PhD Projects 2025

Department og Electric Energy

April 2025

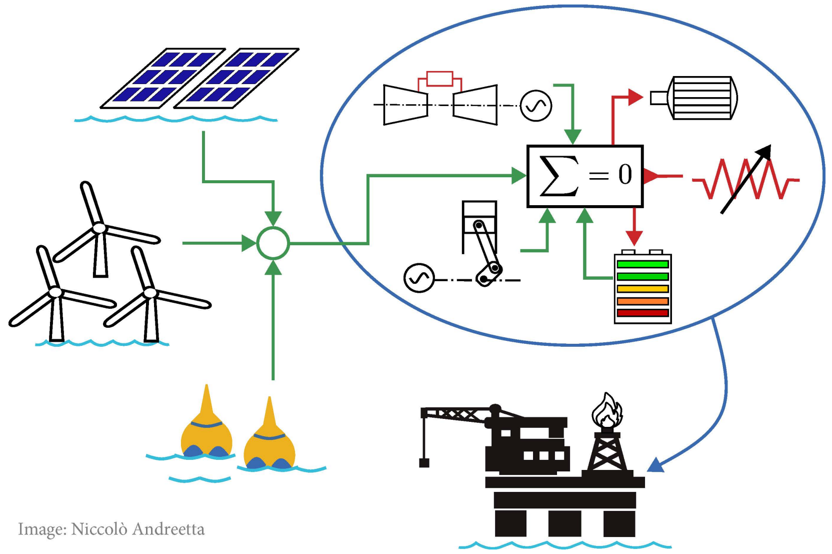

Image: Niccolò Andreetta

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electric Energy

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Department of Electric Energy

At the Department of Electric Energy (IEL), the mission is to contribute to the fundamental and applied knowledge of electric power engineering and to develop technology and systems for the planning, operation, and maintenance of efficient, sustainable energy systems. Both research and research-based education at the Department of Electric Energy cover the broad interdisciplinary aspects of power engineering: generation, transmission, distribution, conversion, and the use of electric energy, including the accompanying techno-economic aspects.

The Department works in close collaboration with industry partners and public administration to develop technology for production of electric energy from renewable energy sources and contribute to research that leads to solutions for the future power grid, with high relevance for the society, addressing industrial needs and global challenges.

The Department has five research groups that are each responsible for research and education within their respective areas:

- Electrical Machines and Electromagnetics (EME)
- Electricity Markets and Energy System Planning (EMESP)
- High Voltage Technology (HVT)
- Power Electronic Systems and Components (PESC)
- Power System Operation and Analysis (PSOA)

PhD Studies

In this booklet, we are presenting ongoing research within all five areas by highlighting the work performed by our PhD candidates. The PhD programme in Electric Power Engineering is standardized to 180 credits (3 years). The final plan for the PhD programme is designed in consultation with the candidate, the supervisor and the Department depending on the subject area of the thesis and the candidate's needs and preferences. Usually, the PhD studies are integrated as part of larger research and development projects that are carried out in collaboration with national or international research and industry partners.

We hope you will enjoy reading about our research!

NTNU, April 2025,

Frank Mauseth
Professor
Coordinator of the IEL PhD programme

Content

Electrical Machines and Electromagnetics (EME)

The main research areas of the group are related to the development, design, optimisation, and testing of electric machinery, especially permanent magnet machines and hydropower generators, for various application areas: industry, and renewable energy production, transportation, and marine sectors. In addition, research is also focused on advanced electromagnetic modelling and analyses of different power apparatus and installations.

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Graduation Year: 2022

Main supervisor: Jonas Kristiansen Nøland
Research Group: Electrical Machines and Electromagnetics
Project: Cryo-Electric Aviation Propulsion

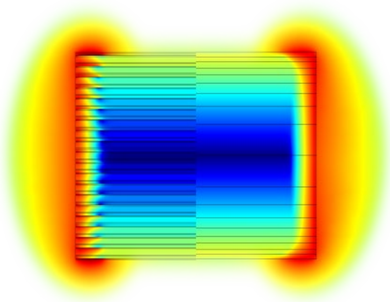
Electro-Thermal Analysis of High-Temperature Superconducting Electric Motors for Cryo-Electric Aircraft Propulsion

Description of the research

Hydrogen-electric propulsion offers a promising path towards sustainable aviation. Due to the availability of hydrogen as cold source, High-Temperature Superconductors (HTS) could be used to improve the efficiency and power density of the drivetrain. This includes HTS cables, cold power electronics, and superconducting rotating machines.

If HTS coils are used in the stator of the electric motor, they experience AC losses due to the alternating currents and magnetic fields. Modeling these losses has been an active research field in recent years, leading to various novel electromagnetic numerical models. At NTNU, these models have been applied and improved to analyze and optimize the performance of such superconducting machines.

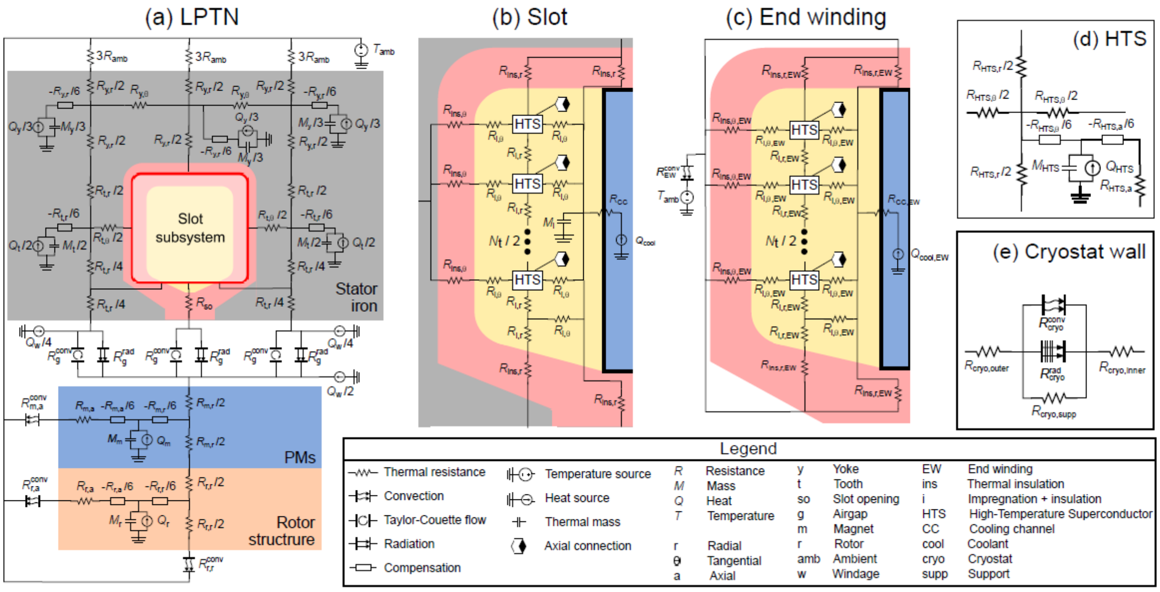
Once these losses are known, the next question is how to dissipate them in order to maintain the operating temperature of the HTS coils below their critical temperature ($\sim 40\mathrm{K}$). This PhD research focuses on the thermal analysis of electric motors employing HTS armatures, and the design of potential cooling methods.



Firstly, homogenized, coupled electro-thermal models have been developed, which can simulate the AC losses in the HTS coils as well as the resulting temperature increase. These models have been used to simulate the temperature rise of HTS armature windings in high-power aircraft propulsion motors.

As a second step, a Lumped-Parameter Thermal Network has been developed to analyze the thermal performance of the entire machine. This thermal model is being used in our research to analyze the impact of different design parameters on both the machine and aircraft performance. So far, it's been used to analyze the motor efficiency, the maximum required amount of liquid hydrogen, the feasibility of using gaseous helium as a coolant, and the stability of the propulsion system during the duration of a short-range flight.

In the final phase of the PhD, these models will be used to further study the performance of superconducting machines, and parts of the model will be validated with experimental prototypes.



Innovation potential and possible applications

Various groups have been researching cryo-electric propulsion methods for aircraft, including the recently concluded ASCEND project by Airbus. The tools developed in this PhD research will support the ongoing research into aircraft propulsion, as well as other applications of High-Temperature Superconductors, such as hydrogen ships, fusion reactors and superconducting electricity grids.

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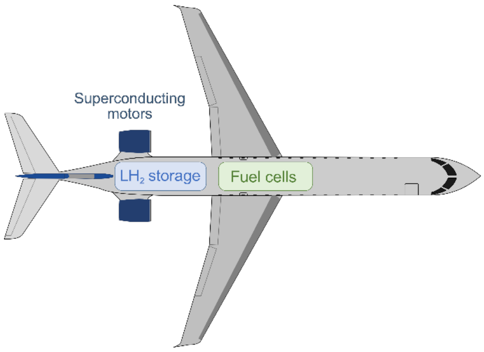
University: NTNU
Graduation Year: 2021

Main supervisor: Jonas Kristiansen Nøland
Research Group: EME
Co-Supervisor: Ole Morten Midtgård
Project: Clean aviation

Design of superconducting electric machines for hydrogen aviation

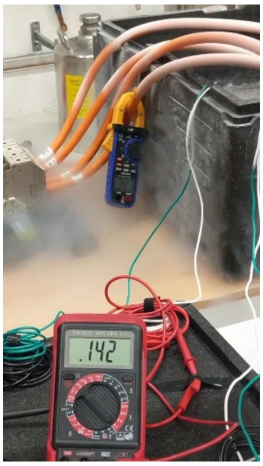
Description of the research

To electrify aircraft, the electric components must be as lightweight and energy efficient as possible. In our project, we are exploring whether a cooling synergy with the liquid hydrogen fuel could be used to enable disruptive technologies like superconducting motors for propulsion. However, superconductors produce losses when operating in AC conditions. I am investigating these losses closer to estimate the cooling requirement, and evaluate the potential and viability of the technology in this application.



Innovation potential and possible applications

Our analysis thus far has shown that an electric motor with a superconducting armature has some potential, but also considerable downsides. It can be designed to have a higher density than conventional machines, and since it has much lower armature losses, it can be extremely efficient (given free cryogenic coolant). However, the cryogenic cooling is very challenging and will introduce significant system complexity.



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Graduation Year: 2021

Main supervisor: Pål Stabel Keim
Research Group: Electrical Machines and Electromagnetics
Co-Supervisor(s): Kaveh Niayesh
Project: Clean Aviation

PhD work title: Electrical insulation systems in superconductive power trains for aircraft propulsion

Description of the research

Electrification of aviation can result in reduction of emissions related to it. The main hurdle in aviation electrification is weight. This can be overcome by using motors based on superconductors. Powertrains based on cryogenic technologies can be applied to significantly reduce weight without compromise in powertrain efficiency. These powertrains still need to be insulated for use and a suitable insulating material need to be employed during the operation in cryogenic temperatures.

The insulation system of superconducting rotating machines must satisfy the thermal and mechanical requirements as well as electrical specifications. These specifications include: "high dielectric strength, low dielectric losses in the case of AC voltage, high heat conductance in the internal electrical insulation for heat diffusion reasons, low heat conductance in the bushing, especially high mechanical strength in large superconducting magnets, and high radiation resistance in magnet coils for fusion reactors and accelerators".

Organic insulation materials deteriorate at a faster rate compared to metallic and ceramic elements due to the cryogenic temperatures of these systems. Electron avalanches (partial discharges) caused due to breakdown mechanisms of the material used for insulation accelerate the deterioration of the insulation material. AC losses due to superconducting windings are a predominant cause for insulation degradation and windings need to be cooled with a suitable coolant, usually liquid hydrogen at 20 K.

Insulation materials also experience additional mechanical stresses at cryogenic temperatures due to microstructural changes at these temperatures. Harmonics from PWM fed systems cause additional degradation and accelerate ageing of the insulation materials due to thermal and mechanical stress on the insulation.

The materials used as insulation in these machines should be able to withstand electrical, mechanical, and thermal stresses during operation and protect the superconductors from damage due to these stresses. There is a lot of information available on the materials used for conventional machines and the stresses experienced during their operation but not much information on the insulation materials in cryogenic temperatures and the response of these materials in cryogenic temperatures. There are also additional challenges of not being able to extrude the insulation material on the conductor to encapsulate it as the temperatures in the process of extrusion may damage the superconductors.

Thus, the main scope of this PhD study is to investigate insulation materials used in cryogenic temperatures and to provide suitable design options of electrical insulation systems for the power dense aviation motor considering the typical stresses involved in operation.

Innovation potential and possible applications

This project will contribute to the development of clean aviation and the reduction of emissions created by flight propulsion. This will help the aviation industry to meet the 2030 and 2050 emission reduction goals as well as paving the way for net zero emissions and carbon neutrality.

Electricity Markets and Energy System Planning (EMESP)

The main research areas of the group are related to the integration of renewable energy sources, energy storage and consumption in the electricity market, and how to optimize the integration of the power system with other parts of the energy system, e.g., heating and transport.

Alexandra Sheppard

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Graduation Year: 2021

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Research Group: EMESP
Co-Supervisors: Magnus Korpås (NTNU), Magnus Moe Nygård (IFE)
Project: HydroSun

Market integration of hybridised solar PV and energy storage power plants in different energy markets

The Norwegian HydroSun project aims to capitalise on technological diversification between hydropower and solar PV by using existing hydropower plants to accelerate integration of solar PV. The project captures the benefits of physical co-location of hydropower and FPV, such as shared electrical infrastructure and costs, reduced reservoir evaporation, and seasonal complementarity of resource availabilities between inflow and solar irradiance.

The PhD investigates the case of market entry and participation for hybridised power plants, in different market structures, through multi-market optimisation modelling. Linear programming models are used to optimise operation of the hydropower plant, solar PV dispatch, and in some cases battery operation, over different time resolutions. Sub-hour solar fluctuation mitigation is balanced against seasonal storage decisions under uncertainty of solar irradiance forecasts, day-ahead market prices, and balancing market prices.

Innovation potential and possible applications

Hybridised renewable power plants provide an opportunity for to integrate greater shares of renewable energy into the power market. The PhD aim is to identify the market levers which greatly impact profit and market integration of hybridised power plants. This can be used by asset owners, power contract designers, and policy makers to inform future decisions regarding hybridised power plants and accelerate market acceptance.

Ali Kaboli

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Graduation Year: 2024

Supervisor: Jayaprakash Rajasekharan
Research Group: Electricity Markets and Energy System Planning (EMESP)
Co-Supervisor(s): Magnus Korpås, Gro Klæboe
Project: FME NTRANS

Advanced Informatics for Distributed Grid Balancing Through Flexibility Aggregation

Description of the research

The increasing integration of renewable energy sources, such as solar and wind, poses challenges due to their unavoidable uncertainty and variability. Additionally, energy decarbonization efforts, such as the retirement of thermal power plants, have decreased the availability of grid inertia traditionally provided by these plants. Consequently, the power system operation requires an increase in its capacity to respond to unexpected fluctuations in generation or transmission. In this regard, demand-side flexibility could maintain the balance between generation and demand in electrical grids.

