Norwegian University of Science and Technology, NTNU
Faculty of Information Technology and Electrical Engineering

PhD projects 2020

Department of Electric Power Engineering

An overview over PhD Projects 2020
at

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

This report gives an overview of current PhD research projects at the Department of Electric Power Engineering.

Currently more than 50 students are registered in our PhD program. This number is now peaking after a steady growth for several years, reflecting the increased general interest in energy and electric power from renewable resources. The department has 12 professors, 11 associate professors, 7 adjunct professors, 3 lecturers, and 3 researchers. The number of Postdocs is 4. In addition to the scientific and administrative staff, the department houses a mechanical workshop and an electro technical laboratory.

The research activity at the Department is mainly covered by the research topics of our five groups:

- Power Electronic Systems and Components
- Electricity Markets and Energy System Planning
- Electrical Machines and Electromagnetics
- High Voltage Technology
- Power System Operation and Analysis

The PhD projects presented here focus on topics from broad range of research areas with electric power engineering. The research projects are both theoretical and practical and based on extensive use of our computer and laboratory resources. The projects are also influenced by our collaboration with industry and our neighbour institution SINTEF Energy Research AS. Since the PhD projects represent the main part of the professors’ research, this folder also gives a good overview of the entire research activity at the Department.

The nominal duration of PhD program is three years of full-time research, of which a half year is devoted to post graduate courses. A typical PhD project, however, lasts up to four years, where the additional time is booked within university/educational activities.

For further information about the research projects presented, please contact the individual researcher given by name in this folder.

NTNU, November 2020

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Research Group: Power System Operation and Analysis
Co-Supervisor(s): Michael Martin Belsnes (SINTEF), Magnus Korpås
Project: Industrial PhD (SINTEF) / CINELDI

Optimal coordination of distributed energy resources

The energy system in rapidly changing from being dominated by centralized dispatchable generation, to a system with an increasing share of distributed non-dispatchable generation from renewable sources. The demand side is also changing from relatively passive consumers, to smart and active consumers capable of providing flexibility to the energy system.

Increasing penetration from renewable power generation such as solar and wind, and the increasing number electric vehicles (EV) may cause high peak loads in the distribution grid. On the other hand, flexible resources in the distribution grid serves as an alternative to expensive grid expansions. A key challenge in the future energy system will be optimal coordination of distributed energy resources considering the limitations in the transmission and distribution system, and the goal for this project is to develop methods and tools for this. The methods should be flexible and generic enough to be applicable both on high level systems, such as transmission, as well as low level system like distribution grids and microgrids.

The method development involves:

- Account for grid limitations by including AC power flow.
- Manage uncertainty due to intermittent generation and load variations.
- Model different types of end user flexibility: EV charging including V2G, atomic shiftable loads, building thermal storage, batteries (grid installed or household)

- Account for flexibility operation costs in terms of battery degradation, user comfort etc.
- Interaction with transmission system
- Coupling of models with different degree of details

The outcome of this research can be used for analyzing the value of flexibility in the distribution grid. It is also possible to compare different expansion strategies compared to increasing flexibility. The methods may also be useful as a decision support tool for both transmission and distribution system operators, and aggregators.

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Research Group: Power System Operation and Analysis (PSOA)
Co-Supervisors: Elisabetta Tedeschi and Mohammad Amin
Project: Networked Control for Power Electronic Grids

Networked Control for Power Electronic Grids

Description of the research

Power systems are shifting towards more power electronics-based generations and loads which are distributed across the network. This trend is due to the ever-increasing demand for eco-friendly and automated energy systems where the power electronics-based converters play a vital role as the main interface between energy resources and the power grids. In addition to what they bring to the table, the converter-interfaced units pose some challenges to the power systems stability, control, and optimization; therefore, they must be properly controlled to address the challenges ahead.

Proportional power sharing and voltage/frequency regulation are both of great importance for the long-term effective operation of power systems. This research project aims at designing control strategies that stably drive the power systems to a desired operating point where those requirements are fulfilled. These controllers rely on sparse neighbor-to-neighbor communication networks where each converter-based unit shares information only with its most immediate neighbors. To properly model the power systems under study, the project *may* also cover some topics on primary control of converters which are commonly implemented in a decentralized fashion.

It is worth mentioning that distributed control and optimization of power networks lies in the intersection of the fields of power electronics, power systems, control systems, and information and communications technology (See Fig. 1). Therefore, as an interdisciplinary project, this research can potentially cover different aspects of the system. However, our main goal is to *unlock the potentials* of distributed cooperative control strategies for power systems optimization and control so that the control goals which are difficult or even impossible for an individual unit to achieve can be established in a collaborative effort of converters.

Innovation potential and possible applications

With the increasing demand for green and digitalized energy systems, penetration of converter interfaced energy resources and consumers into the power systems is also increasing. Therefore, stable optimization and control of these units are inevitable for long-term effective and stable operation of future power systems. On the other hand, the information and communication technology, e.g., wireless communications, are rapidly developing so that the industry can exploit these new technologies to positively contribute to power systems operation. Therefore, networked control systems can potentially bridge the gap between the power systems industry and the digitalization trend by integrating the power electronics-based energy resources into the grid.

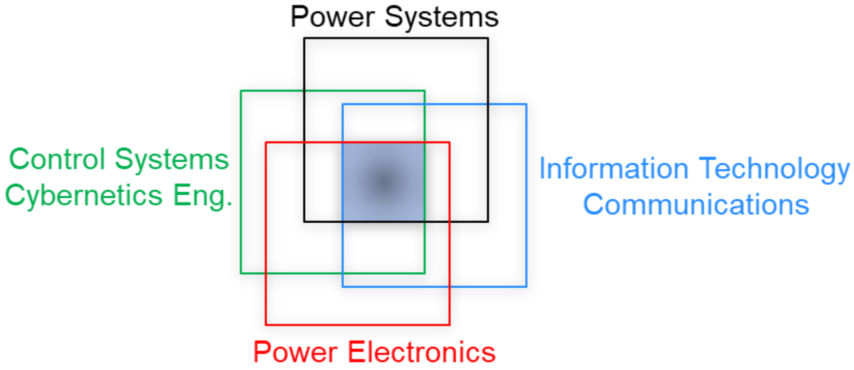

Fig. 1: Where the Networked Control for Power Electronic Grids lies in.

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Research Group: High Voltage Technology
Co-Supervisor(s): Øystein Hestad
Project: LowEmission center - SP3

Wet Design of AC Power Cables for Future Offshore Power Grids

Description of the research

The main aim of the PhD project is to examine and determine the critical ageing mechanisms for a wet design AC power cables, which is a project carried out under the umbrella of the LowEmission Centre. The scope of the project covers the investigation of wet design offshore HV cables and subsea compensation units with the objective of:

1. Identifying or developing cost-efficient reliable power components for offshore/subsea power distribution

2. Testing components or insulation systems based on models of typical load patterns

3. Developing models to estimate the GHG emission reduction due to electrification

The work consists of experimental characterization and modelling of wet cable design insulation systems under service conditions with load cycling and the associated temperature variations. It is within the interest to investigate the effect of humidity, cleanliness, defects and interfaces on the ageing of the insulation material.

Innovation potential and possible applications

This project will contribute in developing new technologies and concepts for offshore energy systems, energy efficiency and integration with renewable power production technologies for application on the Norwegian Continental Shelf (NCS). This will help the industry to meet their 2030 and 2050 emission reduction goals, as well as paving the way for zero-emission petroleum production by 2050.

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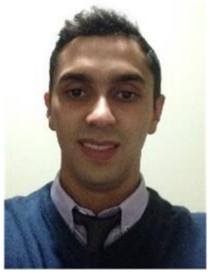

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Graduation Year: 2018

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Research Group: Power Electronic Systems and Components (PESC)
Co-Supervisor(s): Danilo Iglesias Brandao
Project: NB_POCCREI

Cooperative Control Methodology for Distributed Generators with Multiple Operational Considerations in AC Microgrids

Description of the research

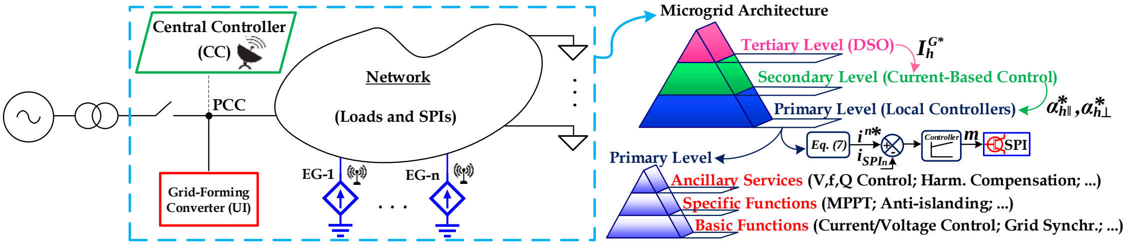
Dense penetration of distributed generators (DGs) in electrical grids, particularly at the distribution level, is increasing and it has been playing a key role in enhancing the performance of power systems by reducing energy losses and by supplying ancillary services that support the network under critical conditions. Particularly in this work, the perspective of low-voltage (LV) distribution networks is considered and the peculiarities of weak power systems, such as microgrids, is accounted for the development of a cooperative control methodology capable of coordinating multiple dispersed DGs. The proposed control strategy, named Generalized Current-Based Control (GCBC), aims at coordinating DGs in such a way that multiple operational goals can be offered, while also accounting for power quality improvement.

The GCBC has grounds on a three-layer hierarchical control approach, implemented on the basis of a master/slave architecture, on which low-bandwidth communication links are used to interconnect dispersed DGs to a central controller that manages the overall operation of the electrical system. Fig. 1 shows an overview of such control architecture. In brief, the main features of the GCBC strategy are:

- Capability to coordinate DGs regardless of the grid topology (i.e., in single- or three-phase three/four-wire systems), also enduring operation under non-ideal grid voltage conditions;

- Accurate active and reactive current sharing can be performed by DGs, concomitantly to distributed and selective harmonic compensation. Besides, reduction of neutral currents is also inherently achieved for applications in four-wire systems;
- By taking advantage of definitions within the Conservative Power Theory, the GCBC is able to distributedly compensate unbalance currents. Additionally, by driving DGs to synthesize resistive loads, voltage resonances can be damped and high power factor operation can be offered for the microgrid while operating under distorted voltage conditions;
- Automatic overvoltage control can also be offered by the method, leading to the offering of coordinated Volt/Watt and Volt/VAR functionalities, allowing to regulate voltage profiles within the microgrid without causing increased active power curtailment;
- Finally, the strategy is able to provide phase-dependent three-phase power flow control at the point of common coupling (PCC), allowing a microgrid to act as a dispatchable entity and offering power support to the distribution system if desired. This feature is of significant relevance to support the incorporation of microgrids within the context of Transactive Energy Systems.

All the above-mentioned goals are intended to be validated by means of simulation and experimental results in a low-voltage microgrid considering the presence of several DGs.



Innovation potential and possible applications

The outcome of this PhD project is likely to be implemented in microgrids of relatively low size existing in low-voltage systems, such as the case of clustered distributed energy resources. The strategy can also be adopted by power utilities to take better advantage of interconnected distributed generation systems, increasing the flexibility to coordinate power dispatch at the distribution level, and supporting the implementation of Transactive Energy Systems.

