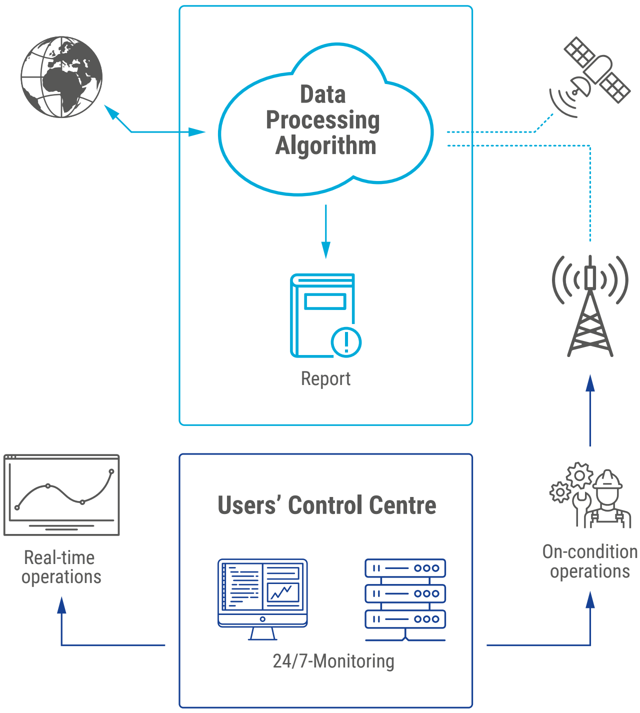
Application specific.

Best Practice Application

- Using high resolution satellite imagery for high and medium voltage power line monitoring
- Satellite communications (SatCom) applications for remote locations and for network backup / resilience
- Satellite support for autonomous drones (UAVs)

Research & Development

Vegetation management of transmission corridors
Pylon movements and ground displacement [2]



Credit: GridWatch IAP project [2]

REFERENCES

[1] https://en.wikipedia.org/wiki/Satellite

[2] https://business.esa.int/projects/gridwatch

Software-Defined Security

Software-defined security (SDS) is a model in which the information security is controlled. The functions of network security devices, such as firewalling, intrusion detection, access controls, and network segmentation are extracted from hardware devices to a software layer. SDS exploits the software-defined networking (SDN) to enhance network security. The concept of SDS is intended to define the necessary security services as IT infrastructure transitions from a hardware based to a software-defined market.

Technology Types

Following the SDS architecture concepts, the design of security solutions to protect organisations from distributed denial of service (DDoS) and malware attacks can drastically change and evolve to a more dynamic and sophisticated implementation.

One of the inherent capabilities of an SDN controller is the fact that it has knowledge of the network topology and infrastructure and it provides visibility of the traffic.

Components & enablers

- **Host:** The host is to send or receive data through the network. For the SDS, all security techniques are transferred to the controller.
- **Controller:** The controller is fully software-based. All security checks are done inside the controller. It has visibility of the traffic flows. It collects and processes information about the network.
- **Switch:** The switch consults the controller to decide whether to accept or reject a request. A reactive caching mechanism is adopted in SDN. However, it makes switches vulnerable to a DDoS attack.

Advantages & field of application

- Efficient and dynamic mitigation of security threats and attacks.
- Hardware cost reduction, due to the virtualisation of the network security applications in commodity hardware.
- Utilisation of existing network appliances, even if they do not support advanced traffic monitoring mechanisms.
- Dynamic configuration of existing network nodes for the mitigation of an attack, where and when needed.
- Harmonised view of logical security policies, which exist within the SDN controller model and are not tied to any server or specialised security device.
- Visibility of information from one source
- Integration with sophisticated applications to correlate events in a simpler manner and respond more effective and intelligently to security threats
- Central management of security, which is implemented, controlled and managed by security software through the SDN controller.
- May help to overcome cybersecurity issues. Facilitates IoT & BYOD connectivity. Abstracts security away from hardware vulnerabilities.

Technology Readiness Level

TRL 8 – TRL 9

TRL 5 – 6

TRL 8 or even 9 but still 5/6 in TSO context

Research & Development

Solution implemented in the industries: hardware, software, telecommunication, banking, insurance, etc.

Best practice application

The technology is present in the market, for now in the beginning stage; start-ups being a strong presence in this area.

The development of the following use cases has been prioritised:

- Policies should be bound to workloads, such as virtual machines, containers, applications, services or microservices.
- Write security policy in one place and deploy in multiple places, where workload policy would then be enforced.
- Must be able to measure the ability of network workloads to ensure the confidentiality, integrity and availability (the Security Triad) of the services they are delivering.

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