Different sources of demand-side flexibility can be combined to form innovative solutions for power system operation. Considering current regulations in Norway, small and medium consumers on the demand side cannot participate directly in the balancing markets to provide their flexibilities due to the low tradable volumes, engagement cost, and reliability issues. This has led to the rise of a new player, the 'aggregator,' who aggregates these flexible loads and participates in the balancing markets on behalf of end-users to support the security of supply considering network, generation, and consumer constraints.

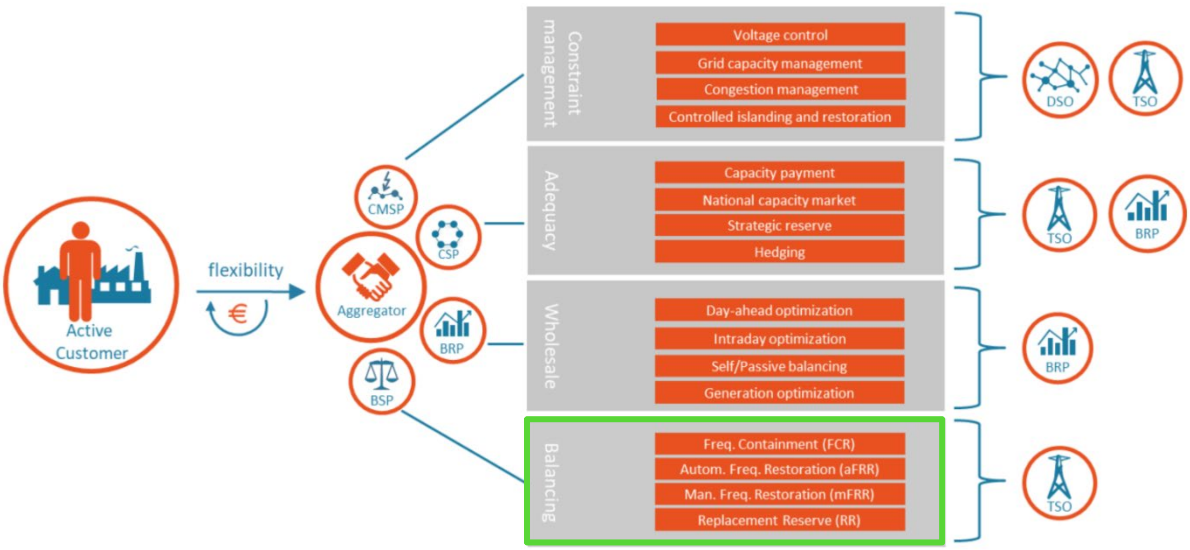

Figure 1: Overview of demand-side flexibility and active parties.

Recently, there has been a growing interest in providing flexibility services from distributed resources, such as Electric Water Heaters (EWHs), to transmission grid operators through aggregated demand response. EWHs have significant potential for offering demand-side flexibility, as they are power-intensive devices with thermal storage capabilities. To effectively integrate EWHs into the balancing markets, aggregators must estimate available flexibility values, optimize market bids, schedule and monitor distributed resources, enhance their operations, deliver the promised flexibility, and validate its delivery. The technologies and tools employed for these tasks should be low-cost, reliable, robust, scalable, and highly accurate.

The main research question to be answered in this project is: How can we address the challenges and issues that hinder the aggregator's effective integration of EWHs into the balancing markets?

Innovation potential and possible applications

The main objective of this project is to develop, validate, and assess advanced operational tools designed to assist aggregators in integrating small and medium-sized distributed energy resources, particularly EWHs, into the balancing markets. This integration supports grid balancing and offers financial benefits to end users, enabling them to profit from flexibility extraction while contributing to the overall stability and sustainability of the Nordic power system.

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Graduation Year: 2019

Main supervisor: Magnus Korpås
Research Group: EMESP
Co-Supervisor: Steve Völler
Project: FuChar – Grid and Charging Infrastructure of the Future

Modelling of electric vehicle charging in distribution grid planning

Description of the research

With increasing shares of electric vehicles (EVs), the EV charging must be considered in the planning and operation of the power system. In my PhD work, I am investigating how the EV charging could be modelled in distribution grid planning. I am especially interested in which characteristics of the EV charging that are important for the investment decisions.

Distribution grid planning involves performing a techno-economic analysis considering different measures (e.g. line reinforcement, new transformers, or active measures like reactive power compensation or demand side flexibility), where the goal is to find the socioeconomic rational development of the grid. This typically means to find the combination of measures that gives the satisfactory quality of supply to the least cost. The techno-economic analysis require that one defines a set of inputs. E.g. one need estimates of the investment costs of alternative measures, a network model including impedances and topology, and data and assumptions regarding the load profile of existing load and new connections during the planning horizon. EV charging is one type of new load that, at least in many grid areas, is relevant to consider.

Since there are many inputs and assumptions in the grid planning process, and these are associated with uncertainty which might be more or less important for the result of the techno-economic evaluation and the investment decision, the idea of this PhD project is to assess the importance of the EV-related inputs compared to other inputs. Global Sensitivity Analysis is used for a distribution grid optimization model to analyse the importance of the uncertainty of the input factors for the investment needs and investment decisions.

Innovation potential and possible applications

The results can be used to guide the development of EV load models. Moreover, the results and the methodology are relevant for validating grid planning models and for prioritizing efforts in improving quality of input data, assumptions, and modelling choices.

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Graduation Year: 2021

Main supervisor: Hossein Farahmand
Research Group: Electricity Markets and Energy Systems Planning
Co-Supervisor: Christian Andre Andresen (Sintef Energi)
Project: Ocean Grid

The Representation of Hydrogen in Energy System Optimization Models

Description of the research

Hydrogen has come to the forefront of discussion, particularly due to its carbon-free nature at its point of use, and long-term storage potential. Computational models based on mathematical optimization have been widely used in the literature to better understand the role of hydrogen in highly renewable energy systems. Traditionally, the representation of space, time, and physical laws has been significantly simplified to provide a holistic view with given computational resources. However, there is a consensus that these simplifications are no longer justified for modeling hydrogen in highly renewable energy systems. This PhD project therefore aims to apply and further develop methodologies that more accurately capture real-world phenomena and thus account for the flexibility potential of hydrogen. This includes:

- **TIME**: Develop a time-series aggregation method that better captures the variability of wind energy and corresponding hydrogen storage needs
- **UNCERTAINTY**: Using two-stage stochastic optimization to address the short-term uncertainty from renewable hydrogen
- **PHYSICAL LAWS**: Using DCOPF and model coupling to better identify grid bottlenecks and required flexibility services from hydrogen technologies

Innovation potential and possible applications

The novelty lies in applying and adapting solution methods from other research fields to hydrogen modeling. The idea is that improved methodologies in Energy System Optimization Models can provide a sound basis for decision-making in highly renewable energy systems.

Erik Seeger Bjørnerem

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University: NTNU
Graduation Year: 2021

Main supervisor: Magnus Korpås
Research Group: Electricity Markets and Energy System Planning
Co-Supervisor(s): Christian Naversen (SINTEF)
Project: HydroConnect

System Impacts of Connecting Norwegian Hydropower to the European Power System

Description of the research

European countries are phasing out fossil power generation to achieve ever more ambitious climate change mitigation targets. Simultaneously, the share of capacity from variable renewable generation such as wind and solar is increasing. The intermittency of these technologies needs to be balanced by flexible technologies, such as hydropower.

During periods of surplus variable renewable generation, hydropower production can be withheld, and stored for a later occasion. Additional pump capacity may further utilize the variations from wind and solar generation and reduce curtailment, while supplying power in peak demand hours. However, pumped hydropower storage upgrades feature large investment costs, and current investment models overestimate the flexibility of hydropower through aggregation and simplification.

This PhD aims to improve the representation of hydropower in capacity expansion models to accurately compare the allocation of flexible resources from hydropower storage to other technologies such as battery or hydrogen storage. This is then applied to various policy scenarios for CO2-emissions to investigate how the 85 TWh of reservoir capacity in Norway can contribute to decarbonizing the European power sector, as well as quantifying the impacts for Norway.

Innovation potential and possible applications

This work will provide new insights into capacity expansion modelling of hydropower storage and high shares of variable renewable generation on a European scale.

Jarand Hole

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Graduation Year: 2018

Main supervisor: Magnus Korpås
Research Group: EMESP
Co-Supervisor(s): Harald Endresen, Steve Völler

PhD work title: Integration of solar power in the Norwegian power system

<u>Description of the research</u>

More renewable and zero emission energy is needed for decarbonization and new industrial activities, and solar energy is a part of that picture. My research is focused on Norway's future electricity supply, what role solar power and other technologies can play in this and developing better tools to increase our understanding on the matter. Analysing wind and solar power integration calls for fine granularity in the models used, and the hydro power dominated market increases the complexity as the decision problems are highly stochastic.

The main activity in this research is the work with investment models based on stochastic dual dynamic programming (SDDP). Using the open source SDDP.jl, we can make use of the policy graph concept to structure the decision problems, and by using a non-standard policy graph like the one shown below, optimal investment decisions can be integrated with optimal dispatch decisions. This ensures that resulting investments also consider that the system operates differently with different capacities.

J. Hole et al.

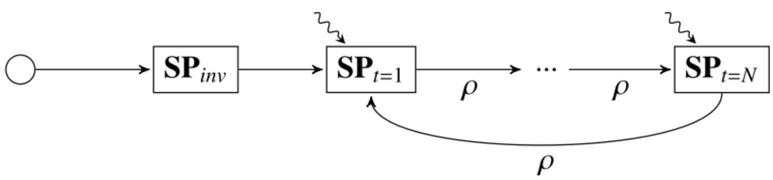

Fig. 3. The policy graph structure for **INV – HTP – ∞**.

Innovation potential and possible applications

The models developed in this project will be of interest to actors who are interested in energy system planning. The results produced throughout the research will hopefully give insight to the energy authorities and provide a better knowledge base for decision makers.

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Main supervisor: Jayaprakash Rajasekharan
Research Group: Electricity Markets and Energy Systems Planning
Co-Supervisor(s): Kasper Emil Thorvaldsen & Sébastien Gros
Project: FME NTRANS (Research area 3 - Future energy markets)

PhD work title: Multi-market Decision-making under Uncertainty Using Distributed Heterogeneous Flexible Resources

Description of the research

This PhD research explores strategies for optimising the integration and utilisation of distributed, heterogeneous energy resources in evolving energy markets. It focuses on developing decision-making frameworks that enable aggregators to effectively manage portfolios of distributed heterogenous flexible resources and engage across multiple energy markets, including balancing markets. The research aims to address challenges related to market dynamics, uncertainty, and risk management.

A key objective is to ensure compliance with emerging regulations while maximising value through multi-market participation. The underlying hypothesis fuelling the research is that decentralised flexible resources can contribute to grid stability, congestion management, and renewable energy integration, thus supporting a transition to more sustainable and resilient energy systems.

Statnett, the Norwegian TSO, expresses a clear desire for more flexibility in the energy sector, as it is a viable alternative to constant grid reinforcements and will help stabilise the grid in a time where intermittent production accounts for more and more of the total supply. Making sure the energy mix is in alignment with the Paris agreement is imperative, and creating a framework that incentivises end-user participation will be key to accelerating this transition.

Innovation potential and possible applications

An expected result of the research conducted will be the novelty that is the application of reinforcement learning based MPC on electricity markets. This will yield an RL-MPC framework, that can give insight into and quantify the value of value stacking and of heterogeneous portfolios.

Hopefully this can result in a model that European aggregators can use to maximise profits when bidding in multiple short term markets, such as the day-ahead, intra-day and balancing markets with a focus on the upcoming market structures resulting from the collaboration between the Norwegian, Swedish, Finnish and Danish TSOs (The Nordic Balancing Model).

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Graduation Year: 2023

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Research Group: Electricity Markets and Energy System Planning (EMESP)
Co-supervisors: Arild Helseth (SINTEF) and Hongyu Zhang (University of Southampton)
Project: RES100 - Modelling a 100% Renewable Electricity System

New Methods for Analyzing a 100% Renewable Nordic Electricity System

Description of the research

The increasing share of production from variable, renewable energy sources that is currently being deployed in the electricity system is causing increased price volatility. The Nordics, and especially Norway, have a large share of hydropower that can act as an important flexible resource to help balance the renewable energy production. Through this PhD work, the impact of improved modeling of the Nordic region in a 100% renewable European electricity system will be investigated.

The objective of the PhD is to investigate new methods suited for modeling a fully renewable energy system. The focus will be on possible ways of incorporating short-term effects into long-term modeling. New methods for integrating the uncertainties in a computationally efficient way will be proposed. The multi-horizon approach to stochastic programming will be investigated as a method for combining short- and long-term uncertainties.

Innovation potential and possible applications

The PhD work will contribute to the RES100 project in establishing a new prototype power market model tailored to a fully renewable energy system. New methodologies and algorithms will be developed and built upon the existing framework. The prototype models will provide a useful tool for planning and decision making that can complement or replace existing models.

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University: Norwegian University of Life Sciences
Graduation Year: 2012

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Research Group: Electricity Markets and Energy System Planning (EMESP)
Co-Supervisors: Stein-Erik Felten (Industrial Economy NTNU) and Stefan Jaehnert (SINTEF Energy Research)
Project: Next-generation market models

PhD work title: Advanced modeling techniques for power markets with a large share of hydropower

Description of the research

The main challenge when planning hydropower operations has traditionally been to balance the uncertainty in future inflow and power demand with the risk of emptying or spilling from the reservoirs. In future decarbonized power systems, the level of uncertainty in planning will increase and flexible generation from hydropower resources are expected to become increasingly important. This necessitates modifications or even redesign of the planning tools used.

To properly valuate hydropower flexibility, a detailed description of the hydropower assets and short-term variations, in addition to the long-term uncertainty in hydro inflows, will become more important when modelling hydropower operations. Formulating the long-term hydrothermal scheduling problem as a two-stage stochastic linear problem solved in a rolling horizon using Benders' decomposition has been demonstrated to be well suited to value the flexibility in the hydropower system.

However, the approaches based on stochastic programming operate under the premise that the underlying probability distributions are accurately identified, even though future scenarios themselves are inherently uncertain. In addition, hydropower scheduling based on stochastic optimization models that focus on maximizing social welfare, may result in reservoirs being managed quite aggressively. Both aspects can result in operational strategies that are vulnerable to unexpected events in an increasingly uncertain future.

Distributionally Robust Optimization (DRO) does not rely on precise probability distributions; instead, it identifies the worst possible probability distribution within a family of distributions and performs optimization within this set called ambiguity set. Hence, DRO formulation will be more risk averse as the worst-case average cost over all distributions is optimized. The objective of this work is to explore how a DRO formulation of the long-term hydropower scheduling problem affects the long-term strategy for hydropower reservoirs.

Innovation potential and possible applications

We will evaluate if adding some robustness to the hydropower scheduling problem by using DRO can improve the strategy and give more realistic operation of hydropower reservoirs. The results from the DRO formulation are compared to the results from a stochastic formulation to demonstrate the benefits and weaknesses of our method. This will give valuable insights in the development of the next generation market models used for long-term hydropower operation in Norway.