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Graduation Year: 2016

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Research Group: Power Electronics Systems and Components
Co-Supervisor(s): Magnus Korpås
Project: HES-OFF - Innovative Hybrid Energy System for Stable Power and Heat Supply in Offshore Oil & Gas Installations

Contributions to the design and operation of islanded ac power systems with high penetration of converter-interfaced generation

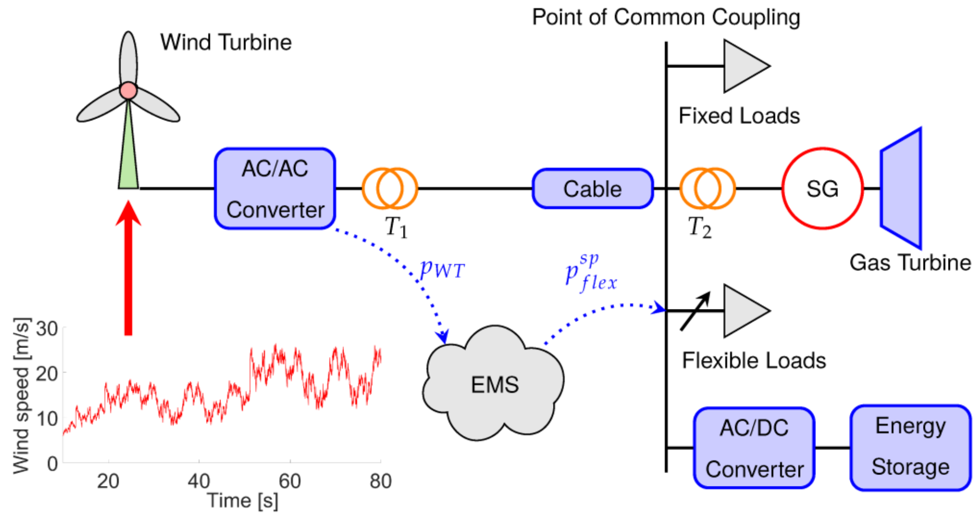
Description of the research

Offshore oil and gas platforms are energy-intensive environments, where power demand is typically larger than 30 MW and natural gas is widely used to fuel equipment in the production, gathering and processing of gas and conventional crude oil. Hence, in many countries, they contribute greatly to the emission of greenhouse gases. For instance, the petroleum sector was responsible for 27.6% of the Norwegian emissions in 2019 from which about 80% comes from power generation.

This led to increased interest in the integration of wind power into offshore platforms in parallel to gas turbines, especially where power from shore is not technically or economically feasible. The industry is already driving this concept further, and a pilot installation in the Norwegian Continental Shelf is under construction and should be operational in late 2022.

The HES-OFF project is developing this concept further with a novel concept for stable electric power and heat supply in offshore oil and gas installations. In the proposed hybrid energy system, wind power is combined with hydrogen energy storage and CO_2 emissions can be reduced in up to 40% when compared to current concepts used in the oil and gas industry. The figure below presents an idealized diagram for the electric grid of this concept.

The concept proposed by HES-OFF might also be a steppingstone for establishing large-scale hydrogen production hubs in existing offshore oil and gas platforms, where offshore wind power is abundant and existing natural gas infrastructure can be repurposed for hydrogen.



My interests and contributions to this project are in the:

- Optimization procedures to size and design the energy storage system, considering long- and short-term energy demands of the electric system
- Control strategies to guarantee the stability and power quality in the electric system
- Validation of design proposals using Power Hardware-in-the-Loop

Within this context, this PhD research aims to pinpoint power quality and system stability issues in hybrid energy systems operating in islanded mode with high penetration of power electronics-based converters. The main objectives are:

- Describe qualitatively and quantitatively the power quality and stability issues induced by the variability of loads and wind power in a reference oil and gas platform;
- Identify how they affect the required energy storage size;
- Develop sizing methodologies and control strategies to mitigate the identified power quality and stability issues;
- Validate methods and algorithms through hardware-in-the-loop tests.

Innovation potential and possible applications

Results will contribute to implement hybrid energy systems in existing and future offshore oil and gas platforms, where the cost-benefit of power from shore is questionable.

From a broader perspective, the explored topics and theoretical approach are general. Therefore, other types of hybrid energy systems, such as electric ships, remote communities, and even large grids with high penetration of renewables can benefit from this research.

Not least, the concept proposed by HES-OFF can be an important building block for the digital green shift and a future net-zero society.

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Research Group: Electricity Markets and Energy System Planning
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Project: FME ZEN

Policy issues for distributed energy resources as a part of larger energy systems

To reduce and eventually eliminate carbon emissions from the energy sector it is necessary to substitute power generation from fossil energy resources such as coal or natural gas with renewable energy resources. However, energy resources come in many forms ranging from large scale projects connected at the backbone of the energy system to small scale distributed deployment at the consumer level. If we take the goal of increasing the share of renewables as a presumption, the next question is then what constitutes efficient deployment of renewable energy? To which extent should we rely on small scale distributed or large-scale centralized resources? For which purposes do one have qualities that makes it preferable to the other and ultimately how should policies be designed to ensure optimal deployment of energy resources by market participants?

The overall research question for the thesis is: *How can we design the regulatory framework so that decentralized decisions concerning distributed energy resources are harmonized with their impact on the power system?*

The main part of the research is the development of and analyses with mathematical models. The main model that is developed in the project will be a game theoretic description of distributed energy resources as a part of the energy system. The goal is to carry out analyses that can suggest which roles different technologies should ideally play in the energy system and how regulations should be designed so that the desired outcome is realized by market participants.

The model development focuses on formulating equilibrium problems for neighbourhood energy systems that are representative of the market settings under consideration. A mixed complementarity problem (MCP) formulation will be capable of answering the question of "under the given set of assumptions, who should do what in this market?". Further, the MCP model can be extended to a mathematical program with equilibrium constraints (MPEC) to consider bilevel Stackelberg games where e.g. a policy maker (the leader) wants to achieve some objective by implementing a policy. An overview of complementarity model types is provided in Figure 1.

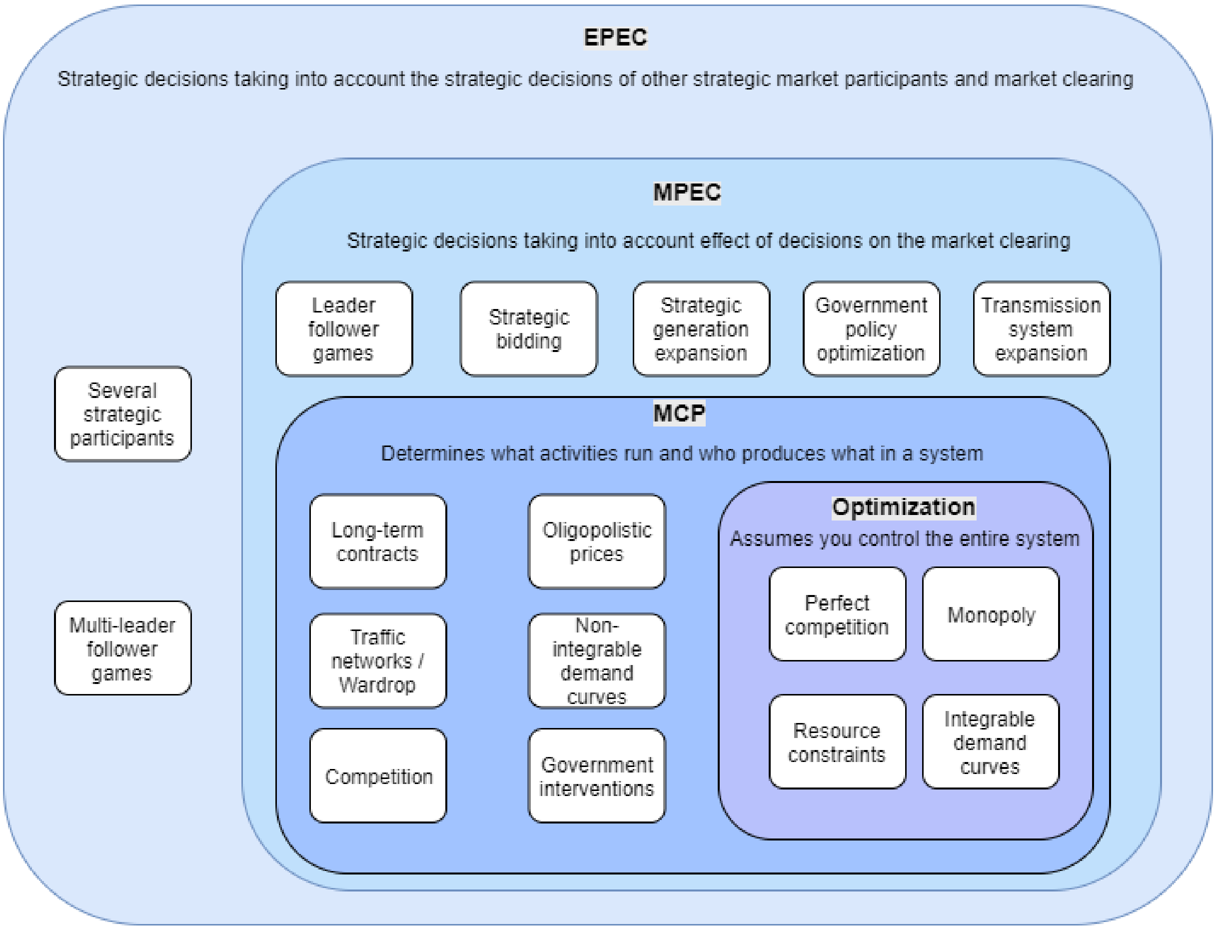

Figure 1: Complementarity model types

Innovation potential and possible applications

The overall goal of the research project is to provide insight to how distributed energy resources should be regulated as an integrated part of the energy system. To achieve optimal deployment when considering the energy system as a whole it is necessary that the incentives and regulations align the interests of market participants so that the social costs are minimized, and suboptimal outcomes are avoided. In this regard, policy instruments for a system with increasing amounts of active end-users will be evaluated to provide information on how the regulatory framework should be designed.

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Project: SynchroPhasor-based Automatic Real-time Control (SPARC)

Optimal Coordination of Special Protection Schemes

Description of the research

Due to the increasing amount of power demand the challenging task of using the existing power system more efficient while considering technical, economical and geographical restrictions appear [1]. Electric active power can flow over long distances from the generation to the load centers, where at several places bottlenecks may exist. Special protection schemes (SPS) can be armed to operate the system closer to its limit and thus increase the transfer capacity. These schemes typically detect abnormal system conditions and take some predetermined corrective action. Examples of installed special protection schemes are generator rejection, islanding schemes and load shedding [2].

In my project I want to use the information coming from different PMUs to estimate the current system state and precalculate based on this information an optimal control action for given contingencies that could potentially happen in the future (Figure 1). Optimal means in this case minimizing a certain cost function such that the post contingency situation is stable, and no other devices are overloaded. Currently I'm working on a kind of SC-OPF which considers the droop of the different generators and thus allows to precalculate an optimal generator rejection.

Innovation potential and possible applications

With the progress in communication technology, optimization theory and solver engines, such solutions may in the future be integrated into the transmission system to improve the coordination of the already existing special protection schemes.

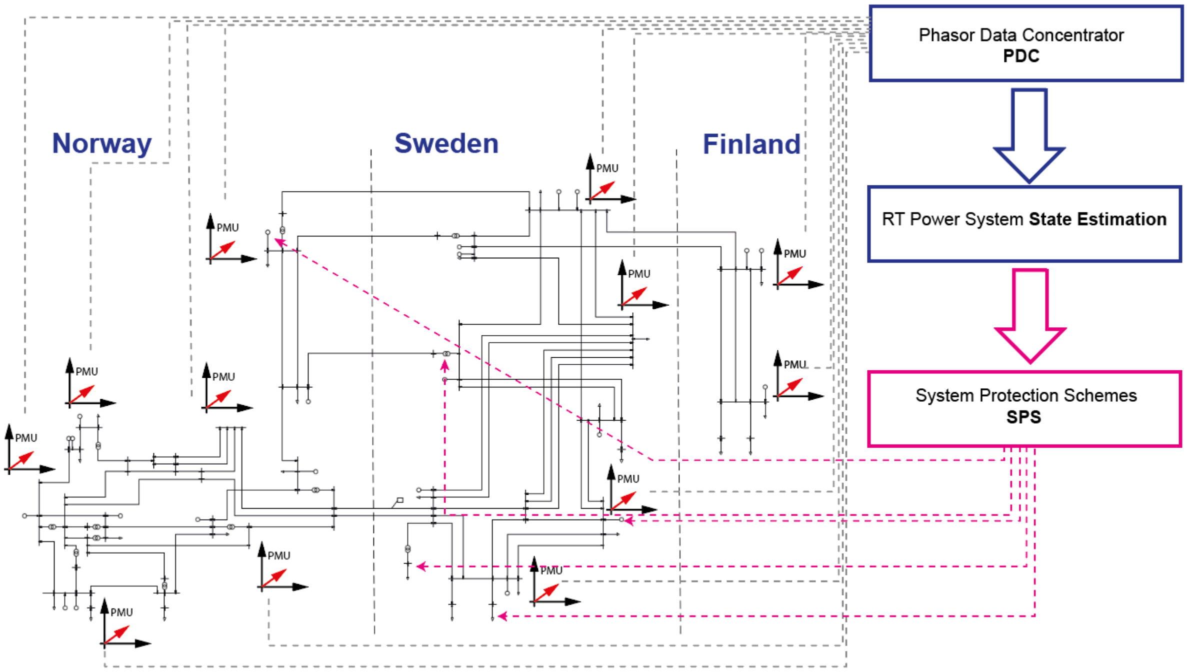

Figure 1 Schematic illustration for the Nordic 44 example

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Integration of Power Electronics Converter-based Distributed Generation Using Advanced Control System with the Grid Support Functionality

Description of the research:

Due to the limitations of high fuel cost, environmental pollutions, lower generation efficiency, and unavailability of fuels, fossil fuel-based power generation plant are unable to meet the desired power demand at present. This has motivated the use of renewable energy source-based power generations in the developing and developed countries. Solar energy is the major renewable energy source which has faced a rapid growth for electricity generation instead of its high dependence on varying environmental conditions [1]. This has been made possible due to vigorous research in power converter technologies, control techniques, maximum power extraction techniques to yield utmost improved quality of power from the renewable energy sources [2].

Moreover, power electronics converter controller brings many advantages, for example, supplies power to the critical loads even when the grid is lost by utilizing energy storage, plug and play operation functionality, less effort needed to integrate more renewable resources [3-5]. However, the traditional converters control algorithm has many challenges. For example, the commercially available inverters operate at fixed power factor and trip when voltage and frequency are outside of fairly tight limits [6]. They control the current injected into the grid, regardless of the grid condition. These characteristics were acceptable previously, but new grid codes at the state level and upcoming IEEE standards require the converters to provide essential features that are expected to support grid operations. The traditional current-controlled inverters are inherently incompatible with the grid, in which the generation is dominated by synchronous machines. Moreover, the inverters rely on a communication network in their low-level control, which could lead to serious concerns about reliability. When the number of inverters reaches a certain level, managing the communication network is itself a challenge [7]. These challenges will require advanced control technology for penetration of a significant number of power electronics-based distributed generation (DG) and load.

Innovation potential and possible applications:

This research will advance the state-of-the-art and explore advanced techniques for future high performance, reliable power electronics system design. The proposed technology will allow modern distribution grids and microgrids accommodate more DG sources such as wind energy, photovoltaic (PV) systems as well as more electric vehicles, energy storage systems and dynamic loads. A next-generation power electronic inverter technology will be developed together with a suite of protection solutions to meet the needs of the future electrical grid. Analytical tools will be developed to enhance the understanding of the power electronics components control algorithm. In this aspect, the emerging control for power electronics system will be modeled analytically in the MATLAB/SIMULINK environment and then will be tested in the hardware-in-the-loop (OPAL-RT) test platform. Afterwards, the controller will be tested in the real-time experimental setup. Finally, the controller will be deployed for various applications as wind energy and/or photovoltaic (PV) systems and/or energy storage systems.

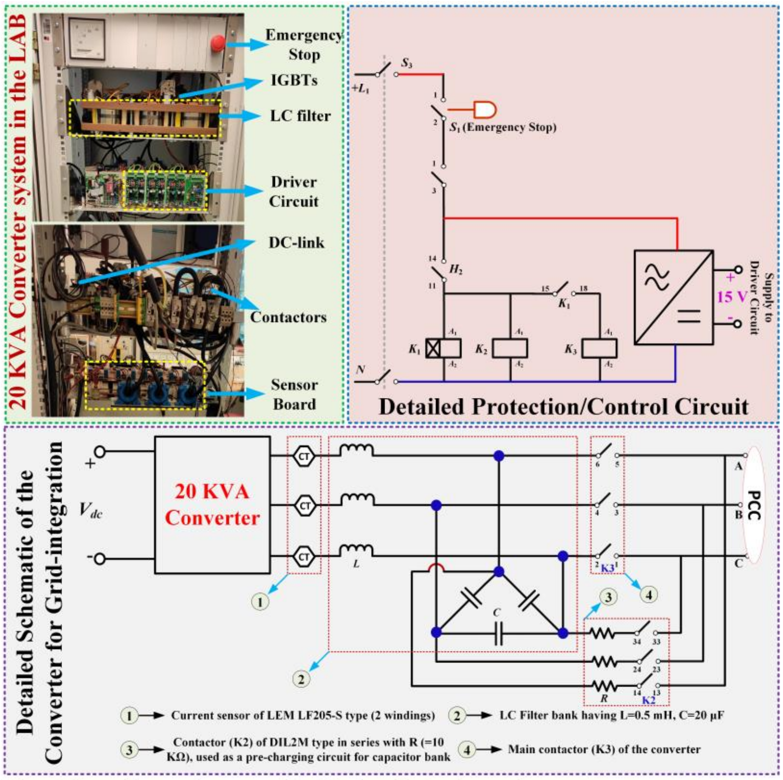

Fig. 1 Experimental setup with it's detailed schematic

In order to carry out the experimental work, the 20 KVA converter system as shown in Fig. 1 will be used for the grid-tied renewable energy system.

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Research Group: Power Systems
Co-Supervisor(s): Poul Einar Heegaard, Department of Information Security and Communication Technology
Project: NTNU 'TSO-Energi' project titled 'Reliability Studies in Information and Communication Technology (ICT)-dominated Power Systems'.

Reliability Studies in Information and Communication Technology (ICT)-dominated Power Systems

The PhD project has been granted at the Department of Electric Power Engineering (IEL) to address the challenges in the Strategic Research Area - Energy at NTNU, also as a means to support the activities of CINELDI. Further, given the cross-disciplinary nature of the project, there is collaboration with the QUAM lab at the Department of Information Security and Communication Technology.

Reliability assessment is indispensable to the conception of effective planning and operational schemes in the emergent variants of smart grid realizations across the world. In this context, research focus is on improving adequacy in Cyber-Physical Power System (CPPS). However, the extensive utilization of Information and Communication Technology (ICT) in CPPS makes the resulting reliability modeling complex and challenging.

The overall objective of the PhD project is to create a framework as a means of decision support for power system planners and operators towards quantifying the smart grid reliability in the form of suitable metrics (e.g., Loss of Load Probability, Expected Energy Not Served, etc.) WHEN extensive ICT permeates the planning and operation of power systems. The ever-increasing implementation of ICT in power systems creates challenges that require the effect of a wide range of interdependencies between the ICT infrastructure and power system infrastructure to be qualified and quantified. Hence, special emphasis in the PhD work will be laid on the failures brought on by the interdependencies between the power system infrastructure and the ICT infrastructure in the reliability assessment of CPPS. Once the reliability quantification platform is in place, the target for its exploitation would be to identify the consequent reliable planning and operation criteria in CPPS.

The PhD work involves developing new methods and models for the necessary estimation of the reliability of CPPS. Quantitative metrics that capture the interdependent effects of the power system and ICT infrastructures will be developed. In the first phase of the project, a model for the reliability assessment of a single cyber-physical microgrid (CPMG) was developed. In the second phase, a model based on Monte Carlo simulation is being developed to be applicable to smart distribution systems.

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Project: N/A

Optimal Design, Operation and Control of Microgrids for Security of Supply

Description of the research

The future distribution system will be dominated by intermittent generation and stochastic loads connected to the grid through Power Electronic converters. As such, there is a need for newer microgrid solutions with respect to design, operation and control, to ensure security of supply. The idea of microgrids imposes a series of challenges for the network designer. As opposed to the traditional grid structures being uni-directional, passive and often radial of nature, the microgrid (MG) introduces a vast variety of new concepts, as well as structural and technical changes that will affect the operation of such systems to a massive extent. At the heart of these changes lies the change from passive to active distribution systems (ADS) where distributed generation (DG) is introduced at distribution levels and even loads can be actively controlled to some extent . The introduction of DG at distribution levels can potentially enable a cluster of loads and DGs to interact as a single controllable entity and even be disconnected from the grid to operate in island mode given that the DGs have been dimensioned for and their control designed for such operation. This is a MG and with it follows a vast list of challenges.

As such, evaluating the reliability, in particular the supply security of MGs will be of a much more complex nature than that of traditional systems. The reliability will among other factors depend on:

- Type of Protection equipment used (CB, fuses, sectionalizers etc.) as well as the their placement
  and coordination strategy
- Fault rates (PCS, DG, lines etc.) as well as their magnitude and other characteristics

- Control of DGs and their interfacing PCSs as well as the control of other power electronic equipment.
- PCS topologies used and their robustness regarding faults and abnormal conditions as well as the
  redundancy of the topology.
- Number of DG, their type and the combination, as well as their size and location
- Network configuration (radial, ring etc.) and possible reconfiguration states as well as nested microgrid
  Schemes
- Network topology (AC, AC/DC or DC)
- The ICT of the system, its failure rate as well as the system's dependability on this network.

The main focus of the PhD project is on the broader research question of the optimal design, operation and control of microgrids for security of supply. Procedures and conditions for a safe and secure transition to a stable microgrid from both dynamic and steady state perspectives will be a focus research topic, including the impact of local storage and renewable energy sources from a reliability (security of supply) point of view. Further, investigation is to be aimed at quantifying the integration of power electronics and their control schemes with respect to reliability in microgrids. Thus, the PhD project will include an appropriate mix of power systems analysis perspective and power electronics perspective. The objective of the PhD project is to develop a viable, representative and customizable model of a MG including DG, PCSs and protection equipment as well as control systems and protection coordination for the purpose of conducting security of supply studies. The model should be customizable in a manner as to allow the investigation of different network configurations and topologies. This model will then be used to investigate in particular the overall system control, fault management system, power electronic components as well as energy storage devices and their impact on the reliability of the system.

Innovation potential and possible applications

The work and models built could serve as reference and tools for further studies in the field within the department. The cross-field nature of the research could also serve as a platform for interdisciplinary work between fields, in particular power systems and power electronics.

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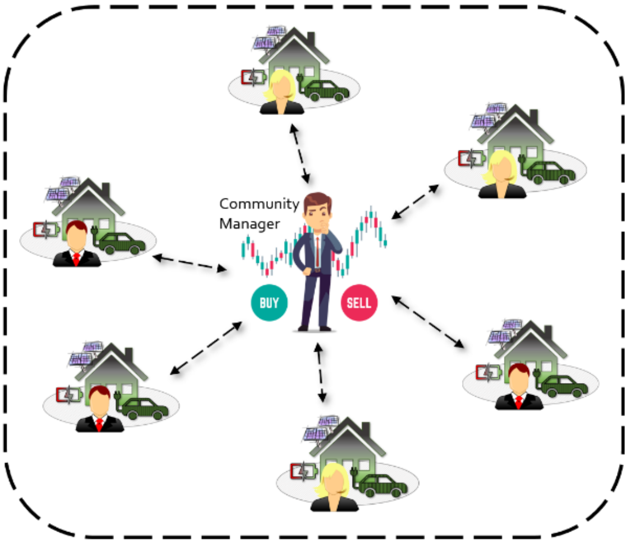
Project: Digital Economy

Consumer-Centric Electricity Market Design Integrating Peer-to-Peer and Flexibility Markets

The decreasing costs of distributed energy resources such as photovoltaic and wind has lead to massive installations of local production at end-user level. Meanwhile, communications technologies enable smart control of demand side flexibility such as flexible loads, EV charging and batteries in order to provide flexibility to the system.

In order to fully integrate end-users, a consumer-centric market design is required in order to incentivize efficient use of distributed energy resources. In addition, the prosumer era market design must allow participation in flexibility markets such as distribution grid congestion management, reserve and balancing markets.