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Graduation Year: 2014

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Research Group: Electricity Markets and Energy System Planning (EMESP)
Co-Supervisor(s): Magnus Korpås, and Irina Oleinikova
Project: HYDROGENi

PhD work title: Adaption of the Electric Energy System for Large-scale Hydrogen Production in Norway

Description of the research

Large-scale hydrogen production can be achieved via electrolysis – a process whereby water is split into hydrogen and oxygen using electricity generated from entirely renewable energy sources. This process demands the installation of energy-intensive hydrogen production facilities (electrolyzers, compressors, storage, fuel cells, power electronic converters, and other auxiliary components) that interact with the existing power grid.

Such grid-tied hydrogen production facilities do have opportunities in line with their flexible operation like grid congestion management, voltage and frequency variation adjustment, grid balancing services, seasonal, long-term energy storage provision, combined heat and power (CHP)-cogeneration offer, and power curtailment reduction. On the other hand, increased power/energy demand, grid integration difficulty, system optimization and feasibility study, project spatial allocation, and the need for massive investment are among the challenges of the same facilities.

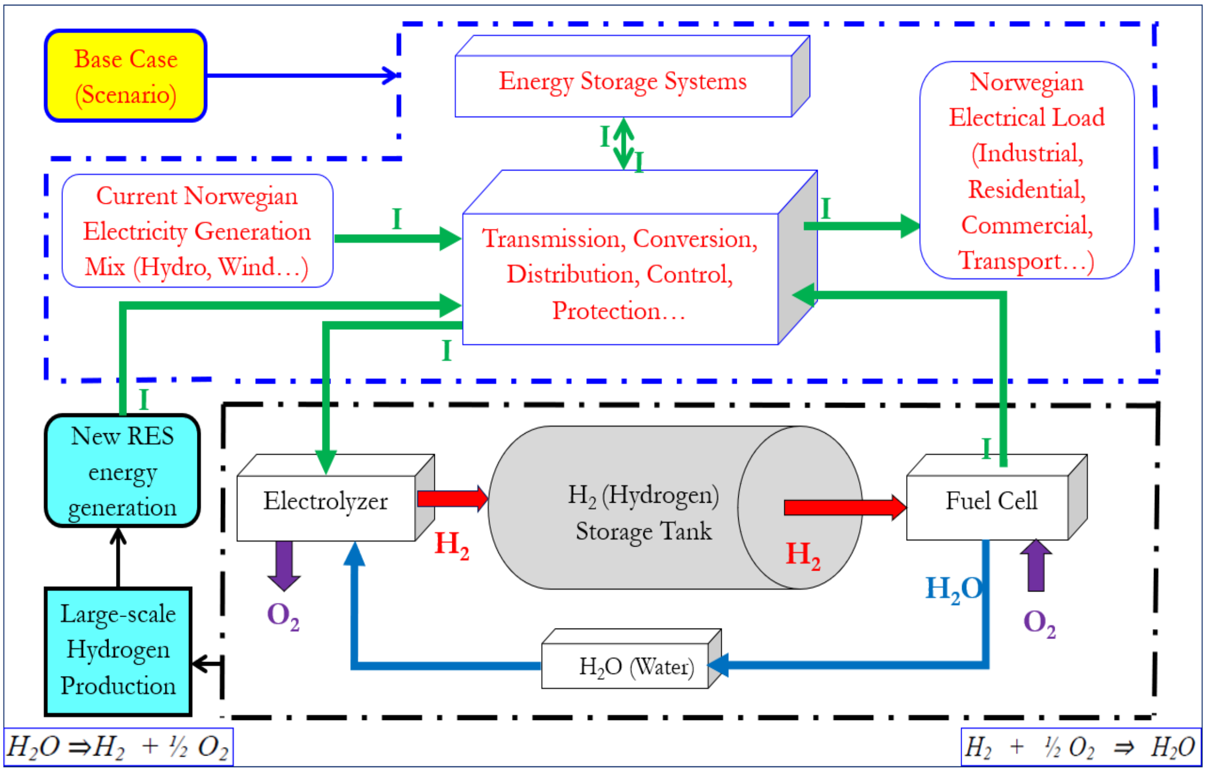

Figure 1: Large-scale Hydrogen Production Conceptualization in Norwegian Power Grid

Hence, to address these challenges and opportunities, my research revolves around the following objectives:

- Study the need for new renewable energy generation and grids to support new hydrogen installations.
- Assessment of the technical ability of hydrogen systems to provide flexibility/grid services to the energy system.
- Conduct a techno-economic analysis of the economic benefits of providing grid services versus normal operation.
- Evaluation of different energy storage technologies (H2 and/or electrical) for flexibility in production and cost containment.
- To work with actual use cases to assess e.g. the local grid constraints and operation modes of the hydrogen systems.

Innovation potential and possible applications

Ultimately, it is anticipated that the findings of this research will be highly significant for energy firms and hydrogen producers, by expanding knowledge on how green hydrogen production can be included in the energy system in a technically sound and financially viable way.

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Project: NTRANS

PhD work title: Decentralized Transmission Expansion Planning for a resilient and just Energy Transition

Description of the research

This PhD thesis focuses on developing a decentralized transmission expansion planning model designed for the Norwegian electricity grid, with broader applications to the European power system. The model prioritizes resilience, self-sufficiency, and just transitions by integrating local perspectives and addressing distributional effects.

Innovation potential and possible applications

The optimization model developed in the context of this thesis presents a novel decentralized approach to transmission expansion planning that integrates local perspectives, resilience, and fairness. The research addresses significant challenges in energy systems, such as increasing energy demand, the integration of variable renewable energy sources, and the need for just transitions. The model represents a major contribution to the field, providing a practical framework for balancing technical optimization with societal needs and contributing to a sustainable and equitable energy future.

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PhD work title: A 100% renewable energy system – is it possible? Navigating land use requirements and trade-offs between land use and integration of renewable energy.

Description of the research

One of the core strategies for achieving a climate-neutral economy is promoting renewable energy deployment. The electricity and heat sectors currently contribute about 30% of total greenhouse gas (GHG) emissions, and integrating renewable energy sources (RES) has the potential to significantly reduce these emissions. While several studies have investigated future scenarios for energy systems, most tend to focus on techno-economic aspects, which may be insufficient for understanding the future role of RES.

Moreover, recent years have seen conflicts arising from RES development, particularly concerning land use requirements and the consequences of RES development, such as loss of biodiversity or undisturbed nature. This PhD aims to understand the future role and integration of renewable energy, specifically focusing on land use requirements, addressing the following questions:

R1. How much area is needed to achieve a 100% renewable energy system?

R2. What are the trade-offs between land use and the build-up of renewable energy?

In Norway, despite favorable wind conditions, opposition to onshore wind development has led to the downscaling of existing projects and several conflicts. Nevertheless, Norway is expected to face a power deficit by 2027, coupled with increased electrification, resulting in the need for more power. As part of this PhD, I will additionally investigate the role of solar photovoltaic (PV) in the Norwegian energy system to determine what role solar PV could play in a future Norwegian energy system.

Innovation potential and possible applications

This research aims to clarify the impact of RES development and the consequences of achieving a net-zero emissions energy system by 2050, particularly in terms of land use change and requirements. It will provide valuable insights for policymakers, helping them understand how RES expansion will affect land use and the extent of land use requirements needed to meet future goals. Ultimately, I hope my research will reduce conflicts and uncertainties surrounding RES development, resulting in less conflicts related to RES expansion.

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Project: IntHydro

Hybrid Machine Learning Approaches for Explainable Reservoir Inflow Forecasting

Description of the research

Hydropower is the main source of electricity production in Norway, accounting for over 90% of the total electricity generation. With over 1600 hydropower plants in operation, it produces around 153TWh of electricity per year. Hydropower is a renewable, clean and flexible source of energy with a low carbon footprint. However, hydropower production is highly dependent on weather and environmental conditions, which leads to uncertainty in production levels. To overcome this production uncertainty, it is important to effectively estimate the future water inflow into the reservoirs. There are many existing methods to achieve this, including physical models, machine learning models and hybrid models. Even though there are high-performing machine learning models, explainable models are few. To improve the reliability of water inflow prediction, model explainability is crucial, and this project aims to address it.

The main research questions to be answered in this project are:

1. How to improve the interpretability and transparency of inflow forecasting models by integrating physical principles with machine learning approaches?
2. How can spatial and temporal factors be effectively integrated into explainable inflow forecasting models?

Hybrid machine learning-physical models present a favorable strategy for improving inflow forecasting. The ability to experiment with diverse model architectures enables a careful balancing of predictive performance and model explainability. Considering the substantial influence of catchment spatial information on inflow dynamics, its integration—through methods such as statistical analysis and graph neural networks—can lead to significant gains in both model performance and interpretability.

Innovation potential and possible applications

Explainable inflow forecasting models can be useful for hydropower plant operators. Which helps them in better decision-making and optimal hydropower scheduling.

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PhD Project	Future Renewable Energy Systems
Research Group	Electricity Markets and Energy Systems Planning
Main supervisor	Magnus Korpås
Co-supervisor	Corinna Schulze-Netzer
	Department of Energy and Process Engineering

The potential of waste-to-energy technologies for integrating with other forms of renewable energy systems, to create a more diverse and resilient energy system towards a future Renewable Energy Mix

Descriptions of the research

Under the Future Renewable Energy Systems project, the Waste-to-Energy (WtE) domain and its role will be studied. The following are the objectives of the study.

- To investigate and gain a comprehensive understanding of the existing WtE systems along with biofuel production and their role in the future energy mix.
- To access the key operational and technical challenges that arise during the integration modelling alongside evaluating the limitations of using WtE technologies.
- To model a hybrid WtE system combined with other forms of renewable energy systems and analyse the potential performance and benefits, the Trondheim Municipal Council, Norway case.
- To assess the environmental, economic, and social impact of implementing the WtE technologies, and identify potential mitigation measures to minimise negative impacts.

To fulfil the objectives, the study will answer the following research questions.

- What are the current WtE technologies and their potential to generate electricity, heat, and biofuels in Norway?
- What are the current operational and technical challenges of integrating WtE systems with variable renewable energy sources such as wind and solar, and how can they be addressed to improve the flexibility of the overall energy systems in Norway?
- How can the integration of energy storage systems with WtE systems improve the flexibility and reliability of the overall energy system in Norway?
- What is the potential of WtE systems in producing biofuels in Norway, and how can they be maximised to contribute to the renewable energy mix?

Innovation potential and possible applications

- The study during the Phd period aims to provide a diverse decision-making tool (Multi-criteria Decision Analysis) for selection of the best waste-to-energy technology combinations to improve the municipal solid waste management and maximise the use of energy content from waste streams
- Furthermore, the innovation lies in applying a structured, multi-criteria AHP methodology to simultaneously optimize technological performance, economic feasibility, environmental sustainability, and socio-cultural acceptance in retrofitting CCS units to waste incineration plants.

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Co-Supervisor(s): Karen Byskov Lindberg
Project: COFACTOR

PhD work title: Data-driven Load Disaggregation and Building Load Profile Classification.

Description of the research

The focus of the Ph.D.-project is disaggregation and classification of HVAC-loads (domestic hot water, space heating, other appliances, etc.) and EV-charging from the AMS-meter data of buildings. The main research questions are;
R1. How can aggregated energy metering be disaggregated into typical load profiles per energy service?
R2. How can building load profiles be classified based on disaggregated load data?

Innovation potential and possible applications

The methods developed in the project could be used to improve the methodology for calculating the peak load of buildings, improve the commercial standard NS3032, and the methodology for calculating the peak load element in the energy label of buildings. The methods could also be used for improving commercial products for load disaggregation and classification of building energy loads

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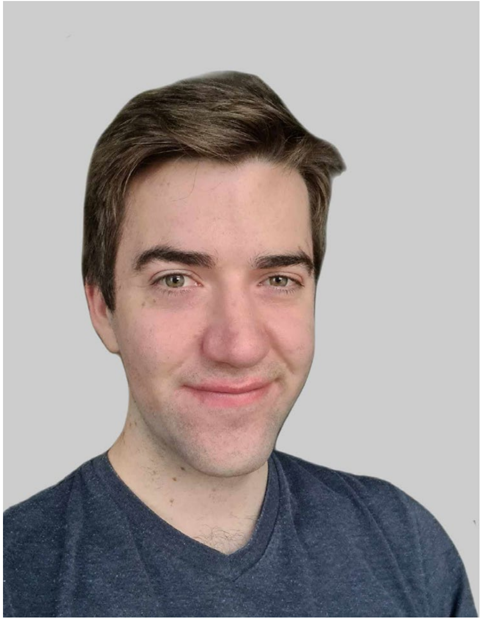

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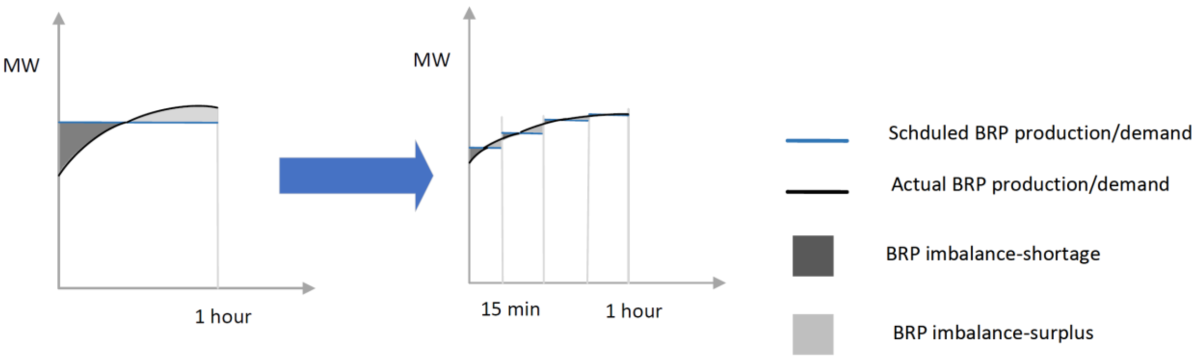
Co-Supervisors: Masood Parvania and Christian Naversen

Flexibility Coordination in Sub-Hourly Power Systems Balancing

Description of the research

In the transition towards a low-carbon future, massive amounts of variable renewable energy sources are expected to enter the power system. However, the intermittent nature of RES challenges the system-security the flexibility of conventional generators is pushed to its limits.

Currently the Nordic system operators are working on establishing a new Nordic Balancing Model. Among other things, the new Nordic Balancing Model changes the the day-ahead market resolution from hourly to a 15-minute time resolution. This helps reduce the need for balancing, as shown in the figure below, but also poses challenges to the established process of conducting balancing coordination manually. The system operators must handle these challenges by digitizing and increasing automation.