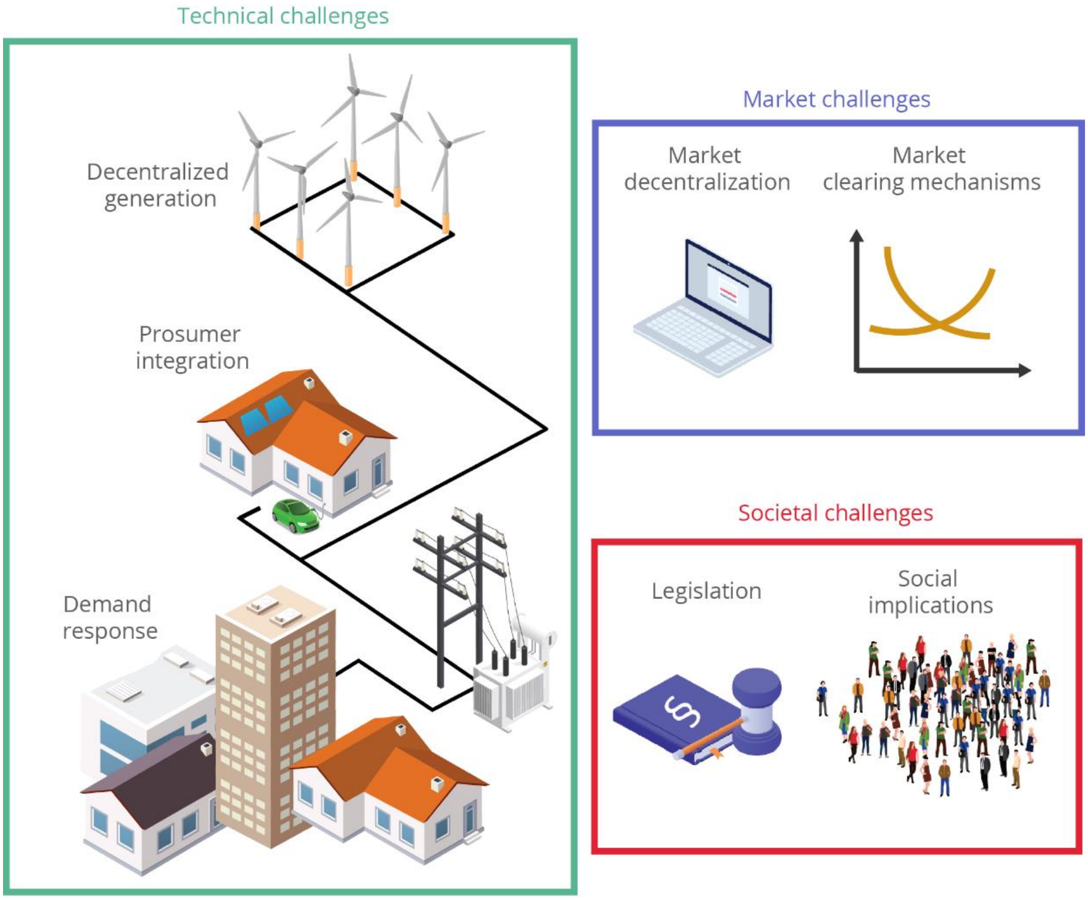
The PhD project aims to illuminate how the future digital energy economy can function in order to involve and engage end-users to participate in the green shift towards a carbon-neutral energy sector, using decentralized community markets with local interaction. This requires faster, more precise and decentralized transactions between peers in order to meet the increasing volatility in demand and production.

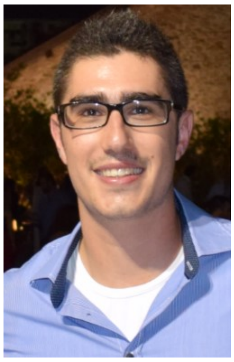


Innovation potential and possible applications

The products developed in this PhD mainly consist of optimization problem formulations for local market clearing including participation in local and system flexibility markets. The optimization problem can be used by aggregators, DSOs or end-users in order to coordinate flexibility from prosumers in order to increase the revenue from flexibility provision.

Another takeaway from this PhD work are analysis of grid and economic impact under a noncooperative game-theoretic framework. This allows regulators or system operators to see the monetary or grid impact of price signals and regulations under competition on end-user level.





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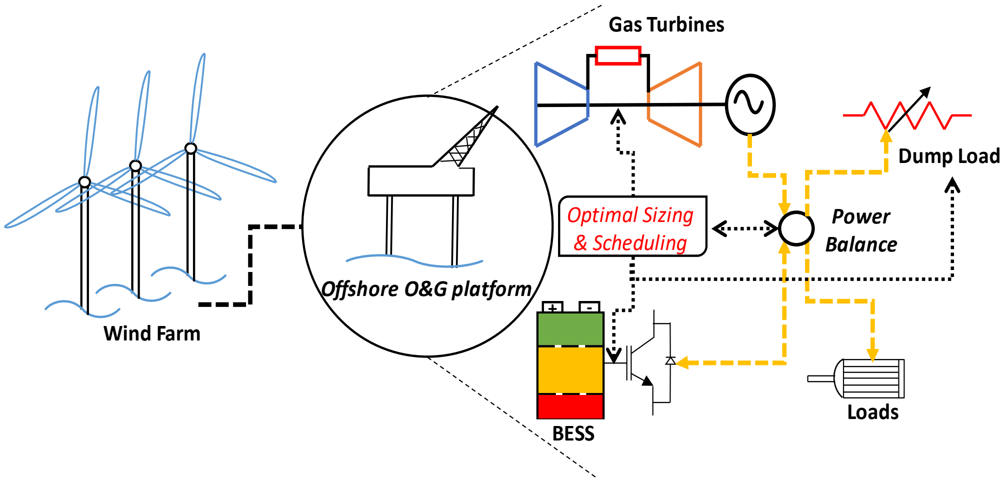
Project: EGO-OFF-STORE

Energy management and control of offshore platforms integrating renewable energy

Description of the research

In order to achieve a more sustainable offshore O&G platform operation, the latest industry trends are focused on finding ways to replace conventional onsite power generation systems with renewable based power supply. However, to achieve that and targeting for an emissions-free platform operation, additional components and methods are needed to overcome the existing technical constraints and limitations. Such new power systems which are governed by stochasticity in power generation and time varying inertia due to intermittent conventional power generation, are prone to various technical problems in different time scales, ranging from suboptimal operation to power quality issues.

To deal with the aforementioned problems, the idea proposed through this PhD research project, is the integration of appropriately sized energy storage to the platform's power system and the development of a corresponding smart energy management system (EMS) that will operate it. The goal of the proposed solution is to compensate the stochasticity of the intermittent renewable power generation, considering at the same time the different possible operational patterns of a platform and the plant uncertainties that arise from the constantly increasing number of power electronic interfaces to such weak grids. The storage technology of interest is chosen to be Li-Ion batteries, due to their constantly decreasing costs, the higher life expectancy and in general the higher technological maturity. An overall conceptual representation of the project's main research area is depicted in the following figure:



Innovation potential and possible applications

Considering the current situation where the offshore renewable power is evolving into a key role player in energy production and the future perspectives that demand efficient and cleaner resources utilization, the proposed PhD project comes as a natural interlink between the current and the future status. The results and knowledge gained from this project will be pivotal for the robust and optimal operation of the next generation O&G platforms with significant renewable penetration, sanctioning the future offshore smart grid concept.

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Project: CINELDI

Managing Energy Transitions: New Methods in Insights for Simultaneous Electricity Decarbonization and Transport Electrification

Managing Energy Transitions: New Methods and Insights for Simultaneous Electricity Decarbonization and Transport Electrification

Description of the research

Most visions for a future decarbonized economy call for the simultaneous decarbonization of electricity and electrification of road transportation. Meeting climate policy goals such as those of the Paris Agreement requires the accomplishment of these energy transitions at speeds high enough to keep society within prescribed greenhouse-gas budgets. This requires a greater understanding of how energy systems change over time, how such change can be influenced, and how the transitions of separate energy sub-systems may interact.

Managing the decarbonization and electrification transitions in particular will rely on knowledge of the feedbacks between electric transportation and power systems. Electric vehicles may impose costs as well as confer benefits on power systems depending on how decision makers take advantage of their flexibility.

This research investigates the simultaneous electrification of transport and decarbonization of electricity by combining methods from operations research and dynamic simulation modeling. The project aims to develop new methods for modeling the dynamics of energy transitions to study the determinants of the direction and speed of system change, the effects of alternative policies, and the interactions between electrification and electricity decarbonization.

Innovation potential and possible applications

This work aims to provide decision makers with new insights to manage the decarbonization of the power system in conjunction with vehicle electrification. The project is developing new decision support tools for studying energy transitions and informing policy choice. It will introduce a new energy system model of electricity generation planning and operation that simulates the dynamic evolution of the power system. This model is meant to enable a wide variety of future policy and system behavior experiments.

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Project: Digital Electrical Energy

Digital Solar Electricity

It was once believed that while solar energy was a promising technology of the future, it was too expensive for widespread use. But prices have been falling, and with that, installations at both a utility scale and consumer level have been increasing. The revolution in solar electricity continues around the world, and even in Norway, a country with abundant hydro and wind power resources, solar electricity is gaining traction. As the cost continues to drop and solar electricity becomes attractive both in new zero-emission housing projects, home owners wish to be wholly or partly self-sustained with electricity.

To realize the full potential of solar electricity, digital transformation of this energy source is very essential. This PhD research is concerned with investigating the technologies required to implement digital solar electricity in the future's intelligent and sustainable electric energy sector. Some of the different technologies that are considered in this PhD research are,

- Artificial Intelligence (AI) and Machine Learning (ML)
- Energy Optimization and Energy Storage Systems
- Distributed Ledger Technology (DLT) and Block Chain (BC)

The role each of the above technologies can play in the transformation of solar energy is summarized in *Figure 1* below.

The current grid was not designed to accommodate the diversity of renewable energy sources and the inherent variability of solar power creates challenges in meeting variable load. The utility industry is increasingly confronted with variable supply trying to match variable load. AI and ML can be used to help mitigate this challenge and make solar electricity an equal player in providing reliable electricity. AI methods can improve the integration and adoption of solar electricity resulting in a modernized electrical grid supporting the reliability and resilience of the overall grid. AI and ML can add new capabilities for integrating microgrids and helps in optimal placement of photovoltaic systems. The power electronics technology plays a vital role in conditioning and maximizing the amount of energy harvested from the sun. It also together with energy storage contribute in integration of photovoltaic systems with the utility.

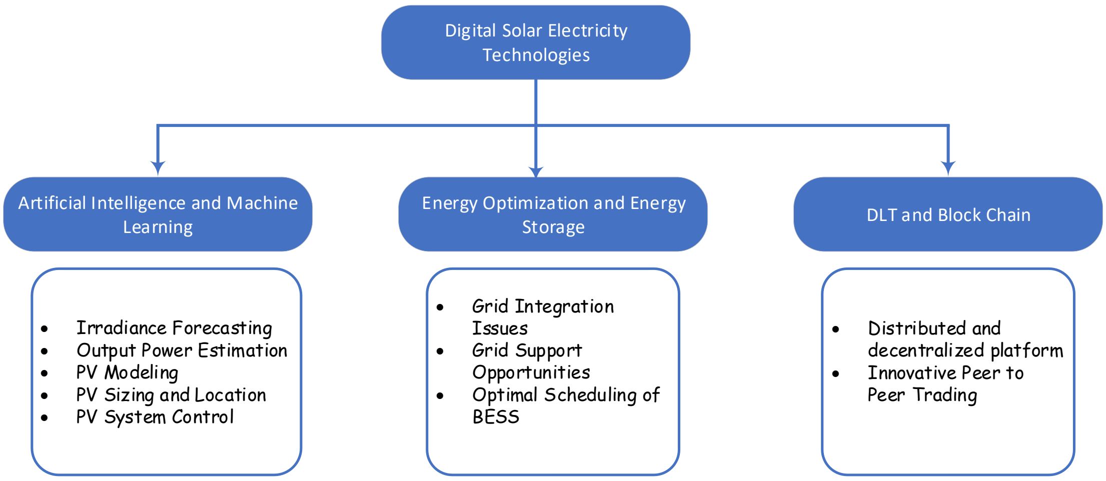

Figure 1: Digital Transformation of Solar Electricity

Innovation potential and possible applications

Outcome of this research can be used and implemented in the future's intelligent and sustainable digital electrical grid.

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Project: Short-circuit current making of MV switching devices with environmentally friendly gas

Investigation on Fault Current Making Operation of Medium Voltage Load Break Switches

Medium voltage (MV) load break switches (LBS) are required to withstand short-circuit fault currents of several tens of kiloamperes while avoiding severe contacts degradation in making operation. Regarding the switches operation (current interruption and making), there are several experimental results published so far in the field of contacts erosion in current interruption which is typically limited to <1kA, while there is a lack of understanding for the impact of electrical test condition on contacts erosion and welding during pre-strike arc and closed position in making operation. Therefore, it is essential to put more effort into discovering the interface of arc and the electrical contacts during short-circuit making operation to *maintain* and *improve* MV-LBS *reliability*. Besides, using air-filled devices as an alternative to SF_6 makes the switchgear more *environmentally friendly*. Unfortunately, this replacement leads to a more challenging operation due to lower dielectric strength and consequently higher arc duration, leading to higher energy dissipation and increases melting and welding possibility.

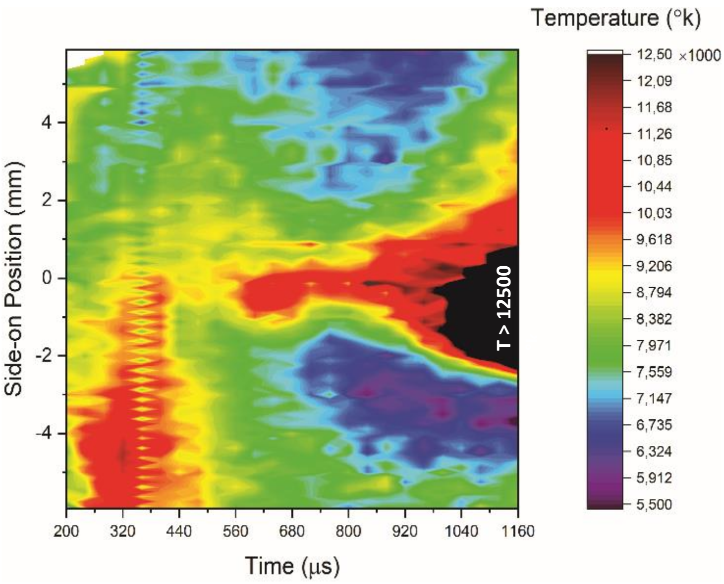
This Ph.D. thesis work is on an experimental study on fault current making operation in MV-LBS to improve the switch operation by better understanding the pre-strike arc behavior and the switch operation. For this purpose, different diagnostic methods are employed, focusing on how electrical test conditions and mechanical switch properties are relevant to the electrical contacts degradation.

The key issues regarding to this work objectives can be summarized as follows:

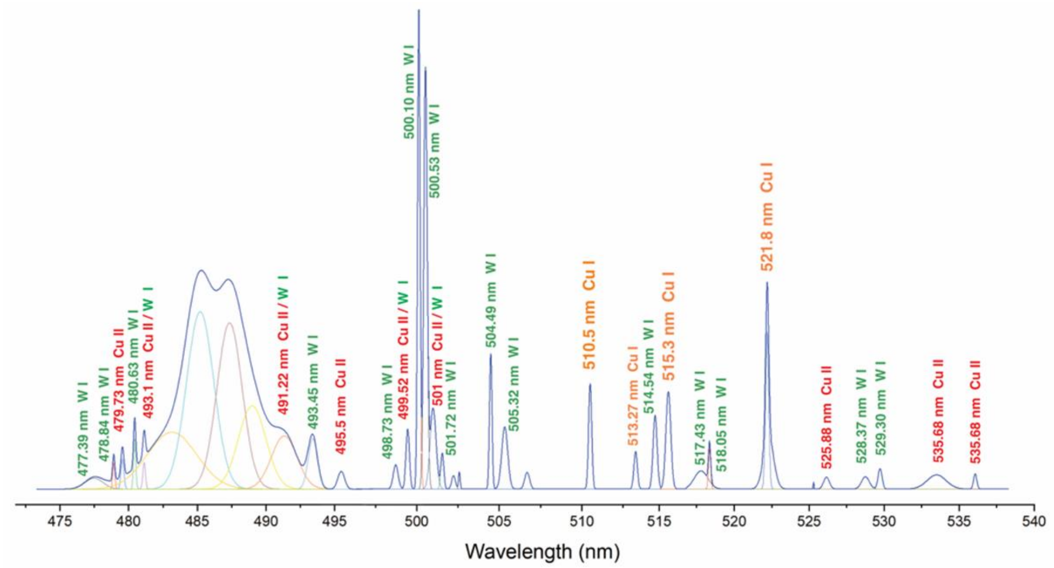
- Understanding how making operation (pre-strike arcs) at different currents affects contact degradation (time and spatial evolution of contact surface)

- Describing the interaction between pre-strike arc and contact surface for different circuit parameters
- Investigating the influence of gas mixture (e.g. AirPlus) on contacts degradation and electrical properties
- Developing an empirical model for contacts erosion by arcs during making operation valid for different parameters

Some recent results show the pre-strike arc dynamic motion from the ignition to the stable position while the electrical contacts are closing. The results can be used in arc behavior prediction, which provide information for more accurate modeling and simulations and improving the switch function. The below images show the temperature profile for pre-strike arc at a test voltage of 18 kV and 50Hz half-cycle making current of 17 kA and the metalic composition of the arc due to the contacts surface evaporation.



Temperature profile of pre-strike arc for 18 kV breakdown voltage and 17 kA load current (50 Hz)



Spectral profile of arc composition at 240 μs with spectral lines correspond to atomic and ionic copper and atomic tungsten

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Research Group: Electricity Markets and Energy Systems Planning
Co-Supervisor(s): Vijay Venu Vadlamudi
Project: Energy Informatics

Blockchain Technology and Optimization Algorithms for the Future Local Energy Markets

Description of the research

In this project, TSO-DSO interactions and local market level potential energy blockchain and advanced optimization use cases, such as peer-to-peer energy trading and flexibility management use cases with energy storage, distributed energy resources and electric vehicles penetration will be investigated.

The work will largely focus on developing models, methods, simulation tools and possibly prototypes to create and assess different solutions for realizing blockchains for electricity sector transformation. The models may target to develop new local power market designs and important components such as local energy market price signals and control strategies by using advanced deterministic and stochastic optimization models and machine learning algorithms. Functional requirement of different architectures (both from the system's perspective and the user's perspective) will be established first. Social broader impacts of the use of blockchain technology within the context of future power markets and systems will also be investigated.

Innovation potential and possible applications

Next generation local energy trading algorithms will be proposed and developed using cutting edge technologies, such as distributed ledger technology and (distributed, hierarchical and federative) optimization methods to answer real-life challenges. The main motivation includes relieving stress and reducing investments in the grid, as well as democratization of energy. The outcome of this PhD project may thus be an important contribution to the realization of upcoming transactive energy markets.

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Co-Supervisor(s): Robert Nilssen, Urban Lundin
Project: Electromagnetic Analysis and On-line Fault Detection in Hydropower Generators

Electromagnetic Analysis and On-line Fault Detection in Hydropower Generators

Large synchronous generators play an important role in the power generation industry and its duty in this way is indispensable. Although synchronous generators are reliable, they are subjected to some modes of failures. If a generator continues to operate under faulty conditions, its efficiency drops considerably, and its life span is shortened. As a matter of fact, the generator stoppage and outage from the energy generation process causes huge economic loss. Consequently, fault diagnosis at initial stages of occurrence not only prevents the fault extension, high periodical expenses and outage of the generation loop but also preserves the nominal life of the generator. These failures in synchronous generators may be inherent itself or due to the operating conditions. Faults in synchronous machines include: static, dynamic, and mixed eccentricity, stator, and rotor Inter-turn and ground short circuit fault, broken damper, and end ring fault. Few methods have been proposed and applied in order to detect several kinds of failures in synchronous generators at different stages, however, most of them are unsuccessful in detection procedures.

The basis of any reliable fault diagnosis method is the inclusion of the real behavior and conditions of the faulty machine. Consequently, a proper and at the same time the most important step will be modeling of the problem. Modeling method is the foundation for the next step of fault detection. In this study, Ansys Electronic will be used as a way to simulate a synchronous machine in a healthy and different type of faults from no-load to full load. Experimental results should be used to certify the simulation results. For this purpose, experimental set up which is provided with different types of fault like Static Eccentricity, Excitation short circuit fault, and broken damper bar fault.

The main goal of this project is based on the fact that new indices should be introduced in order to detect the fault at its early stage, as a matter of fact, novel theoretical indices for eccentricity short circuit and broken damper faults based on magnetic flux, electromotive force and vibration should be extracted. These analytical indexes should be precise enough for fault detection purpose therefore, the saturation and stator slot effects should be considered. The output of the FEM simulation of the synchronous generators such as current, electromotive force, magnetomotive force, air-gap magnetic flux, vibration and shaft flux, and voltage should be analyzed using time or frequency domain-based processors. Novel theoretical indices should be demonstrated in the processed signals of nominated processors. Finally, classifier and artificial intelligence tools should be used to discriminate the severity and type of faults.

Experimental set-up of synchronous generator for fault detection purpose

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Co-Supervisor(s): Maider Santos - Mugica

Project: IDeCON

Embedding Control Design in the Topology Optimization of HVDC Grids

The global tendency towards the implementation and improvement of the Distributed Energy Resources (DER), especially renewables, in response to the realization of smart grid policy is extensively growing in recent years. The motivation for the integration of renewables into the global energy network is not only to meet the increasing energy demand but also to improve the energy availability, reliability, security, and quality as well as to compensate for the adverse impact of fossil fuels and nuclear energy on global warming. Among different renewables, offshore wind farms have attracted considerable attention mainly in Europe due to their geographical feasibility, especially in the North Sea. High Voltage Direct Current (HVDC) cables together with Voltage Source Converters (VSC) are the common technology to transmit large amounts of wind power, in particular from offshore applications to the land power system. HVDC networks are going to be an inevitable part of smart grids since they are one of the most reasonable alternatives where long-distance transmission networks or submarine cable routes are required.

This Ph.D. project, as a part of the IDeCON research project, is focusing on the design and control of offshore HVDC networks. The main aim of the Ph.D. project is to provide a comprehensive guideline for the design and modeling of offshore HVDC grids while utilizing optimization methodologies and including control constraints, to satisfy initial design considerations. The study should offer solutions not only for the design and development of new HVDC grids from scratch but also it needs to cover strategies for the expansion of currently existing networks. In particular, it is intended to extend the design and modeling approach from point-to-point topology to radial and multi-terminal configuration and further into meshed networks. The most significant challenge through the development of the models is to reassure the stability of the system under steady-state and transient conditions while taking into account, for example, the techno-economics and environmental considerations. Therefore, there is a demand for the implementation of multi-layered control strategies comprising optimization constraints. The topology optimization should not only be limited to the equipment level, and it needs to be so comprehensive to embrace the entire system.

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Digital Solar and Storage for Energy Access and Future Power Systems

Description of the research

The Sustainable Development Goal 7 – Affordable and Clean Energy – indicates a responsibility to increase knowledge on energy access. From the latest *Tracking SDG7: The Energy Progress Report 2020** it results that we won't achieve the 2030 goal for SDG7, if we continue at the current pace. There is a need for new knowledge, tools and methods to accelerate clean and affordable energy access.

In this research project we develop and improve tools and methods (energy system planning and operation) for energy access with a focus on solar and storage units. We study the feasibility of local and decentralized solar and storage systems for rural areas in emerging and developing countries under dynamic grid conditions, by making use of digital technologies (sharing with DLT, prediction with AI, communication with IoT) and incorporating flexibility (generation, storage, demand, mobility).

The main question to answer during the research are: Can the proposed solution provide an acceleration of electrification timeframes, an improvement of service delivery, a reduction of electricity costs and a better redistribution of social benefits?

Innovation potential and possible applications

The innovation potential lays in improved local energy system by e.g. optimal dynamic placement of mobile storage units, optimal local cooperation and energy exchange and/or optimal share of off- and on-grid solutions. The developed tools and methods are both relevant for national governments and their electrification roadmaps, investors or technology providers analyzing the market potential in different electrification areas and policy makers' incentives that can accelerate the electrification timeframe to achieve the SDG7 for 2030.

*https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/May/SDG7Tracking_Energy_Progress_2020.pdf

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Time-frequency analysis to enhance and simplify stability assessment in power electronics dominated grids

Dealing with the rapid increase of converter-interfaced components in Smart Grids involves improving our means of stability assessment. Analytic modelling and analysis of small to large power systems is hampered by uncertainty and complexity of their constituent parts and should be aided by measurement-based approaches. Time-frequency analysis spans more than traditional system identification algorithms as the field is dedicated towards signals that vary both in time and frequency. Such signals are frequently encountered in Smart Grids: global and local load and production variations, harmonic oscillations in power electronic dominated grids and abnormal frequency oscillations, to mention a few.

In particular, I believe single-phase synchronisation should receive a thorough assessment of its contribution to stability issues in Microgrids. Synchronisation techniques have become very complex and sometimes measurement interpretation with and without perturbation may be the only way for accurate assessment. In Figure 1 and Figure 2, the so-called harmonic transfer functions are shown for two simple synchronisation units; the complex ones are not easily modelled and will benefit from time-frequency analysis.