The purpose of this PhD project is to develop model tools that can aid decision-makers in coordinating balancing of the interconnected North European power system. A promising method for examining and reducing structural imbalances in a system with hydropower and thermal generation is using a continuous-time commitment model. Continuous-time optimization represents parameters and variables as polynomials by expressing them as a linear combination of Bernstein basis-polynomials, thus eliminating the need for instantaneous jumps from one timestep to the next. This approach is computationally demanding, so one of the objectives in the PhD is to employ decomposition-techniques and scale it to a realistic Nordic system.

Additional objectives in the PhD will be:

- Reflecting sub-hourly balancing in the system dispatch (day-ahead market clearing). This will allow the day-ahead dispatch to efficiently manage power system flexibility by adequately utilizing ramping resources.
- Investigating the impact of power grid bottlenecks in sub-hourly system balancing and estimating optimal flow-reliability margins on transmission corridors.
- Incorporating short-term uncertainty in a fundamental continuous-time power market model.

Innovation potential and possible applications

This research could help reduce the cost of balancing the power system by reducing the structural imbalances resulting from discrete time resolution in the in the day-ahead market. This will directly benefit Transmission System Operators, but it could also benefit other market participants in the day-ahead, intraday, or balancing markets by informing better bidding strategies and increasing income.

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Project: SusHydro

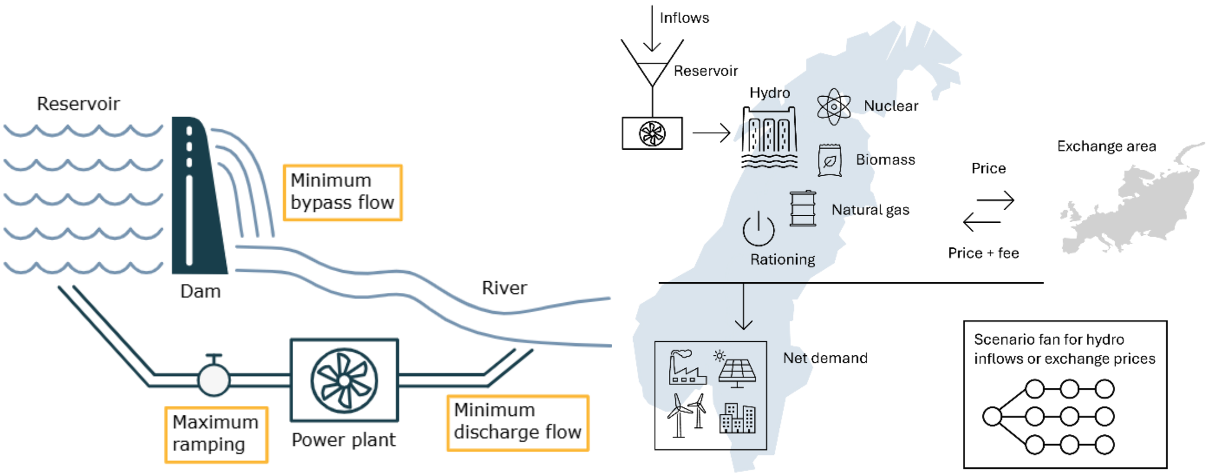
Hydropower in future power systems: challenges and opportunities for policy

Description of the research

In the face of both the climate and biodiversity crises, power systems are undergoing significant transformations. Extreme events induced by climate change amplify the pressure on its infrastructure and the uncertainty in its planning. Meanwhile, policies aimed at mitigating the environmental crises impact power plant operations. They also accelerate the economically induced shift of power mixes towards renewable energy sources and away from fossil fuels.

Hydropower, typically a cheap technology with low GHG emissions, can play an essential role in these future power systems. Its storage and flexibility potential are gaining value with the decommissioning of dispatchable thermal plants and the rise in intermittent VRE generation. However, hydropower is vulnerable to floods and droughts, the frequency of which is set to increase with climate change. This may compromise the reliability services that we hope it can offer.

But what role exactly should hydropower play in future power systems? Is the current power market design fostering the most efficient use of hydropower? What policies and market design should be put in place to ensure hydropower achieves its potential in supporting future power systems in a sustainable way? This Ph.D. tries to contribute to answering those difficult questions through the angle of reconciling society's and private producers' interests in liberalized markets.



More specifically, I look at how hydropower plants and the power system respond to stricter environmental constraints in the context of the transition to high shares of variable renewable energy sources. I also investigate how rising uncertainty in power systems impacts hydropower management and energy security in hydropower-rich regions. Finally, I explore the implications of different policies targeting energy security when applied in those regions.

Innovation potential and possible applications

We should ensure that an institutional framework and economic incentives are present for sustainable, reliable, and affordable hydropower operation, within environmental constraints. This PhD hopes to give policymakers and relevant authorities insights on policy and market design that would foster efficient use of existing hydropower in future power systems.

High Voltage Technology (HVT)

The main research activities of the group are related to the design, modelling and operation of electric power components. With close working links with industry, research into better insulation materials, both for ac and dc, is being conducted. There is ongoing research and development of new technology and expertise in the following fields.

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Project: New Gases for GIS

Ageing of New Environmentally Friendly Insulation Gases

Description of the research

SF_6 has been used as the preferred insulation medium in most of the gas insulated switchgear (GIS) in operation since 1960s. However, being an extremely stable compound, SF_6 molecules have an atmospheric lifetime of 3200 years and a global warming potential (GWP) 25,200 times higher than that of CO_2 over a 100-year time horizon. Due to its high GWP, alternative gases are being investigated to replace SF_6 in electric power applications. C5-fluoroketone (C5-FK) and C4-fluoronitrile (C4-FN) are found to be very promising in this regard in addition to natural origin gases like nitrogen (N_2), oxygen (O_2) and carbon dioxide (CO_2).

The insulation gas in a GIS may experience partial discharges (PD), dielectric breakdowns and electric arcing which may lead to decomposition and ionization of the gas. Unlike SF_6, the by-products created from the new insulation gases may not recombine and the dielectric properties may change over time, resulting in gas degradation and ageing.

'New Gases for GIS – long-term reliability and fundamental understanding of insulation properties' is a project led and coordinated by SINTEF Energy Research, where NTNU is one of the research partners along with other international research institutions, gas and switchgear producers, and grid operators. The fundamental characteristics and long-term dielectric performance of the new environmentally friendly insulation gases (e.g., C5-FK and C4-FN mixtures) for medium and high voltage GIS are being investigated in this project for future assurance of a safe and sustainable power grid. This PhD research lies within the scope of this project where the impact of different types of electrical discharges leading to ageing is investigated on long term dielectric performance and chemical decomposition to develop a knowledgebase for condition assessment and safe operation. The main scopes of the PhD research can be summarized as follows.

- Investigation of ageing of C5-FK and C4-FN gas mixtures in addition to natural origin gases (e.g., dry air and CO_2) by means of medium voltage (MV) and high voltage (HV) arcing and PD tests simulating real-life scenarios.
- Evaluation of the effect of ageing on the long-term dielectric performance by conducting AC, positive lightning impulse (LI+) and negative lightning impulse (LI-) breakdown tests before and after the ageing process.
- Investigating gas decomposition via gas chromatography coupled with mass-spectrometry (GC-MS) and spectroscopic method, namely, Fourier Transform-Infrared Spectroscopy (FTIR) in case of solid by-products accumulation at the electrode surface.

Innovation potential and possible applications

The expected lifespan of a typical GIS is several decades, and early degradation of the equipment would entail considerable risks to the grid operators. Therefore, extensive research is needed to investigate the effect of ageing while introducing the new environmentally friendly insulation gases to the electric grid. Based on the findings of this PhD project, it will be possible to anticipate the change in gas density or insulation performance as the composition changes when exposed to electric discharges. This can serve as a useful tool for condition assessment of the gases and the findings will help in establishing guidelines for design and development of new SF_6-free GIS.

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Project: New Gases for GIS

Characterisation of discharges in new environmentally friendly insulation gases for switchgear

Description of the research

Gas-insulated switchgears (GIS) are used in the power grid for interrupting the current during faults and maintenance, and for changing the grid when required. Sulphur hexafluoride, SF_6, is used as the insulation gas in most operating GIS. This gas has excellent properties from a technical point of view: it is not poisonous, non-flammable, has high dielectric strength, and is able to interrupt the current with a significantly shorter distance between the conductors than for instance air is able to, thus reducing the size of the installation. Unfortunately, SF_6 is an incredibly potent greenhouse gas with an approx. 25 000 times higher global-warming potential (in a 100-year perspective) than CO_2. Other gases and gas mixtures are therefore being considered as replacements for SF_6, and there is already switchgear with alternative gases commercially available. The behaviour of these new gases is, however, not fully understood. In order to replace SF_6 in GIS, whilst still maintaining security of supply, the performance (both long-term and short-term) and the ageing of the gases and gas mixtures used as replacement have to be studied further.

The two main objectives of this PhD-project are to:

- Achieve a fundamental understanding of electrical discharge behaviour of new gas mixtures for GIS through experimental testing.
- Develop accurate computational models of the electrical breakdown processes in new gases.

How the polarity affects the streamer inception in air, for an inhomogeneous field, has become the main focus of this PhD. A polarity dependence for streamer inception probability was observed for air when the field was very inhomogeneous, see figure below. The physical explanation for this has been investigated and a simulation model has been made to explain it. You can read more about this in our publication *Streamer inception probability in air at atmospheric pressure – an experimental and theoretical analysis* (by Skirbekk et al., published in Plasma Sources Science and Technology). I am currently looking at the statistical time lag for streamers in air at different pressures, and how the polarity dependence of the time lags is affected by pressure.

The streamers have also been imaged using a high-speed camera. You can see an example image of a negative and a positive streamer in air (both at 1 bar absolute pressure) below.

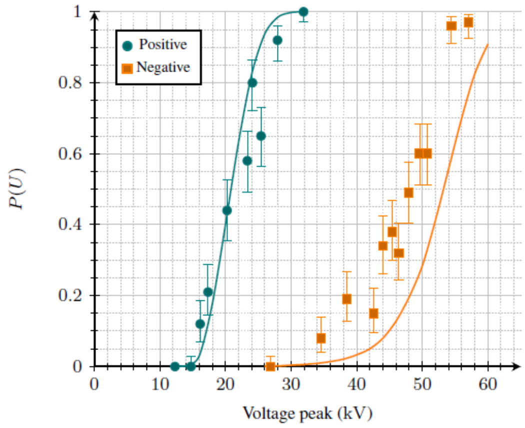

Figure 8. Streamer inception probability. The scatter points are the probabilities measured in the lab using equation (21), with error bars indicating the 95 % confidence interval, and the lines are the results from the baseline simulations.

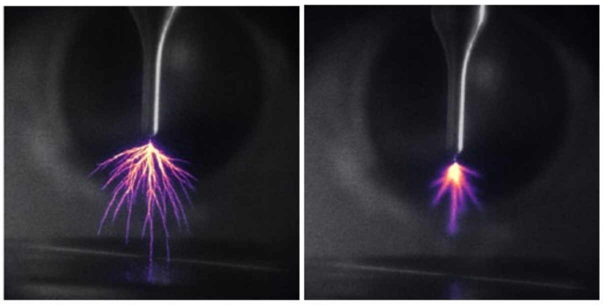

Figure 5. Example images of positive and negative streamers in the experiments. Left: Positive streamer for a peak voltage of $|V_{\text{peak}}| = 25.4\,\text{kV}$. Right: Negative streamer for a peak voltage of $|V_{\text{peak}}| = 54.4\,\text{kV}$.

Innovation potential and possible applications

The research findings are expected to clarify the pre-breakdown and breakdown mechanisms in environmentally friendly substitute gases for MV and HV switchgear. This can help develop tools for condition assessment of GIS insulated with new gases. This will make GIS with the new gas mixtures more reliable, which in turn will make the grid more reliable and reduce the need of SF_6-insulated switchgears.

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Graduation Year: 2022

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Project: FreeSwitch

PhD work title: Pre-breakdown and breakdown mechanisms in natural origin gas insulation systems

Description of the research

Gas-insulated switchgear (GIS) are used in the electrical grid for interrupting the current during faults and maintenance. For decades, sulfur hexafluoride (SF6) has been the state-of-the-art insulation gas for high and medium voltage GIS. However, it is known for being the most potent greenhouse gas know to date. Consequently, the EU has decided to strictly regulate the use of SF6 and other F-gases in medium-voltage switchgear, effective from January 1, 2026. Among the most promising alternatives are high-pressure natural origin gases (NOG) such as air.

Traditionally, the pressure range used for high-voltage applications has been more explored than that relevant for medium-voltage applications. There is a knowledge gap concerning the dominant mechanisms in the pressure range of 1-3 bar absolute for air. It is expected that several discharge mechanisms scale with the product of distance times pressure. Another knowledge gap pertains to critical design areas found in switchgear such as triple junctions, where gas, dielectric material and metal meet. How discharge phenomena in triple junctions scale with pressure has yet to be fully understood. The aim of my PhD is to address some of these questions through experiments and simulations.

Innovation potential and possible applications

The findings of the PhD project are expected to enhance our understanding of the insulation system used in the new eco-friendly product portfolio for medium-voltage GIS. Manufacturers can leverage this knowledge to develop future products, making the grid more reliable and safe without relying on SF6.

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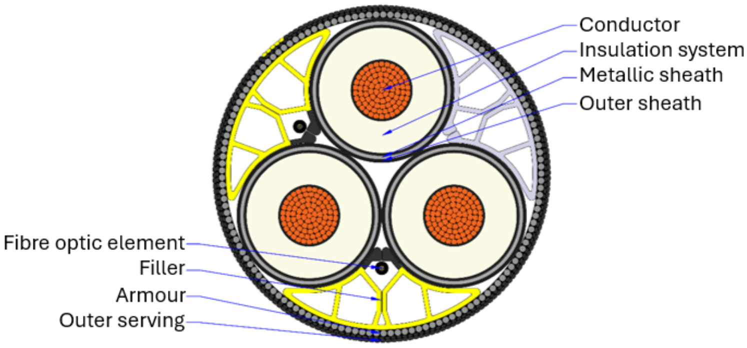
Project: NFR Industrial PhD – Electromagnetic modelling of high-voltage power cables

PhD work title: Electromagnetic modelling of high-voltage power cables

Description of the research

Since the early 2010s significant improvements have been made in electromagnetic modelling of armoured three-core cables, with the aim of improving the accuracy of current rating calculations. The cross-section of such a cable is depicted to the right.



The avalanche of activity on this topic was initiated by an industry realization that the IEC 60287 standard tends to overestimate armour losses, in some cases quite drastically. Various methods have been proposed, and in 2023 a recommendation by CIGRE in the form of Technical Brochure (TB) 908 was published.

However, TB 908 and other published work on the topic have revolved around current rating calculations, i.e. power frequency and positive sequence operation. In addition, the published work has almost exclusively focused on cables with a single layer of round wire armour. Other common armour designs include a single layer of flat or rectangular wire, and two layers of either round wires or flat wires.

A few knowledge gaps can immediately be identified:

- Modelling armour consisting of a single layer of flat wires, two layers of round wires or two layers of flat wires for current rating applications.
- Methods for modelling cable armour that are applicable for both positive-/negative- and zero sequence excitation.
- Wideband models applicable for all four armour combinations and any excitation.

Some of these gaps forms the research questions for the project.

The project is an industrial PhD-project funded by Nexans Norway AS and The Research Council of Norway.

Innovation potential and possible applications

It is expected that if objectives are reached, the PhD-work will contribute to an improvement of the state-of-the-art model representation for armoured three-core cables. Specifically, improvements will be made in the calculations of series impedance and loss calculations. The work may broaden the range of cable designs that can be accurately modelled.

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Co-supervisor: Camilla Espedal (SINTEF Energy Research)
Project: New Liquids for Transformers (NewLift)

PhD work title: Investigating Different Properties of New Insulating Liquids for Power Transformers

Description of the research

The research aims to enhance the knowledge and decision-making processes of manufacturers and users of transformers that utilize the new environmentally friendly "Biodegradable" insulating liquids as alternatives to the non-biodegradable mineral oil. The research will focus on studying the thermal properties of these fluids and their performance.

Innovation potential and possible applications

The research will provide knowledge and fit-for-purpose models to accurately assess the thermal performance of the alternative dielectric liquids for power transformers, which will mitigate risks and uncertainties and facilitate the utilization of the next-generation functionally improved insulating liquids.

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Research Group: High Voltage Group

Co-Supervisor: Bruce Mork

Project: WP5 of ProDig project

Performance and Reliability Assessment of vPAC in a Digital Substation

Description of the research

Substations are vital nodes in an electrical grid infrastructure. Advancement in computing and communication technology has pushed the developments in the field of electric power engineering. These enabling technologies has set the directions of research towards smart grid technology. Socio-economic factors have further accelerated the pace of this grid transformation and digitalization. IEC61850 standard is central to this transformation of digitalizing a substation. The standard virtualizes a substation by introducing a comprehensive data model along with the services to exchange this data. In addition, virtualization technology has already proved its utility in the IT sector, its usefulness, however, demands a careful and thorough analysis before deployment in critical infrastructures i.e. electrical power grid.

The most prominent challenges to convert a conventional substation into digital are:

- Reliability assessment of Digital Substation (DS) vs conventional substation in the presence of communication system and functional integration.
- Proposing, assessing and developing new methods and system tools that supports and requires throughout the life cycle of vPAC based DS.

The scope is very wide even in the context of a DS from design and engineering to operation and maintenance of vPAC based DS. The WP5 of the ProDig project aims at addressing some of these challenges with a focus on its performance and reliability. Introducing new methodologies to conduct the vPAC based DS reliability will assist in choosing the system architecture with desirable or acceptable system reliability and performance levels especially at the design and engineering stage. Thus ensuring a high level of confidence and strong degree of determinism on the performance of the mission critical system.

Innovation potential and possible applications

This research aims at developing or devising the new tools, methods, and techniques to use at various stages of design, engineering, commissioning, and operation of vPAC in a DS.

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Co-Supervisor: Nina Sasaki Støa-Aanensen
Project: MISSION - eMISsion-free HV and MV transmisSION switchgear for AC and DC (Horizon Europe Project)

PhD work title: Characterization of Short and Rapidly Elongating Arcs for Fast Current Commutation in MVDC Circuit Breakers

Description of the research

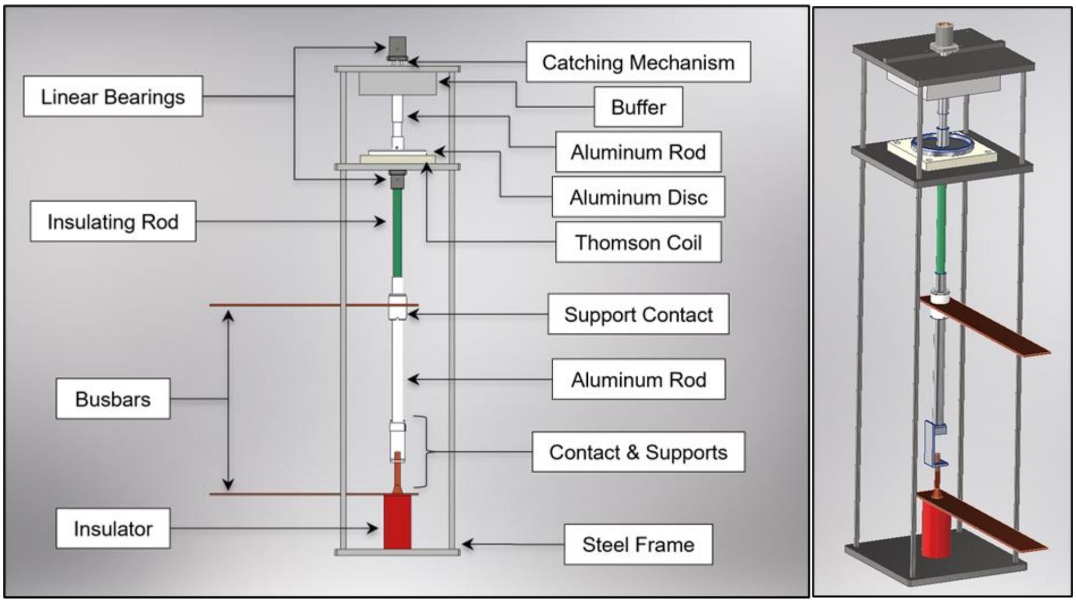
MVDC grids are part of the future power distribution system and have the potential to collect renewable energy sources more effective and cost-efficient. However, circuit breakers for DC are demanding faster switching because of high fault current rise rates and they are more complex to develop because of the missing zero current crossing in DC systems. Recent concepts are using an ultra-fast mechanical switch in form of a Thomson coil actuator (TCA) to commutate the current into a parallel capacitor to break the circuit. The success of the commutation is strongly dependent on the voltage of the arc forming between the contacts of the switch. To understand and optimize the switch and the commutation process, a thorough understanding and characterization of the arcs that occur is necessary. This includes the dielectric recovery of the switching gap as well.

Experiments will be carried out in the high current laboratory in order to characterize short and rapidly elongating arcs by means of different measurements. The research also includes the development of arc models to determine the arc voltage as a function of interruption current. The influence of current, contact material, contact velocity and other influential factors is investigated.

The following specific objectives apply to the PhD project:

- Physical characterization of the arcs and the previous metal vapor discharge
- Evaluation of the dielectric recovery of the electrode gap after arc extinction
- Development of models to describe the arcing, the dielectric recovery and the influence on the commutation process

Lately, the revamp of NTNU's Thomson coil actuator (TCA) is in the focus of my work. The following pictures show the mechanical design of the new drive.



This PhD research is expected to provide new knowledge about the to date little researched rapidly elongating arcs and, thus, enable a more effective and cost-efficient circuit breaker technology for the power market.

Innovation potential and possible applications

MVDC grids are not established in the power system of today and MVDC circuit breakers are not yet commercially available. However, in the future MVDC could be used for the collection of offshore wind energy, local solar power systems, onboard systems of ships, rails systems, gas and oil rigs, mines urban areas with a lot of DC consumers (e.g. university campuses) and local networks for huge data centers. Therefore, MVDC circuit breakers are interesting for the operators of future MVDC power grids. Standards for MVDC grids are on their way now while research on MVDC circuit breakers has been conducted over many decades. MVDC circuit breakers have been developed under utilization of SF_6, vacuum or power electronics in the past. The MVDC circuit breaker based on current commutation by an ultra-fast mechanical switch aims to get by without these and thereby saving costs (OpEx as well as CapEx) and space. The research conducted in the PhD project is supposed to be useful for the design and development of this type of circuit breakers for research organizations and circuit breaker manufacturers, while at the same time providing general knowledge about switching arcs and electrical contacts.

Power Electronic Systems and Components (PESC)

The research activities of the group are related to the development, design, optimization and control of power electronic converters and systems. The goal is to provide innovative high efficiency environmentally friendly solutions within production, distribution, and use of renewable energy. This includes application areas such as onshore and offshore power systems, marine, oil & gas as well as transportation sectors.

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Graduation Year: 2022

Main supervisor: Elisabetta Tedeschi
Research Group: PESC
Co-supervisor: Gilbert Joseph Bergna Diaz
Project: SAFER collaboration

PhD work title: Stability and control of large offshore power plants

Description of the research

The offshore wind energy industry has grown rapidly in recent years, with projections for further expansion. For instance, the European Network of Transmission System Operators for Electricity (ENSOE) nearly doubled its offshore wind capacity from 2015 to 2023. Floating offshore wind, following the success of Hywind Scotland, has opened new markets. The Norwegian government plans to install 30 GW of offshore wind by 2040, much of it floating installations. The sector will play a key role in a decarbonized energy future.

Most modern offshore wind turbines are Type IV, with full power electronics interfaces that decouple grid and generator frequencies. However, these converters have low electrical inertia, which can cause stability issues. As inverter-based generation increases, grid stability may be compromised. Several real-world instability events have been observed, such as harmonic oscillations in Europe and subsynchronous oscillations in Germany due to converter interactions. These issues are expected to persist as converter-based generation grows.

Instabilities can occur across a wide range of frequencies, from subsynchronous to supersynchronous, due to factors like control loop interactions, nonlinear functions, and resonances. Variations in topologies, control strategies, and grid conditions complicate stability, especially as control strategies shift during operation. Assessing potential stability issues and the impact of grid changes is crucial for further renewable energy integration.

This PhD work aims to develop methods for modeling harmonic instabilities and identifying critical parameters that may lead to instability, providing insights into prevention and mitigation strategies.

Innovation potential and possible applications

By developing methods to model and mitigate harmonic instabilities, the research can be applied to the design and operation of future offshore wind installations, ensuring their integration into the power grid without compromising stability. It will be valuable for wind farm developers or operators and grid operators looking to expand renewable energy capacity. Additionally, the findings could help policymakers and engineers optimize grid infrastructure and control strategies to support large-scale offshore wind adoption, contributing to a more stable and decarbonized energy system. Some of the innovations may be applicable to wider converter-based grid-connection such as solar PV or HVDC applications.

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Supervisors	Prof. Roy Nilsen (Main Supervisor) Prof. Marta Molinas Dr. Mohammad Amin (external)
Research group	Power Electronics Components and Systems (PESC)

Working title: AI-based techniques to understand the underlying mechanism leading to small-signal instability in a system dominated by power electronics.

Description of the research:

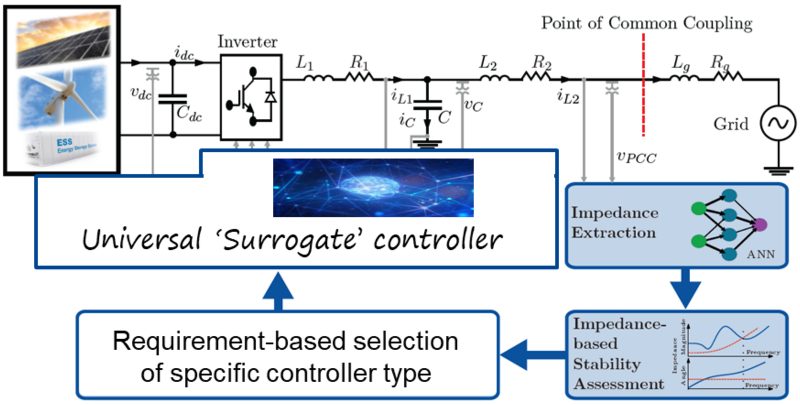

Figure 1

In this PhD project, from the broad perspective, focus will be on improving small-signal stability of grid-tied converters under varying operation points. The overall system consideration for this research work is shown in Figure 1. Each of the blocks is being studied, analysed, and enhanced to improve system performance.

For the impedance extraction, different data-driven methods will be studied and analysed. Based on the impedance extraction, small-signal stability analyses will be performed. During the stability analysis, particular focus is given to a coupling between impedances in the synchronous reference frame. Based on the stability analysis results, suitable controller will be selected to satisfy grid functionality requirements with stable operation.

Innovative potential and application:

Combining data-driven methods with stability enhancement can enable fast response of power electronics converter to any unforeseen unstable operation. A part of this work is useful for the transmission as well distribution service provider and other part is useful for converter manufacturers.

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Research Group: Power Electronic Systems and Components (PESC)
Co-Supervisor(s): Rui Henriques (INESC-ID) and Hugo Morais (INESC-ID)
Project: InnoCyPES - Innovative Tools for Cyber-Physical Energy Systems

Power quality monitoring in electric grid integrating offshore wind energy

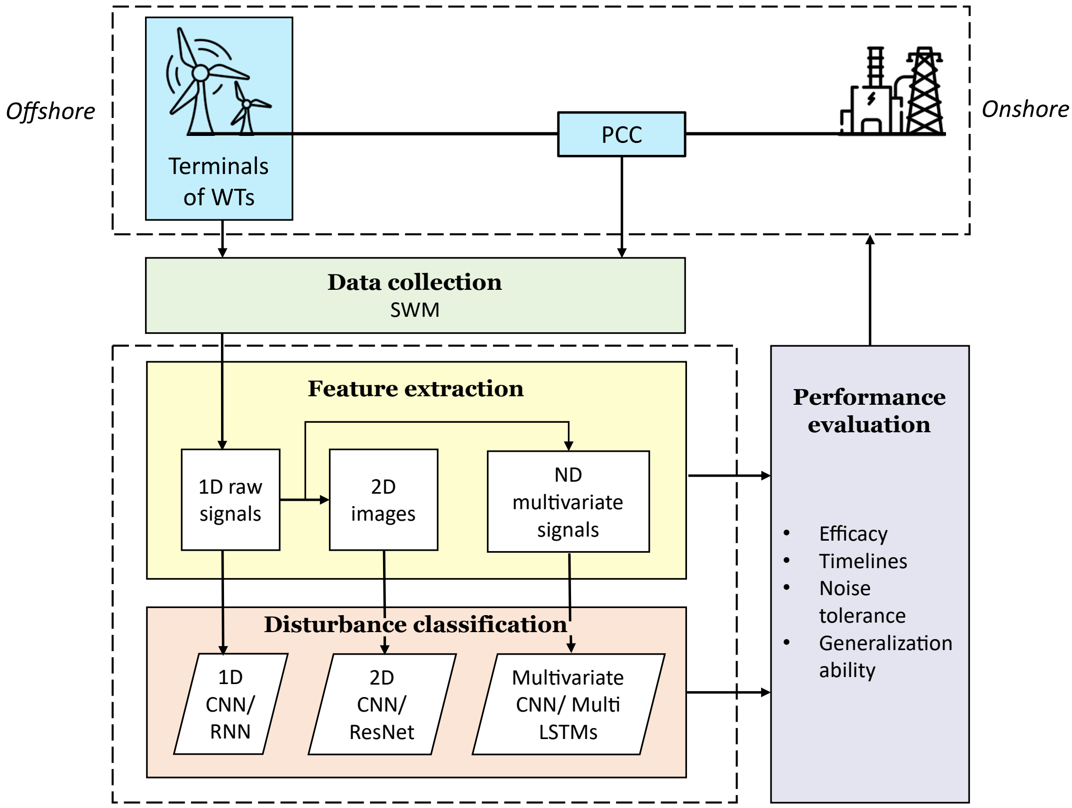
Description of the research

The rising integration of offshore wind energy into the electric grid provides remarkable opportunities in terms of environmental sustainability and cost efficiency. However, it poses challenges to power quality (PQ) caused by variable operational events and power electronic devices used in wind turbines (WTs). PQ concerns, including transient, flicker, harmonics, sag, swell, and interruption, have garnered significant attention due to their potential to cause issues such as inaccurate metering, line overheating, and maloperation of protection devices, which can result in heavy maintenance costs. This renders early-stage disturbance detection and classification tools critical for managing grid systems with renewable energy sources.