Innovation potential and possible applications

The contribution of this PhD is anticipated to be of value for:

- Researchers concerned with modelling and design of power and power electronics systems
- Practitioners looking for easy-to-use system identification techniques

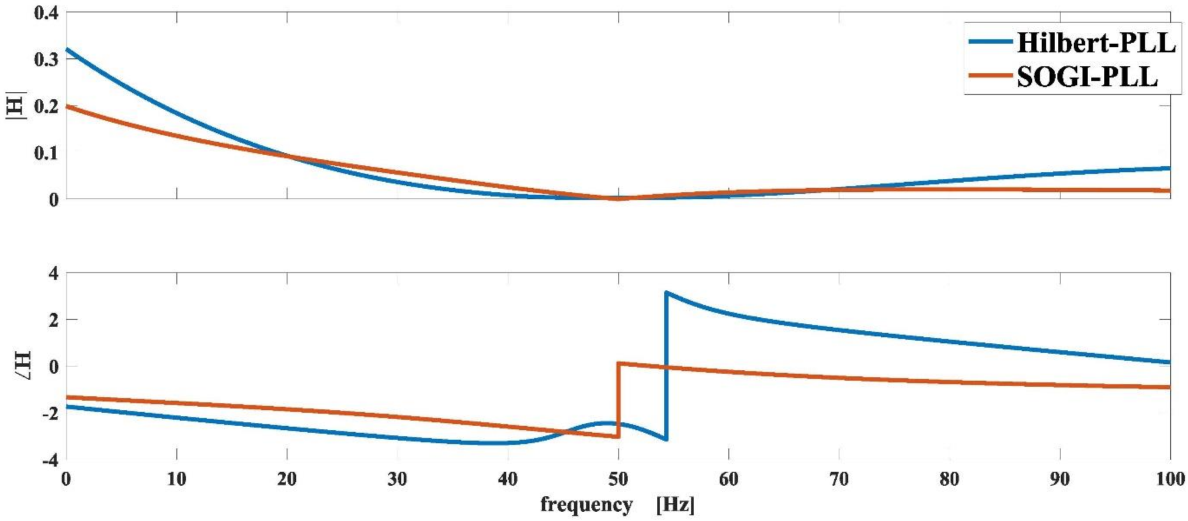

Figure 1: Harmonic transfer function for two synchronisation (Phase Locked Loop) units – this bode diagram relates a sinusoidal input with frequency f to a sinusoidal output with frequency f+50 Hz.

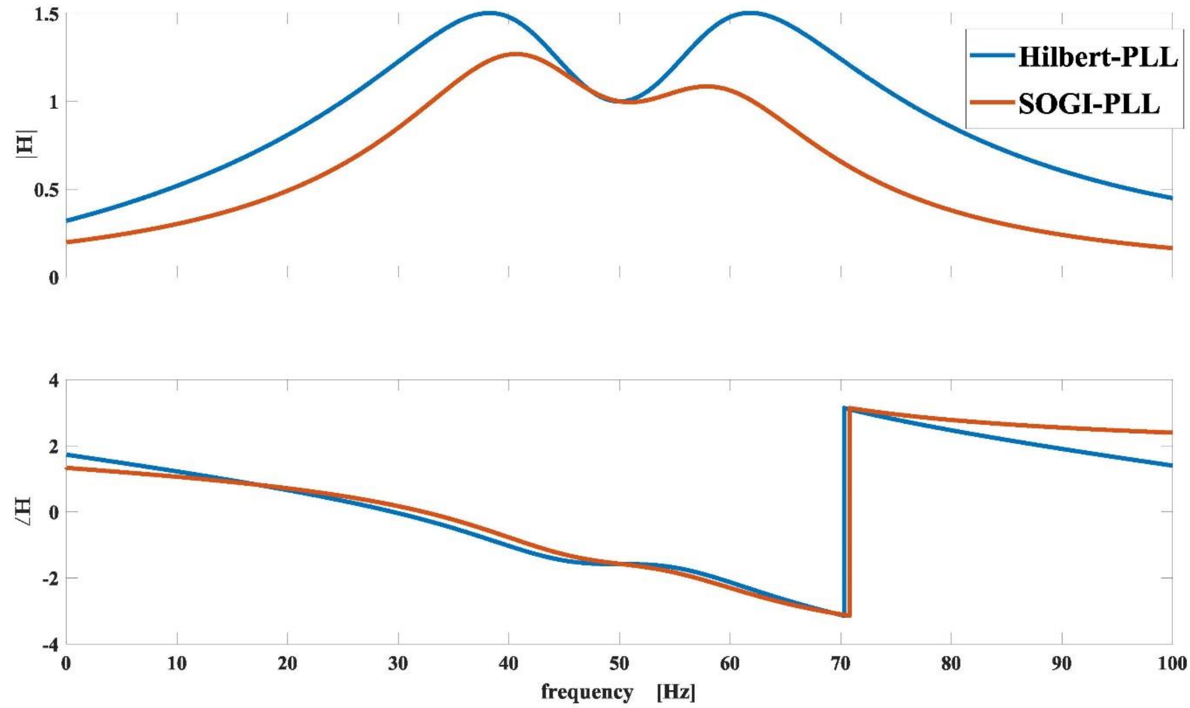

Figure 2: Harmonic transfer function for two synchronisation (Phase Locked Loop) units – this bode diagram relates a sinusoidal input with frequency f to a sinusoidal output with frequency f – 50 Hz

Combined, Figure 1 and Figure 2 describe the synchronisation units.

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Project: Power electronics for MVDC circuit breakers

Power electronics for MVDC circuit breakers

Medium voltage DC (MVDC) distribution grids (either point-to-point or multi-terminal) have started gaining attention due to their advantageous performance compared to the conventional MV AC counterparts (lower losses, flexible power control and elimination of reactive power compensation, etc.). DC distribution grids on vessels and O&G offshore platforms, DC collector grids for offshore wind generation and large-scale energy storage integration count as very promising application areas of MVDC. Fig. 1 shows the most promising future on-shore and off-shore applications of MVDC grids.

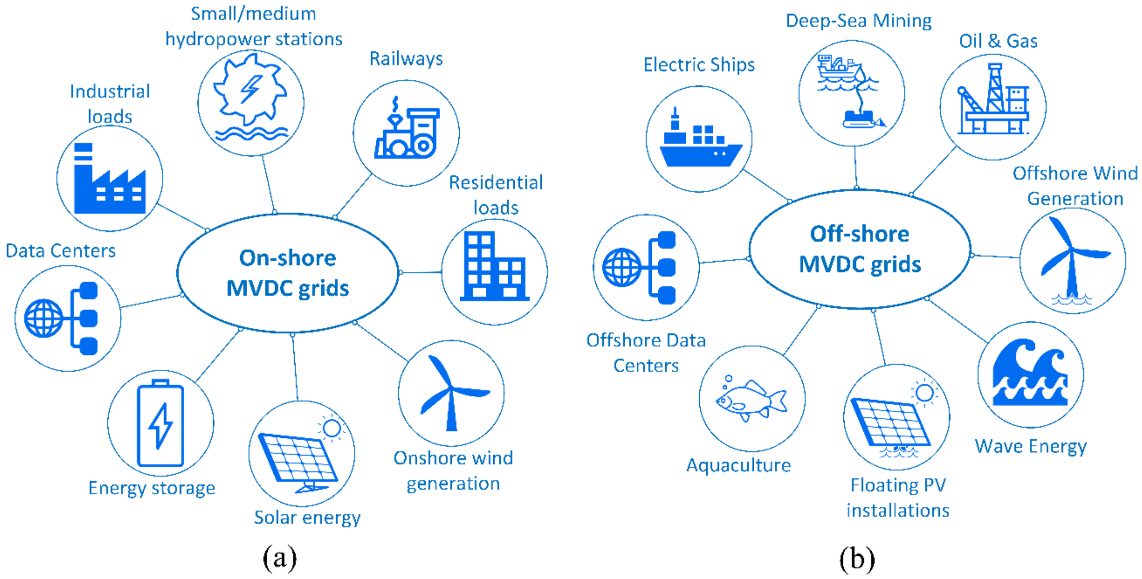

Fig. 1: Potential a) on-shore and b) off-shore applications of MVDC grids.

A design barrier for MVDC systems, however, is associated with short-circuit fault handling. In particular, under a short-circuit fault condition in MVDC systems the absence of natural "zero-crossing" in the direct fault current makes the conventional AC breakers unable to clear direct fault currents. Three MVDC breaker concepts exists: (i) the *mechanical MVDC breaker* which uses a conventional AC breaker along with an electric circuit which creates artificially a zero crossing point for the fault current (ii) the *hybrid MVDC breaker* which combines a conventional AC breaker with power electronic circuits and (iii) the purely *solid-state MVDC breaker* that only employs power semiconductors. Fault clearing times, maximum allowed overvoltage across the breaker and fast residual energy dissipation are listed among the crucial design challenges of MVDC breakers.

The main goal is expected to be the design of novel power electronic solutions for the future MVDC circuit breakers. In particular, the PhD study will investigate the power semiconductor requirements and performance including investigations of novel semiconductor materials (e.g. SiC), their control circuits and auxiliary systems. The PhD project will be implemented using theoretical investigations (simulations and numerical calculations) and advanced experimental validations of various MVDC breaker concepts under real operating conditions.

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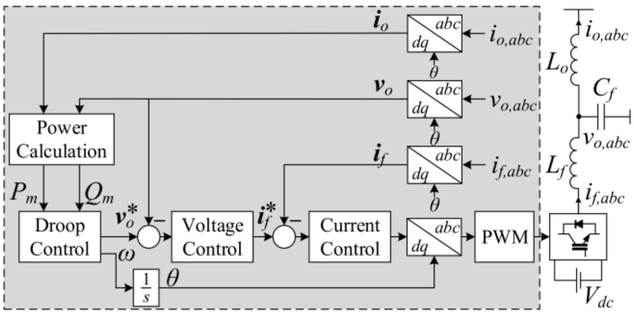
Project: CINELDI

Smart Power Control in Microgrids with Modern Power Converters

With the clear political goal of increasing the share of renewable energy sources in the energy mix, the scientific community has been developing strategies for adapting the electricity grid in order to accommodate the change of resources. Microgrids are seen as one particularly attractive option in this regard, due to the capability of incorporating renewable energy sources. Microgrids can be defined as a cluster of loads and DERs, which are connected to the main grid at a single point, and which is capable of working in grid-connected and islanded modes of operation.

Decentrally controlled microgrids have the advantages of plug-and-play capabilitiy, low-dependence on communications and accurate active power sharing. However, this type of control is known to have poor reactive, harmonic and unbalance power sharing. In addition, the stability of this type of control is sensitive to the system configuration and operating point. The most commonly used scheme for this type of control is the conventional Pf, QV droop control, which is shown in the figure below.



A commonly used method to address some of these issues are virtual impedances. These methods can potentially improve reactive, unbalance and harmonic power sharing, as well as stability margins. On the other hand, these methods typically lead to a reduced power transfer capability and reduced system voltages. The inherent trade-offs when using this method is currently being researched.

The low stability margins observed in many microgrid applications still needs more attention to be fully understood. Hence, improved reduced order models have been developed. These models will be used further in order study what type of controllers are the most suitable in improving the system stability margins.

Innovation potential and possible applications

Reduced-order models of microgrids will become increasingly important to ensure successful integration of more distributed generators. These models are numerically efficient studying systems with many units. Moreover, improved controllers can be built once the details about system stability is better understood.

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Project: Energy Informatics

Title: Electrical Energy Informatics for Transactive Energy and Flexibility Mechanisms at Power System Transmission and Distribution Levels

One of the current challenges the power sector facing is how to evolve with respect to new disruptors in power industry such as increasing number of prosumers, distributed energy resources and electrical vehicles.

The Distributed Ledger Technology (DLT) can allow these increasingly complex systems to be managed conveniently by TSO and DSOs. The development of algorithmic energy trading platforms with blockchain technology and Artificial Intelligence (AI) can allow power sector to utilize microgrids and energy storage in a more efficient and democratized way while maintaining the real techno-economical constraints of power system stability. Meanwhile flexibility management use cases such as active side demand management with Explainable Artificial Intelligence (XAI) and DLT can provide cutting edge platform for forecasting and mitigating imbalances within power system as well as performing anomaly detections.

Innovation potential and possible applications

The usage of emerging technologies such as DLT, new forms of Artificial Intelligence (AI) and other ICTs will be given top priority to manage increasing complexity and data security of power markets. The use of XAI within the context of energy systems such as energy forecasting and anomaly detection will be proposed and developed. The proposed solutions to mentioned new challenges in power sector will be an important contribution for upcoming energy transition.

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Project: Cotutelle agreement with DTU

Smart Wide Area Monitoring and Control for Secure Operation of Power Systems with high penetration of Renewable Energy Sources

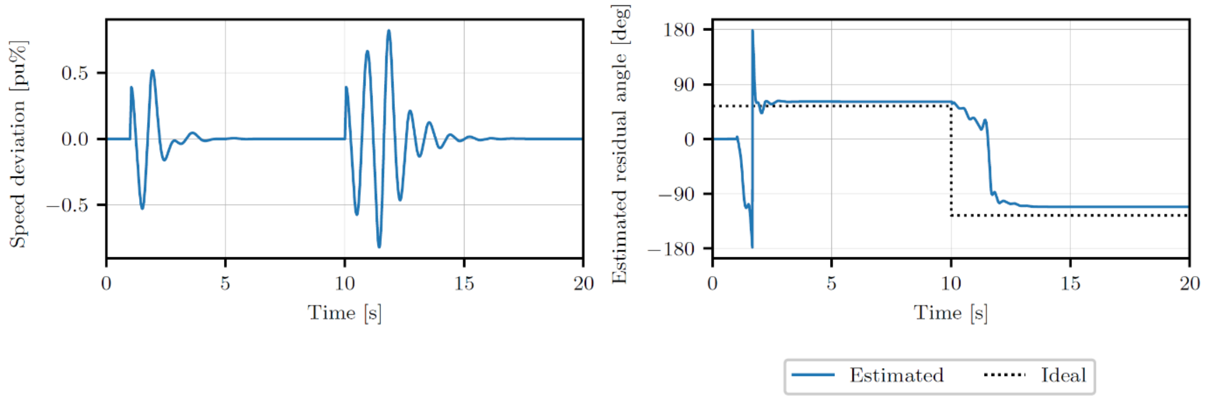
Description of the research

The focus of the project is on developing methods for monitoring and control of large power systems. Recent trends of increasing share of renewable energy sources and increasingly intensive loads cause larger fluctuations in both production and consumption. This requires sophisticated methods for monitoring and control to ensure secure operation of the grid.

Currently the focus is on power oscillations. The first stage of the project resulted in a method that monitors the frequency of power oscillations occurring in the system, as well as the amplitude and phase with which the oscillations are observed in the different parts of the system, referred to as observability mode shapes.

For the next stage, the focus is on developing control methods for mitigation of power oscillations, which make use of the above obtained information. Currently, an adaptive Power Oscillation Damper is being developed. The controller is adaptive in the sense that it estimates the ideal phase compensation between the measured input and the applied control action.

The following figure shows an initial result from applying the adaptive controller to a Single Machine-Infinite Bus system, where the generator speed is monitored and the excitation is controlled (like in a conventional Power System Stabilizer).



The plot to the left shows the measured speed deviation. Short circuits are applied at $t = 0$ s and $t = 10$ s. Additionally, the model is modified such that the ideal phase compensation is changed $180°$ at the time of the second disturbance, requiring the controller to adjust its internal parameters to make sure that oscillations are damped, not amplified. The plot to the right shows the estimated phase compensation, as well as the ideal phase compensation (calculated using modal analysis on a linearized model). The controller performs well in this simple case.

Further testing needs to be done to assess the performance in larger power systems. This constitutes the continuation of this work.

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Regenerative Power Converters for Accelerator Magnets

In order to control the particle beams at CERN large magnets are supplied with currents via distribution lines, and a large number of power converters are used to provide these currents to the DC-lines, as shown in the functional diagram of Figure 1. Depending on the specific experiment, the current pulse can have a varying duration and hold-time between pulses. The energy in the magnets are stored in the magnetic field, and it is recovered back to local energy storage system at the end of the cycle, where it can be reused in the next cycle, while the power losses are supplied from the grid.

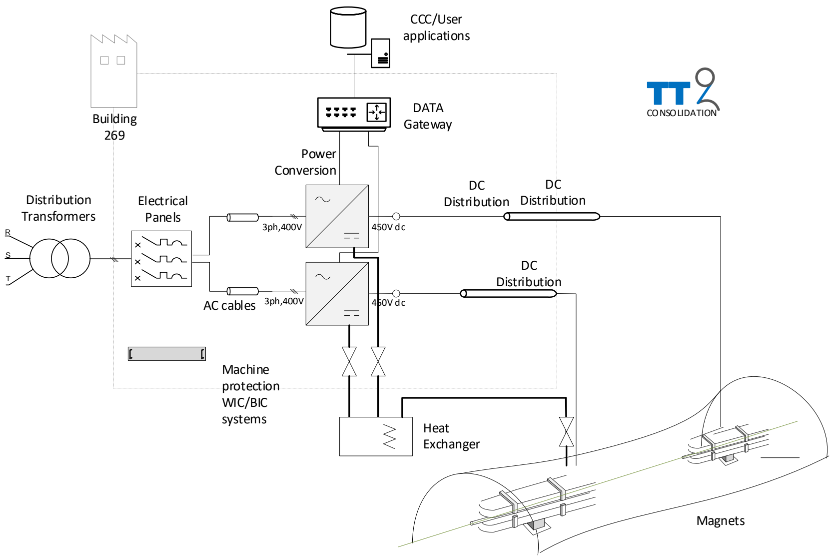

Figure 1 Functional diagram of the current delivery system for the accelerator magnets

The application aims to use many different methods for storing power sources, combining the local energy storage with the grid in a robust and efficient way. The main goal is to make a converter than can easily scaled to the required current level and storage for the cycling.

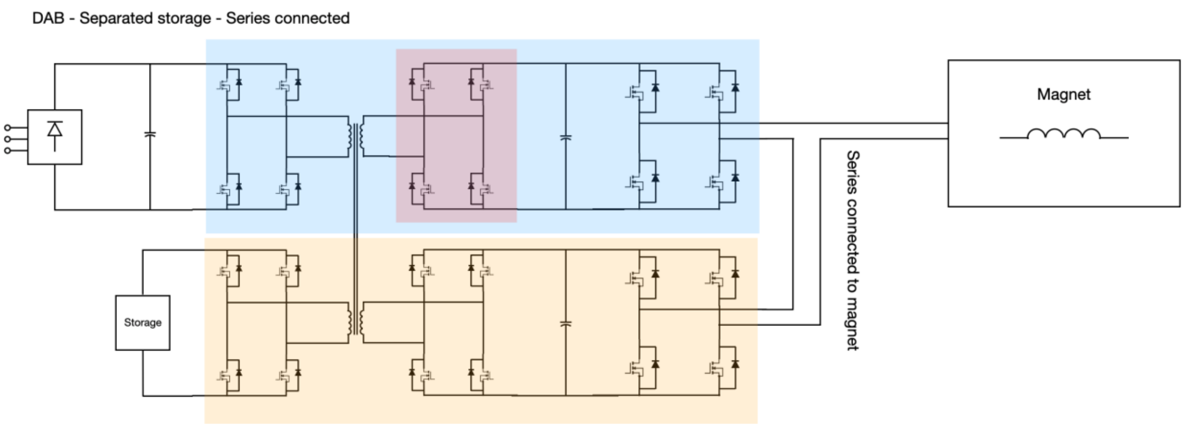

Figure 2 An example of a configuration using DAB with a common core transformer, allowing maximum flexibility in power flow and voltage ratios

Depending on the duration of the pulses, different types of storage might be of interest, such as flywheels, batteries or capacitors. In addition, series and parallel connected converters can be used to reduce ripple on the delivered current and THD. The former is considered extremely important, and can have requirements to be below 5ppm. By using wide band-gap devices, such as SiC MOSFETs, it's possible to get close to this requirement without using big filters, as is the case today.

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Demand side flexibility as an alternative to investments in the transmission grid

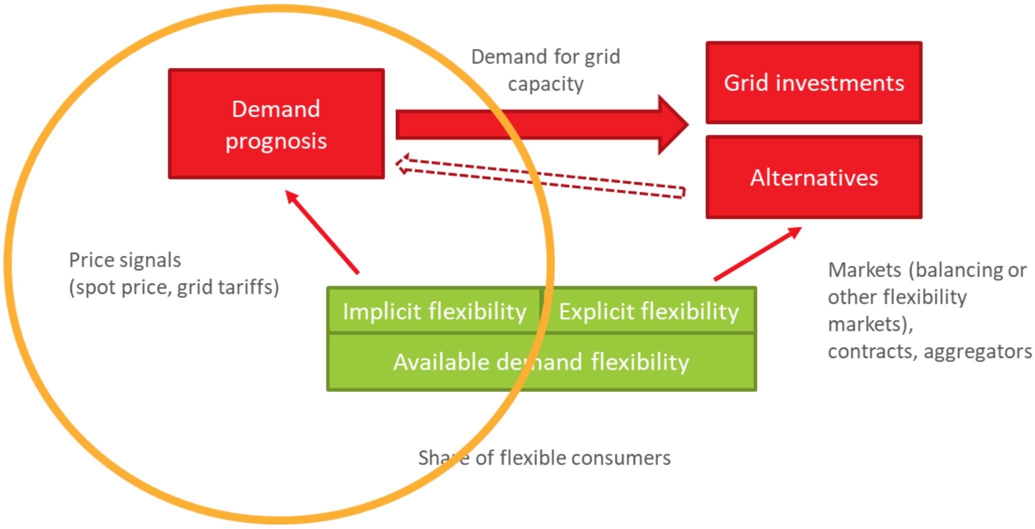
Description of the research

Main objective: *The project will provide empirical based knowledge and research on how demand flexibility will affect the peak load in the future and how it can and should be included in demand forecasts to avoid overinvestment in the grid and to contribute to a cost effective and secure power system.*

The research is focused on households, commercial and public buildings in city regions. In addition, the project will be limited to implicit demand flexibility, meaning demand response triggered by price signals from variable power price and grid tariffs.

The research will be based on the analysis of empirical data from different sources, as data from Statnetts operations, Elhub, Nordpool, existing demo projects, and the design and execution of a new experiment on implicit demand flexibility. Statistical analyses will be used to quantify the existing and future price elasticity of the end users. In addition, statistical analyses will be used to determine what parameters have the highest impact on the price elasticity.

Research will also be performed on the usability of variable grid tariffs for peak reduction and how the available demand flexibility potential in a specific region can be identified based on data from Elhub and/or data from surveys.



Innovation potential and possible applications

The results of the research will be used in Statnett's demand forecasts and in the analyses of future investments in the transmission grid. A short list of expected results that can be applicated is:

- Representative and quantified numbers for the expected demand response from households, commercial and public buildings triggered by price signals from power market and grid tariff (implicit demand flexibility)
- Results on expected demand reduction and shifting from peak hours dependent on different parameters as price, building characteristics, flexible electricity demand sources (heating, warm water boiler, electric car, ventilation, PV, etc.), smart equipment for control of electricity and feedback, local climate etc.
- Quantification of the consequence of implicit demand flexibility on the demand peak in Statnett's demand forecasts and therewith as an alternative to grid investments
- Understanding of the effects on the demand response of different values of the parameters in the proposed grid tariffs for the distribution grid and how they can be used to reduce the peak demand in Statnetts grid
- Method to obtain information about remaining demand flexibility in a specific region based on Elhub-data

The expected results will have an immediate benefit for Statnett and other grid companies as outlined here:

- Improved long term demand forecasts with credible inclusion of demand flexibility
- Realistic estimates of the potential and cost of demand flexibility will be used directly in Statnett's socio-economic assessments of new grid investments and can lead to cheaper solutions
- Increased knowledge for distribution grid companies on how to design an optimal grid tariff that takes into account the potential savings in both the distribution and transmission grid

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Project: Prodig

Interoperability of sensor technologies in digital substation

Description of the research

The substation is a key infrastructure element of an electricity generation, transmission and distribution system where voltage is transformed from high to low or the reverse with power transformers. Since the numerical control and protection technology stepped into substation automation and protection systems (SAPS), several protocols were introduced to define the substation automation system (SAS) architecture. The IEC 61850 outlined the data structure and architecture of communication functionalities, showing more flexibility and functionality than others. In this series of standards, a digital substation is referred to a substation that utilizes the IEC 61850 process bus and integrated intelligent electronic devices (IEDs) in its SAS architecture. In such architecture, the primary signals such as current and voltage measurements, switchgear position status and control, etc. are digitized in the field at the process bus. The process bus accommodates several benefits including reduced cabling cost, faster commissioning, facilitation of low power instrument transformer (LPIT), also known as NCIT in a multivendor environment.