This Ph.D. project aims to develop a coordinated system-level PQ analysis framework for electric grids integrating offshore wind energy. Specifically, the targets related to this project are outlined as follows:

- A data processing workflow is established to facilitate real-time disturbance detection and classification. The proposed monitoring method utilizes signal processing algorithms and deep learning mechanisms to offer a holistic assessment of complex power systems.
- Synchronized waveform measurement (SWM), an emerging high-fidelity measurement technique capturing realistic network transients and dynamic responses, is employed for integrated quantitative analysis at both the point of common coupling (PCC) and WT levels. The signal characteristics of the SWM are fully exploited to develop stochastic modeling approaches, ensuring sensitivity to system-specific PQ problems arising from the grids in conjunction with wind farms.

- A comprehensive assessment scheme encompassing multiple evaluation metrics is presented to evaluate the generalization ability of monitoring algorithms and uncover underlying actionable information.



Innovation potential and possible applications

This project can potentially support system operation and control strategies, contributing to reliable and continuous power supplies. Advanced disturbance detection and classification techniques can empower grid operators and wind farm owners to make informed decisions, reducing maintenance costs and improving energy production reliability.

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Energy Storage Sizing/Control for 100% Renewable Supplied Isolated Grids

Description of the Research

The objective of this PhD project is to study the potential benefits brought by a suitably selected combination of different Renewable Energy Sources (RESs) and Energy Storage Systems (ESSs) in meeting the local power needs of a target Isolated Power System (IPS).

The use of RESs is commonly considered one of the possible solutions for meeting the growing energy demand sustainably since it is expected that their use will contribute to reducing the reliance on traditional fossil fuels in certain applications. However, this technological shift also presents challenges related to the intermittency of primary resources and grid stability. Among the possible solutions, one approach is the simultaneous use of different primary energy sources (i.e., hybridization) and various ESSs. This allows for the exploitation of the temporal and spatial complementarity of different resources and energy storage technologies to ensure a stable power supply to the grid.

A key novelty of this study is the simultaneous consideration of both well-established energy sources, such as wind and solar power, alongside emerging ones, such as wave and tidal energy. The latter, in particular, offer valuable advantages in terms of predictability and availability.

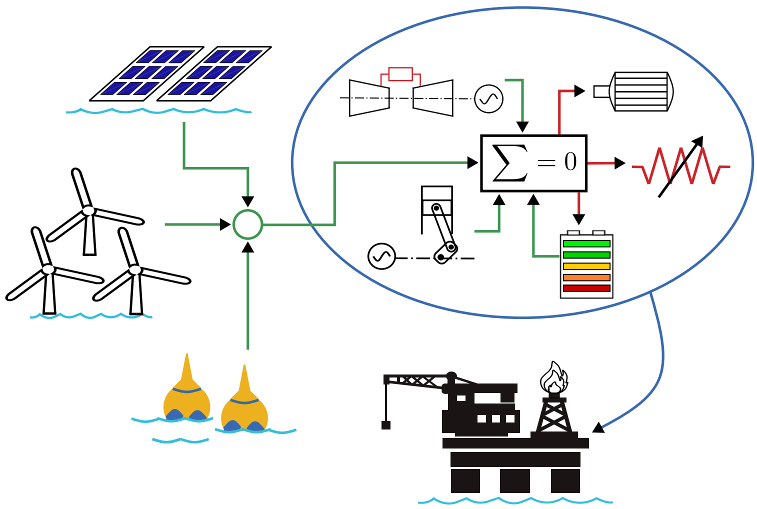
The research is divided into two main parts. The first part focuses on the development of a data-driven tool to support investment decisions for an optimal power generation mix that best matches the demand patterns of a specific use case. The second part aims to identify the most cost-efficient way to operate the proposed system, ensuring that the target grid is supplied exclusively with renewable energy sources.

In summary, this study will investigate how an ESS should be sized and controlled to enable the smooth integration of multiple RESs into isolated power systems. The goal is to create systems that are completely independent of fossil fuels while remaining resilient under various environmental and operational conditions.

Innovation Potential and Possible Applications

This research will generate new knowledge on the optimal and safe operation of fully RES-based IPSs. The findings will contribute to the development of guidelines and algorithms for the sizing, control, and operation of such systems. In particular, decision-support tools for the sizing and control of RESs and ESSs in IPSs will be developed. These tools will assist decision-makers in optimizing investments and accelerating the green transition of polluting power systems.

Although the research will initially focus on specific IPS test cases, such as an offshore oil rig, the proposed methodology is expected to be general enough to be applied to any IPS.



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Research Group: Power Electronic Systems and Components (PESC)
Co-Supervisor: João Henrique de Oliveira
Project: Petronas project

Coordinated Converter Control for Stability and Power Quality in Inertia-Less Grids

Description of the research

In a low inertia autonomous power system (APS), dominated by converter-interfaced energy sources, stability and power quality must be guaranteed over multiple operating conditions. Achieving this is a much more complex challenge than in conventional power systems for several reasons. Converters are fast-acting devices that introduce fast electromagnetic dynamics into the power system leading to a new category of harmonic resonance and converter-driven stability issues.

In this research, the integration of renewable energy sources through grid-forming (GFM) controllers will be explored mainly as it allows converters to regulate the voltage and frequency at their terminals, unlike grid-following converters whose voltage reference is provided externally. The study will investigate converter-driven stability issues of an isolated low-inertia APS of an oil and gas platform and the shared responsibility of GFM controllers when operating with a mix of converter-interfaced assets. These include converters with different control strategies, energy storage systems and controllable loads. The scope also includes how the different assets can be coordinated to share grid services such as real and reactive power injection and power quality. The control is therefore hierarchical as stability and power quality must be ensured at a local level and coordination needs to be performed at a secondary level as shown in Figure 1. The tertiary level of control is not considered for the APS in this work.

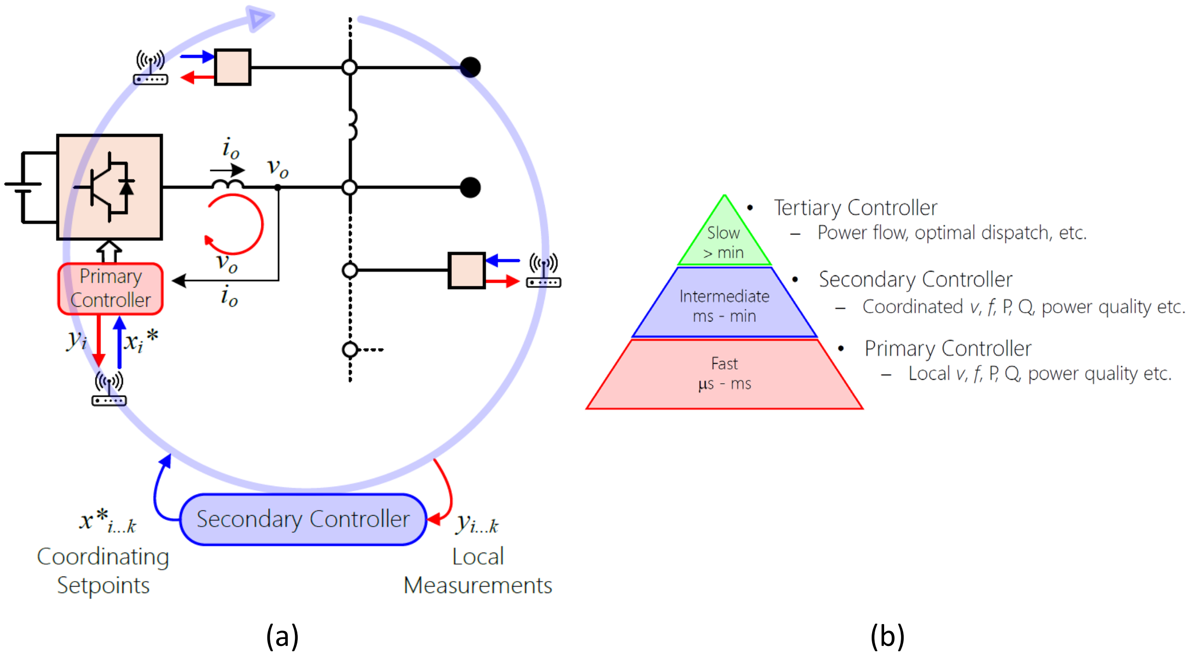

Figure 1: (a) Converter hierarchical control strategy and (b) general hierarchical control levels

Innovation potential and possible applications

With the research, the aim is to elaborate a holistic coordinated control strategy that guarantees stability and power quality of a low-inertia APS under multiple operating conditions by optimally utilising the available controllable converter-interfaced assets. The work will be relevant for isolated power systems such as oil and gas platforms that aim to increase their share of renewable-based energy sources. Recommendations will also be made on how the developed coordinated strategy can be utilized in other contexts.

Power System Operation and Analysis (PSOA)

The main research areas of the group are related to the planning, operation, control, and analysis of power systems, with applications in smart grids, transmission, and distribution grids, microgrids and HVDC systems.

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Research Group: Power System Operation and Analysis (PSOA)
Co-Supervisor(s): Kjetil Uhlen
Project: Advanced System Protection and Control Schemes

Design and Implementation of an Adaptive System Integrity Protection Scheme for Frequency Stability in Low-Inertia Power Systems

Description of the research

Low-inertia power systems pose significant challenges to power system stability, necessitating the implementation of Fast Frequency Reserves (FFR). This research addresses the optimization of FFR in low-inertia systems by introducing advanced System Protection Schemes (SPS) control algorithms.

The impact of reduced inertia on system dynamics is analyzed, and gaps in FFR optimization are identified. Case studies are focused on system stability and frequency response under various scenarios. Insights gained from these studies are discussed, highlighting the challenges for future low-inertia power systems.

To address these challenges, the research proposes advanced SPS control algorithms for FFR optimization in low-inertia systems, including adaptive generation power adjustment and load-shedding strategies. It explores the principles of the adaptive control algorithms and emphasizes their potential for improving FFR performance. Conventional FFR techniques and the proposed algorithms are compared. Evaluation metrics are used to assess SPS performance, including response time, accuracy, stability, and reserve capacity. Wide-area protection and control using OPAL-RT and RTAC are employed to validate the proposed method further, incorporating Phasor Measurement Unit (PMU) measurements. The real-time data from PMUs are utilized to validate the SPS performance under various conditions.

The findings from the case studies, simulation analysis, and real-time experiments will be discussed to underscore their implications for low-inertia power system design and operation.

This research highlights the significance of the advanced SPS in optimizing FFR for low-inertia power systems. It emphasizes frequency stability and grid performance improvement, providing a foundation for future advancements in this field.

The main objective of the project is to develop new knowledge, methods, and tools for digital control and protection of power transmission systems based on PMU data to improve system stability and robustness to contingencies. This will contribute to the future stable and secure operation of power systems with an increased share of renewable generation. This research develops algorithms and methods for real-time system stability improvement and response-based centralized System Protection Schemes (SPS) using IEEE C37.118 synchrophasor measurements and the IEC61850 standard.

Innovation potential and possible applications

The developed algorithms and solution methods can effectively be applied in electric power utilities, TSOs, and DSOs. They can also be used to develop new devices for smart grids. Possible applications include power system planning and analysis, power system operations, power system monitoring, protection and control at control centers, etc.

Substation level Control center level

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Graduation Year: 2022

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Research Group: PSOA
Co-Supervisor: Babak Abdolmaleki

Distributed Resilient Control of DC Microgrids under Scalable Stability Guarantees

Description of the research

Modern power grids are evolving into multi-agent converter-dominated grids, emerging as a strategic solution for the profitable and effective integration and management of renewable energy sources (RES). DC power systems are both compatible with the DC nature of RES and modern electric generations and loads, and offer simpler dynamics, control and management. From a control perspective, it is crucial to develop new control schemes that are suitable for a rapidly and continuously expanding RES grid, and thus able to safely scale with the grid without risking unstable operations. Hence, multi-agent DC electrical systems with communication-reliant control strategies, also referred to as cyber-physical microgrids (MGs), have gained significant attention as a solution to enhance the flexibility, scalability and reliability of modern power grids. This research project aims to optimize a distributed control framework for DC cyber-physical MGs to always guarantee scalable stability conditions, while providing reliable and optimal power utilization.

Proportional load sharing (current or power-sharing) among the distributed generators (DGs) and voltage containment are often considered the two main objectives in DC MGs. Therefore, this projects primal research objective is to design a distributed controller that ensures both control objectives in steady state operations. Our stability analysis, based on time-scale separation and Lyapunov theory, aims to establish scalable stability conditions that guarantees all energized units to contribute an equal amount of power relative to their rated power while operating dynamically within predefined voltage limits when the system converges to the optimal equilibrium.

Despite the operational advantages of including communication technologies in the control system, this implementation increases the cyber-physical system's vulnerability to cyber-attacks. Hence, we investigate the robustness of the controller against different cyber-attacks. We are interested here in the ability of the system to still converge to the desired optimal equilibrium and the capacity to always guarantee stable operations in hostile situations. Based on the findings, we propose a modified resilient version of the controller capable of ensuring proportional current-sharing and voltage regulation even when subjected to potential attacks.

Innovation potential and possible applications

With the increased focus on sustainable energy and digitalization of modern power grids, this research enhances the scalability, reliability and stability of future networked power grids interfacing RES through power-electronic converters. The integration of information and communication technologies (ICTs) in the control of electrical systems, establishes a seamless connection between the power and energy industries and the evolving fields of digitalization and cybernetics. Moreover, in today's global landscape, the rise in cyber threats targeting electrical power systems is a growing concern. This underscores the imperative for a resilient control system capable of maintaining grid stability and optimal performance in the face of these cyber-attacks.

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Main supervisor: Irina Oleinikova
Research Group: PSOA
Co-Supervisors: Hans Kristian Høidalen, Laszlo Erdodi
Project: Data communication, cyber security assessment and its operational impact estimation for digital substation devices

Data communication, cyber security assessment and its operational impact estimation for digital substation devices.

Description of the research

The digitalization of power systems is proceeding rapidly as all components like generation, distribution, and consumption become more interconnected, intelligent, and cost-effective. The integration of digital technologies such as modern sensors, real-time communication, the Internet of Things, and data analytics is taking place. Additionally, it's essential to acknowledge the numerous industrial control systems that monitor, control, and protect elements of power systems. These technologies allow to ensure reliable, secure, and sustainable operation of the power system.

However, digitalization also brings new risks and challenges. Cyber-physical threats are one of these problems. The purpose of attackers may be possible power outages, collection, and data manipulation. Such actions are aimed at causing physical and economic damage to critical infrastructure. Despite the implementation of standards, regular testing and training, and the application of new measures that aim to protect power system elements against physical and cyber threats, new cases of attacks are recorded every year.

In the period of Industry 5.0 dependence on energy supply has never been greater. That makes power system components one of the main targets for attacks, especially with zero-day exploits – undisclosed vulnerabilities until launched by attackers. Therefore, it is important to create a secure and realistic environment to test, evaluate, and validate the effectiveness of the solutions developed against cyber-physical threats.

Innovation potential and possible applications

This project will contribute to developing a cyber-physical testbed that accurately mirrors power system behavior, facilitating the modeling and evaluation of physical and cyber threats. This comprehensive approach enhances prevention, detection, mitigation, and resilience measures for power system components, benefiting the next groups of stakeholders across the energy sector.

Group 1: For energy companies from transmission, distribution, generation, and consumption domains, this research topic could offer guidance on implementing effective security measures and providing cybersecurity training tailored to their specific needs.

Group 2: Government bodies and organizations responsible for creating laws, regulations, and standards in cybersecurity can benefit from this research by validating requirements and recommendations in a secure and isolated environment.

Group 3: Experts and consulting companies can leverage this research to create different scenarios for risk assessment and penetration testing.

Group 4: Power system product vendors, who produce software with close-source code susceptible to hidden vulnerabilities and zero-day exploits, can utilize the advanced cyber and physical threats developed in this research to evaluate their security solutions.

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Co-Supervisor: Sigurd Hofsmo Jakobsen (SINTEF Energy Research)
Project: The Research Council of Norway's Industrial PhD Scheme

A Combined Data- And Physics-Based Approach to Frequency Reserve Modeling and Control

Description of the research

The power system is undergoing a never-before-seen change driven by sustainability concerns. The well-known dynamics of synchronous generators are increasingly being replaced by novel converter-interfaced generation (CIG) like solar and wind power, increasing uncertainty and variability in the system. These changes present new challenges of how to control the system, how to model it, and how to properly analyze it.

Of special interest in this project, is how to balance the power system in the form of frequency reserves, amid varying inertia and system conditions. Particularly the tuning of controllers for frequency containment reserves (FCR), and to some extent fast frequency reserves (FFR), becomes increasingly important when reduced inertia levels in effect make the power system take on the characteristics of a smaller, more volatile system. The challenge is therefore twofold. It consists of adequately modeling the reserve providing units, and properly controlling them.

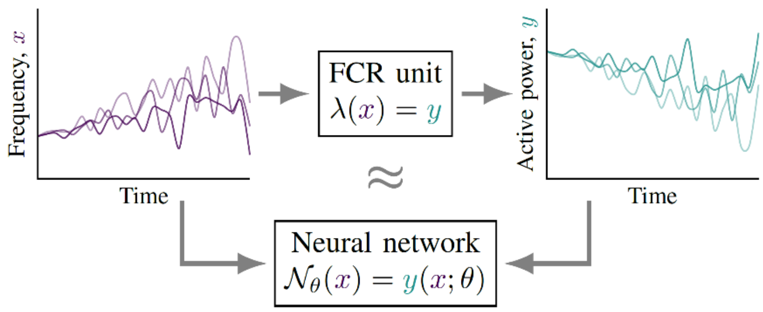
Increased system complexity challenges conventional physics-based modeling (PBM) approaches. At the same time, the advances in data generation and processing, as well as machine learning methods for system modeling and control offer exciting opportunities.

However, data-driven modeling (DDM) approaches are not without their weaknesses. DDM methods, e.g., based on (deep) neural networks, are often presented as black boxes, offering little to no information on their inner workings. They often require large amounts of data and tend to perform poorly on test cases not present in the training data. This is potentially problematic for critical infrastructure like the power system.

PBM methods, on the other hand, are transparent, but can suffer from a lack of fidelity, as they often rely on simplifications and assumptions in order to create a computationally feasible solution.

Based on this, a growing interest in combining the two paradigms has emerged, enabling the leveraging of each of their strengths. The central idea is to employ an appropriate combination of PBM and DDM to model the system of interest, and then use a learning-based control method to control the system. A model based on (and restricted by) the physical understanding of the system, but data-tailored to and validated against the specific case, could be developed and controlled by a controller able to handle variation and uncertainty of ambient conditions.

Moreover, developing learning-based solutions where controller performance and robustness can be guaranteed is central if the goal is to have deployable solutions in a power system setting. A learning-based controller, e.g., actively causing a blackout due to ill-defined objective functions or poorly understood under-the-hood-functioning, will not be acceptable.



Innovation potential and possible applications

The main objective of the project is to explore and further develop methods of data-driven modeling and control of frequency reserves, employing a combined physics- and data-based approach focusing on the faster frequency reserve types.

The overarching aim of the project is to contribute to the transition to a future net zero emissions power system dominated by renewables by improving power system control and frequency reserve provisions. The project will initially focus on a hydro dominated power system like the Nordic one, with increasing penetration of CIG.

The goal of the project is to develop proof-of-concept methods which can be used further in research and further refined into deployable tools by power system actors.

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Flexibility and controllability of distribution grids with a large degree of distributed energy sources

Description of the research

The increasing integration of solar PV into distribution grids can create technical challenges, including reverse power flow, voltage rise, and grid congestion. These issues can lead to operational inefficiencies, increased wear on grid components, and disruptions in power quality. In weaker networks that are not designed to accommodate high levels of decentralised generation, these challenges become even more pronounced. Addressing them requires a combination of technical solutions and improved grid management strategies. This research explores how flexibility measures can help mitigate these challenges while reducing the need for costly infrastructure upgrades. As part of the study, simulations based on real distribution grids and case studies will be considered in collaboration with a distribution system operator (DSO). By analysing operational challenges in such grids, the study aims to identify practical approaches to improving system efficiency and reliability.

Innovation potential and possible applications

The study is relevant for grid operators and policymakers responsible for maintaining a stable and efficient distribution network in areas with a high share of solar PV. It provides insights into how flexibility can be integrated into weaker grids to enhance stability and efficiency, supporting investment decisions and operational strategies. The results may also contribute to the development of new methods for managing voltage stability, alleviating grid constraints, and facilitating a higher share of renewable energy in the system.

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Co-supervisor: Thomas Øyvang
Project: System Optimization between power producer and grid owners for more efficient system services (SysOpt)

Secondary voltage regulation for long-term reactive power management and minimization of network losses

Description of the research

Modern power transmission networks are facing significant changes related to the current trends of electrification and massive integration of renewables-based generation. The resulting increase in bidirectional power flows leads to bottlenecks with limited transfer capacity, lower net export margins and intensification of overall system losses. In addition, TSOs are progressively more overburdened by labor-intensive manual operations within regional control centers (RCCs), particularly in connection with long-term management of voltage quality and reactive power source (RPS) devices.

A mitigation strategy for simplified RCC routines with successful real-life implementations consists of automatic and coordinated voltage regulation through hierarchical control layers. This framework is typically divided into three time-decoupled levels: primary voltage regulation (PVR), on a power plant level; secondary voltage regulation (SVR), on a regional grid level; and tertiary voltage regulation (TVR), on a power system level.

Among the three, the intermediate SVR layer has been the focus of renewed research interest due to its twofold contribution to flatter voltage profiles and fairer reactive power sharing within a predefined control area. These objectives are attained, respectively, by the selection of a pilot bus representative of the area voltage behavior and by the assignment of participation factors to RPS devices involved in the SVR scheme.

The conventional SVR scheme can be divided into two main components: the voltage control loop (VCL), a RCC-located dispatcher of corrective signals for pilot bus setpoint tracking; and a set of reactive power control loops (QCLs), distributed to each participating RPS for reactive power sharing adjustments. Both structures are represented by proportional-integral (PI) controllers with different gains and time constants, which are typically tuned so that the QCLs have a faster response than the VCL within the SVR action time frame (10 – 100s). Fig. 1 shows the implementation of the PI-based SVR scheme in a single control area containing n generator units equipped with automatic voltage regulator (AVR) devices, which constitute the PVR layer of the control hierarchy.

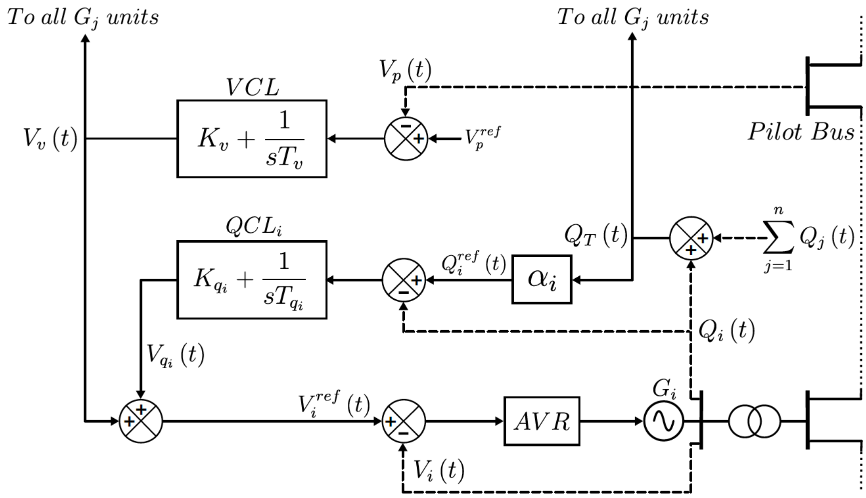

Fig. 1. Functional block diagram of the PI-based SVR scheme.

At the current research stage, the topology proposed in Fig. 1 has been investigated in the context of Norway's control centers, subdivided into RCC-S (Southern Norway) and RCC-N (Northern Norway). The wide-area voltage regulation design strategically places both RCCs in a key role, as they receive and interpret voltage setpoints generated by iterative solutions at a TVR level so as to guide the intermediate SVR layer towards enhanced regional voltage profiles, thereby optimizing local PVR actions and reactive power flow at a power plant level.

Innovation potential and possible applications

Obtained results have attested to the merits of the hierarchical structure using increasingly more complex test systems, including important reactive power control resources such as capacitor banks, on-load tap changers and generator overexcitation limiters.

The coordinated flow of information as well as the increased redundancy against failures in interlayer communication are considered improvements over today's voltage control framework, where the SVR and TVR layers are underutilized or even non-existent in certain portions of the Nordic power grid. Deliverables pertaining to the research project that finances this work (SysOpt) can be of great value to control center operators seeking cost-effective methods to improve daily voltage control routines.

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Research Group: PSOA
Co-supervisor(s): Charlotte Skourup (ABB)
Project: The Research Council of Norway's Industrial PhD Scheme

PhD work title: Coordinated control of industrial processes and power systems for enhanced flexibility and resiliency of operation

Description of the research

The concept to be explored in this PhD project is resilient industrial power system management by means of flexible process control. The *resiliency* of a system refers here to its ability to withstand disturbances, and *flexibility* refers to its ability to change operating point. The goal is to ensure security of supply and flexibility to maximise the utilisation of the available resources and the industrial processes that require electric power.

Utilising the operating range of industrial processes suited for variable operation can significantly improve the stability of the power supply during contingencies. Moreover, industrial system owners may want to vary process production rate based on factors such as market mechanisms, degradation of equipment or total system efficiency. To meet the demands in these circumstances, plant control systems can be designed to balance the available power and the operating point of the process, actively utilising the total operational envelope of the process and power system.

Because of international goals to reduce greenhouse gas emissions, there is an increased interest in processes that can operate with varying power supply from renewable energy sources (RESs), for example green hydrogen production. Such plants that have not yet been realised present an opportunity to design the system topology taking the coordinated control of process and power systems into account, saving costs of reducing the need for expensive equipment such as battery energy storage systems.

Innovation potential and possible applications

The research topic is particularly relevant now with an increasing share of RESs introduced into the energy mix, plans to electrify offshore platforms and plans to introduce large power consuming industrial sites to the grid, all of it making the national grid more prone to unwanted dynamics. It is expected that the research of this PhD will be a contribution to tackling these challenges.

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Co-supervisor: Assoc. Prof. Steve Völler

Project: Digital Solar Electricity

Machine Learning for Solar Photovoltaic (PV) System Performance and Operational Fault Analysis

Description of the research

The adoption of photovoltaic (PV) systems has been rising rapidly due to declining system costs and supportive policies. According to the IEA report [1], by 2030, renewable energy sources are expected to account for 46% of global electricity generation, with PV alone contributing 16%. Given this anticipated high reliance on PV electricity generation, an efficient and cost-effective protection and monitoring system, suitable even for small-scale residential PV installations, is essential to maintain the lifespan, energy yield, security, and reliability of PV systems.

Recently, several fire incidents linked to PV systems have been reported. Additionally, studies indicate that annual energy losses due to various faults can reach up to 18.9% [2]. Consequently, fault detection and diagnosis in PV systems have gained significant attention in recent years, leading to the development of various techniques. However, existing fault detection and diagnosis methods are primarily constrained by the non-linear nature of PV arrays, the need for remote monitoring, and the presence of faults with similar signatures. Moreover, standard protective devices often fail to detect faults under conditions such as low irradiance or low impedance. As a result, many researchers have been studying data-driven approaches, particularly machine learning (ML). Nevertheless, most machine learning (ML) studies for PV fault detection and diagnosis focus on evaluating algorithm performance, with fewer studies on integrating these methods into real PV systems. Additionally, several new ML algorithms have recently been introduced to improve model robustness and accuracy. Assessing the suitability of these models is essential to fully leverage their benefits for PV systems. Therefore, this Ph.D. research project aims to address the following research questions:

1. What are the state-of-the-art machine learning techniques for PV performance and fault analysis? What are the existing gaps, challenges, and future perspectives?
2. How can transfer learning be utilized in PV system performance and fault analysis? What is the performance of less-explored algorithms?
3. How can we develop a modular, flexible, and scalable fault management system (FMS) for PV using machine learning techniques?
4. How can an ML-based PV FMS be integrated into existing protection systems?

Figure 1 provides a simplified illustration of the focus of this Ph.D. project.

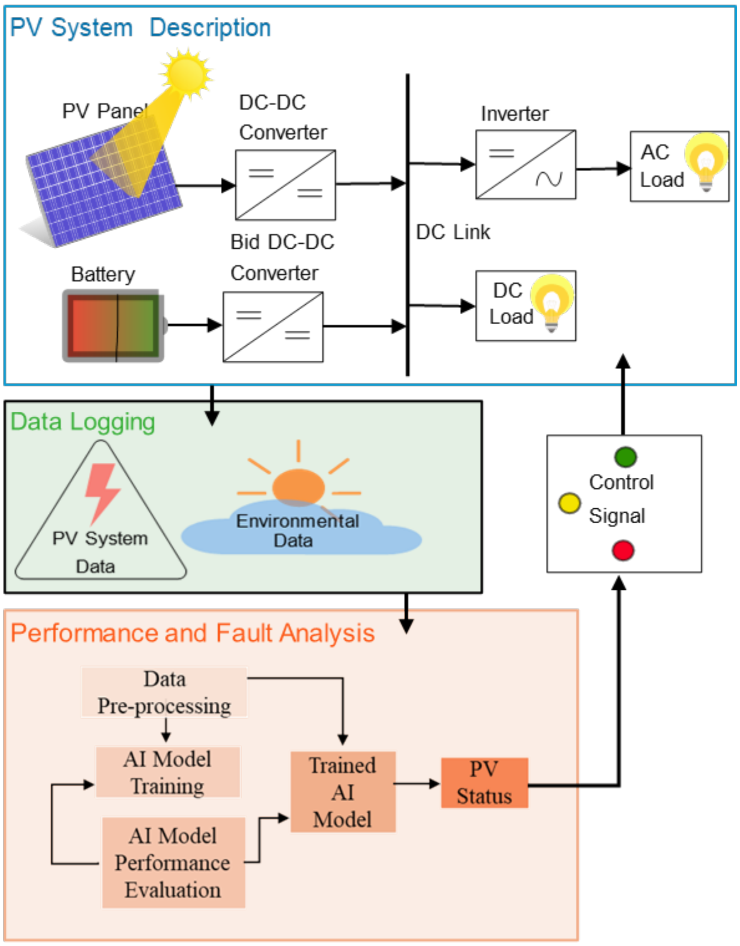

Figure 1: The simplified illustration of the Ph.D. project

Innovation potential and possible applications

The Ph.D. work's results can be used for any PV system, but the focus is on standalone small-scale PV systems, where predictive maintenance is not often practiced and less costly protection and monitoring systems are required.

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Early Warning Early Prevention System for Voltage Instability Phenomena

Description of the research

Several factors have been contributing to the challenges observed in power systems worldwide such as the progressive growth in load demand, the lack of investment in grid infrastructure, and the increasing penetration of power electronics-interfaced technologies. Furthermore, weather disruption events are happening more frequently due to climate change, making the monitoring and operation of these systems even more demanding. Under these conditions, risks of voltage instability events are bound to escalate unless proactive actions are implemented.

A measure of particular importance for Transmission System Operators (TSOs) to effectively tackle the complexities inherent to power system dynamic behavior is to accurately estimate the voltage stability margin in real time. Literature on this research topic is extensive, and several Voltage Stability Indicators (VSIs) suitable for real-time monitoring have been proposed. Synchronized Phasor Measurement Units (PMUs) are commonly used in these methods due to their high sampling rate and widespread presence throughout electrical power systems.

Different approaches might be adopted to the development of VSIs, such as: Thévenin equivalent, sensitivity analysis, machine learning techniques, etc. Regardless of the adopted algorithm, it is paramount to strive for an effective and optimized performance within control centers, aimed at improving daily voltage control routines. The ability to issue early alarms when detecting a rapid decline in voltage stability margin can be decisive for whether corrective actions (automatic or operator-initiated) can be taken fast enough to restore the stability of the system and avoid collapse. Thus, the VSI should be able to identify in advance, without giving false alarms, the onset of voltage stability rather than detect its consequences.

At the current research stage, VSIs based solely on PMU measurements and already proposed in the literature had their performance assessed considering placement of monitoring device, different types of loads, line disconnections events, presence of noise in the measurements, and on-load tap changer and over-excitation limiter actions. Moreover, it was of particular interest to test their ability to detect shorter-term events, since they are understandably expected to work best in long-term stability events due to the need for computations and filtering. For this intent, tests with PMU measurements from a real event that occurred in the Nordic power grid were conducted.

Innovation potential and possible applications

The results obtained highlighted the advantages and disadvantages of each index and served as a basis for the development of a new VSI. This novel approach is thought to respond faster and more accurately to the dynamics of the renewables-rich and interconnected power systems of the future, providing real-time information on voltage stability margins.

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Co-supervisor: Iver Bakken Sperstad
Project: Development of coupled offshore and onshore grids

PhD work title: Development of coupled offshore and onshore grids

The project responds to the ambitious target set by the Norwegian government of achieving 30 GW offshore wind capacity by 2040, necessitating substantial infrastructure development that parallels existing onshore systems. It aims to advance research methodologies and generate comprehensive insights to enable the socio-economically optimal integration of offshore and onshore electrical grids. The scope specifically addresses critical gaps in understanding grid interdependencies, economic implications, and robustness amidst rapidly changing energy landscapes.

Building on current knowledge primarily centered around isolated offshore installations, the project will explore advanced methodologies for coordinated offshore-onshore grid development. This includes sophisticated optimization and simulation strategies to evaluate hybrid connections, energy islands, and meshed AC/DC grids. The research will rigorously examine the socio-economic impacts of diverse grid development scenarios, emphasizing holistic integration rather than isolated enhancements.

A significant research dimension involves ensuring the reliability and resilience of the integrated system. Emphasis will be placed on assessing vulnerabilities, particularly concerning the increased deployment of HVDC technologies and resilience against extreme weather conditions. To facilitate robust scenario analysis, the project will develop reduced, computationally efficient grid models that accurately reflect system interactions while remaining manageable for extensive computational studies.

The project team comprises SINTEF, Statnett, Aker Solutions, GE Grid Solutions, NTNU, and international collaborators from KU Leuven, representing a multidisciplinary consortium that bridges academia, industry, and grid operation expertise. Outcomes will include the provision of open-source datasets, research tools, and methodological frameworks. These contributions will support informed strategic planning and decision-making, reducing uncertainties and promoting sustainable, secure, and economically sound investments in offshore wind infrastructure development.

PhD graduate at the Department of Electric Energy, NTNU, from 2022 – April 2025

2025

Name	Title
Mohammad Khalili Katoulaei	Experimental Analysis and Development of Process Bus IEDs Indigital Substations
Sverre Stefanussen Foslie	The Role of Process Flexibility for Faster Decarbonization of Industrial Energy Demands
Jordon Ashley Grant	The Impact of High-Voltage Circuit Breaker Condition on Power System Reliability
Ida Fuchs	Solar Home Systems and Swarm Electrification: Decentralized Power Systems for Energy Access

2024

Name	Title
Marthe Fogstad Dynge	Local Electricity Markets: Evaluating Pricing Mechanisms, Fairness and Privacy
Emil Dimanchev	Decarbonization of Energy Systems Under Risk
Matthias Hofmann	Implicit Demand Side Flexibility as an Alternative to Investments in the Transmission Grid
Paul Monceyron Røren	Ablation-Assisted Load Switching at Medium Voltage in an Alternative Gas to Sulphur Hexafluoride
Ugur Halden	Advancing Power Systems: Harnessing the Potential of Artificial Intelligence and Disturbed Ledger Technology
Yannick Cyiza Karekezi	Assessing the Impacts of Flexible Operation Strategies on Classic Hydropower Generators for Advancing the Energy Transition
Prabhat Ranjan Bana	Advanced Control Design for Grid-Connected Converters in Renewable Energy Applications
Gard Lyng Rødal	Real-time Simulation and Adaptive Gate Driving of SiC MOSFETs
Kjersti Berg	Local Energy Communities: Member Benefits and Grid Impact Under Various Regulatory Frameworks
Sjur Føyen	Modelling of Frequency-Coupled Power Electronics Systems: Automated Model Generation and Chirp Frequency Scanning, Applied to Single-Phase VSCs
Thomas Treider	Earth Fault Location in Non-Radial Resonant Grounded Networks – Theory, analysis and methods
Atousa Elahidoost	Stability Improvement of MMC-Based Multiterminal HVDC Grids

2023

Name	Title
Daniel dos Santos Mota	Control and Stability of Isolated Grids with Synchronous and Non-Synchronous Generation
Raghbendra Tiwari	Frequency Converter Solutions and Control Methods for Varible Speed Operation of Pumped Storage Plants
Krister Leonart Haugen	Scalable Regenerative Power Converters for Accelerator Magnets
Daniel Simon Baltensperger	Optimal and Adaptive Arming of System Protection Schemes
Daniel Alexander Philipps	On Dynamic Characterization Evaluation and Control of Active Gate Drivers for SiC power MOSFETs
Matteo Leandro	Framework for Analytical-based Digital Twin Development of Electric Drive Using Slotless PM Machines
Linn Emelie Schäffer	Environmental constraints in stochastic hydropower scheduling for long planning horizons
Aravinda Perera	Enhanced Sensorless Control of Electric Drivetrains for Deep-Sea Mining Vehicles
Mostafa Barani	Reliability Studies in Information and Communication Technology (ICT)-dominated Distribution Systems: Adequacy Assessment of Cyber-Physical Distribution Networks Including Microgrids
Stine Fleischer Myhre	Reliability Assessment Tool for Modern Electrical Distribution Systems – A Monte Carlo Simulation Approach
Erick Fernando Alves	Optimization of Energy Storage for Frequency Control in Autonomous AC Power Systems – Frameworks for Planning and Operation
Spyridon Chapaloglou	Data-driven sizing and control of energy storage for wind-powered offshore platforms – Energy Management and Control of Offshore Platforms Integrating Renewable Energy

2022

Name	Title
Wei Wang	Electromagnetic field calculation and power loss evaluation in power transformers –Analysis of Leakage Fields and Stray Losses under Special Operation Conditions
Sigurd Bjarghov	Designing grid tariffs and local electricity markets for peak demand reduction in distribution grids
Kasper Emil Thorvaldsen	A Long-term Strategy Framework for Flexible Energy Operation of Residential Buildings
Hossein Ehya	A Novel Health Monitoring System for Synchronous Generators using Magnetic Signatures
Magnus Askeland	Policy issues for distributed energy resources as a part of larger energy systems
Hallvar Haugdal	Application of Phasor Measurements for Online Monitoring and Adaptive Damping Control of Electromechanical Oscillations
Naghme Dorraki	Investigation on Fault Current Making in Medium Voltage Switchgear in Air
Per Aaslid	Optimal coordination of renewable sources and storage in energy-constrained power systems
Andreas Giannakis	Design of High-Performance Solid-State Circuit Breakers for LVDC and MVDC Applications
Espen Flo Bødal	Hydrogen Production from Wind and Hydro Power in Constrained Transmission Grids

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Year	Name	Title
2021	Torbjørn Andersen Ve	Effect of absorbed water and teperature on charge transport and accumulation in XLPE cable insulation
	Tor Inge Reigstad	Optimal control of variable speed hydropower-Utilising model predicitvie control and virtual inertia for delivering power system services
	Erlend Sandø Kiel	Methods for quantifying and communicating risks and uncertainties related to extraordinary events in power systems
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	Augusto Matheus dos Santos Alonso	Multi-purpose Coordinated Control of Distributed Energy Resources in Transactive AC Microgrids
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2020	Ole Chr. Spro	Design and Optimisation of an auxiliary power supply with medium-voltage isolation using GaN HEMT's
	Gunnar Håkonseth	Transient Electric Field Distribution Estimates for Layered Paper-Oil High Voltage Direct Current Insulation
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	Pål Keim Olsen	Inertial Partial Discharges at High DC Voltage and the Effect of Superimposed AC Voltage
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	Markus Löschenbrand	Dynamic Electricity Market Games – Modeling Competition under Large- scale Storage
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	Rene Alexander Barrera Cardenas	Meta-parametrised metamodeling approach for optimal design of power electronics conversion systems. Application to offshore wind energy conversion systems
	Gilbert Bergna Diaz	Modular Multilevel Converter - Control for HVDC Operation
	Santiago Sanchez Acevedo	Stability Investigation of Power Electronics Systems A Microgrid Case
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	Chuen Ling Toh	Communication Network for Internal Monitoring and Control in Multilevel Power Electronics Converter
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	Aigner, Tobias	System Impacts from Large Scale Wind Power
	Nguyen, Dung van	Experimental studies for streamer phenomena in log oil gaps
	Jafar, Muhammad	Transformer-Less Series Compensation of Line-Commutated Converters for Integration of Offshore Wind Power
	Torres Olguin, Raymundo	Grid Integration of Offshore Wind Farms using Hybrid HVDC Transmission Control and Operational Characteristics
	Wei, Yingkang	Propagation of Electromagnetic Signal along a Metal Well in an Inhomogeneous Medium
2012	Yordanov, Georgi Hristov	Characterization and Analysis of Photovoltaic Modules and the Solar Resource Based on In-Situ Measurements in Southern Norway
	Haileselassie, Temesgen Mulugeta	Control, Dynamics and Operation of Multi-terminal VSC-HVDC Transmission Systems
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	Suul, Jon Are	Control of Grid Integrated Voltage Source Converters under Unbalanced Conditions – Development of an On-line Frequency-adaptive Virtual Flux-based Approach
2011	Marvik, Jorun Irene	Fault localization in medium voltage distribution networks with distri-buted generation
	Krøvel, Øystein	Design of Large Permanent Magnetized Synchronous Electric Machines – Low Speed, High Torque Machines – Generator for Direct Driven Wind Turbine –Motor r Rim Driven Thruster
	Chen, Anyuan	Investigation of PM machines for downwhole applications
2010	Chiesa, Nicola	Power Transformer Modeling for Inrush Current Calculation
	Danielsen, Steinar	Electric Traction Power System Stability Low-frequency interaction between advanced rail vehicles and a rotary frequency converter

	Nordgård, Dag Eirik	Risk Analysis for Decision Suppurt in Electricity Distribution System Asset Management
	Greiner, Christopher J.	Sizing and Operation of Wind-Hydrogen Energy Systems
2009	Eek, Jarle	Power System Integration and Control of Variable Speed Wind Turbines
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2008	Pedersen, Per Atle	Forces Acting on Water Droplets in Electrically Energized Oil Emul- sions; Observations and Modelling of Droplet Movement Leading to Electrocoalenscence
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	Næss, Bjarne Idsøe	Operation of Wind Turbines with Doubly Fed Induction Generators During and After Line Voltage Distortions
	Belsnes, Michael Martin	Optimal Utilization of the Norwegian Hydropower System
	Helseth, Arild	Modelling Reliability of Supply and Infrastructural Dependency in Energy Distribution systems

2007	Di Marzio, Giuseppe	Secure Operation of Regional Electricity Grids in Presence of Wind Power Generation
	Gullvik, William	Modeling, Analysis and Control of Active Front End (AFE) Converter
	Andreassen, Pål	Digital Control of a Zero Voltage Switching Inverter for distributed Generation of Electrical Energy
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	Ericson, Torgeir	Short-term electricity demant response
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2006	Maribu, Karl Magnus	Modeling the Economics and Market Adoption of Distributed Power Generation
	Catrinu, Maria	Decision-Aid for Planning Local Energy Systems. Application of Multi-Criteria Decision Analysis
2005	Hellesø, Svein Magne	Dynamic analysis and monitoring of power transmission cables using fibre optic sensors
	Lund, Richard	Multilevel Power Electronic Converters for Electrical Motor Drives
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	Vogstad, Klaus-Ole	A system dynamics analysis of the Nordic electricity Market: The tran- sition from fossil fuelled toward a renewable supply within a liberalised electricity market