The NCIT compare to conventional instrument transformers have advantages such as excellent insulating property, Free of magnetic saturation and ferro-resonance, anti-electromagnetic interference, wide range of transient response, and high precision. In contrast to the mentioned advantages, the existence vendor specific implementation of process bus and various instrument transformer technologies causes threat to the protection devices.

Thus, this project aims to test and analyze new sensor technologies including non-conventional instrument transformers to quantify the interoperability of existing and new technologies as well as improve selectivity and sensitivity of protection and fault location. To achieve this, it is also required to develop and utilize the test platform for digital protective devices (including time synchronization) connected to process and station bus in NTNU's laboratory. In addition, the online access to laboratories at NTNU and MTU will utilize complementary capabilities and allow the development of remote test procedures in a true multi-vendor environment. Figure 1 shows the interoperability test bed for multi-vendor environment with focus on differential protection scheme.

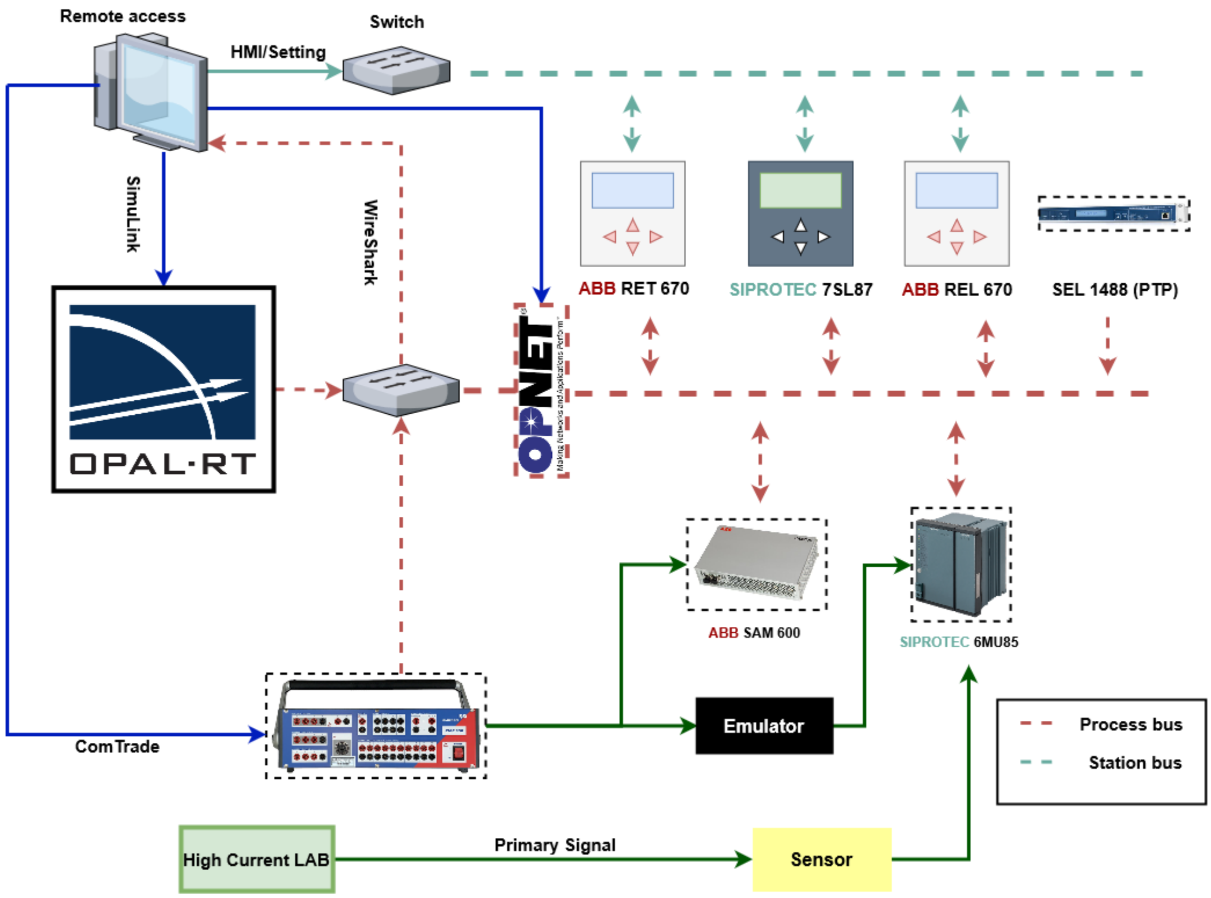

Figure 1: multivendor digital substation testbed

Innovation potential and possible applications

In this work package, the fundamental knowledge about interoperability and testing will be developed which enables smooth transition of the conventional substation into a digital substation. Thus, it is expected that the result of this research is published in international articles and conferences. In addition, this work will contribute to testing and standardization to calibrate expectations, documentations, and competence between users and manufacturers.

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Project: HILP - Analysis of extraordinary events in power systems

Methods for understanding and communicating uncertainties and risk related to extraordinary events

Description of the research

The complexity and uncertainties of the power system are increasing, due to integration of distributed renewable power generation, the introduction new technologies, more extreme weather and stronger integration between the Nordic and European power systems. Extraordinary events such as major blackouts are of special interest as they imply substantial consequences to society. The mechanisms behind these events are not well understood today, and there is a need to increase the ability to identify, understand and assess risks related to extraordinary events.

The PhD project has primarily modeled how threats external to the power system can cause simultaneous or near simultaneous unavailability of power system components, leading to blackouts. These events can happen more frequently than anticipated due to spatio-temporal correlation in threat exposure, e.g. due to major storms, and/or through protection system failures. The project results will provide decision support to make a best possible trade-off between security of supply and societal costs in planning and operation of the Nordic power system.

Innovation potential and possible applications

The results from the thesis could potentially be used to develop software tools to more accurately predict and prevent extraordinary events in the power system.

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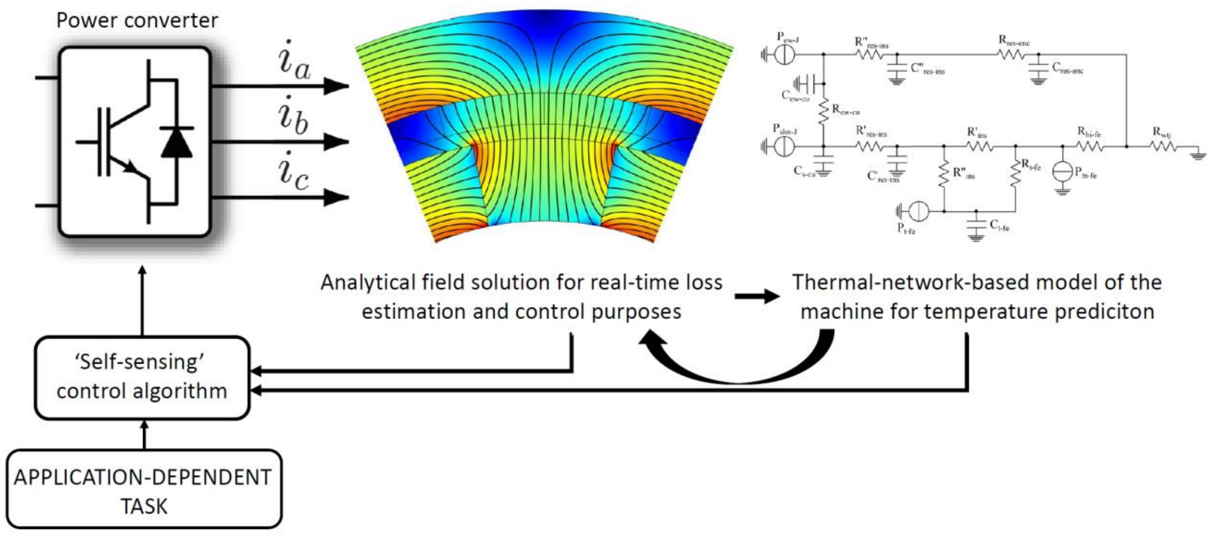
Project: Optimal Utilization of Smart Generators

Digital Twin-Based Performance Assessment and Behavior Prediction for Optimal Utilization of Electric Drives

Description of the research

As of today, the operation of rotating electrical machines, being them used as motors or generators, is usually bound by their rated operating conditions, which are typically defined after the design or manufacturing of the machine itself.

The project aims to modeling the behavior of electrical machines (motors or generators) as a part of a complex system (electric drive or generation system) to be studied as a whole. Among the different stages of the workflow, the electromagnetic analytical model, the thermal modeling of the machine and the 'digital twin' identification of the whole system, represent the main cornerstones of the project. Contextualizing the application will highlight intrinsic constraints to fine-tune the model to operate safely when controlling the system. Nonetheless, the final project could gather up different tools (from the design to the control of electrical machines) which can be benchmarked in different applications and for different machine topology, with the common aim of optimizing the final operation of the machine itself.



The analytical-based digital-twin is to be benchmarked against available commercial software, and its effectiveness to be proved experimentally. As the constitutive elements of the digital-twin represent also fundamental steps in a design process, the so developed tool could represent a "from-design-to-operation" blueprint when manufacturing electrical machines.

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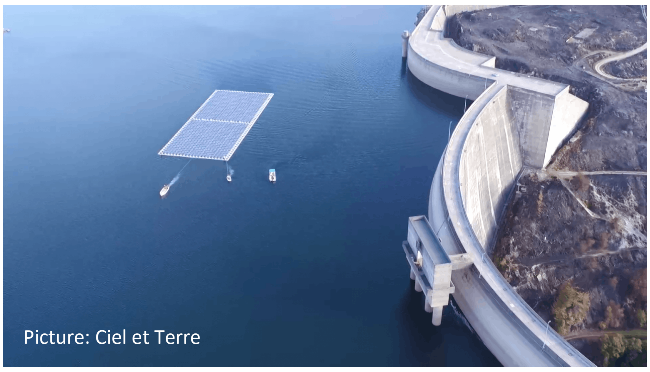
Project: Industrial Ph.D. with Multiconsult

Hybridization of Hydropower Plants with Floating Solar PV: Design and Optimization.

Description of the research

Solar power is widely seen as one of the most promising ways of satisfying the world's growing demand for renewable electric power. As the cost of solar power equipment has fallen dramatically in recent years, a booming international market with exponential growth underpins this promise, but this expansion is starting to encounter barriers in some markets.

Although solar power is cheap and fast to implement, it cannot supply power between sunset and sunrise and must then be combined with other power sources or storage. One such power source is hydropower with reservoirs but, in periods with little precipitation, even hydropower might need to reduce its output.



Picture: Ciel et Terre

Combining hydropower and solar power in a hybrid power plant can mitigate seasonal and daily constraints that both technologies face individually in order to provide a continuous power output throughout the day and year.

Hybridization can further overcome two other barriers that the expansive solar power growth is facing, namely the need for land as well as access to grid. By utilizing floating solar power on an existing hydropower reservoir, one can avoid conflicts regarding land use, while utilizing the same grid connection, implying improved infrastructure utilization and reduced investment cost.

However, solar power output can change within seconds as clouds pass and experience high ramp rates. In order not to cause any challenge for the grid, this must be compensated by the hydropower plant.

The Industrial Ph.D. project seeks to classify different types of hydropower plants according to their suitability for hybridization with solar power, as well as suggest design principles for green field hybrid systems. A cost-benefit optimization model with long term operating decisions will be developed in order to enhance the design and remove perceived risks by potential investors.

Innovation potential and possible applications

Floating solar power is a niche currently experiencing expansive growth, with more than 600% increase in installed capacity between 2016 and 2018 only. The World Bank Group is suggesting a potential on the terawatt scale in its report “Where Sun Meets Water” from 2019. The Industrial Ph.D. project aims at promoting the concept to decision-makers and thus drive project development, especially in emerging markets like Southeast Asia and Africa where connection to the grid and access to land are often barriers to the development of solar power plants.

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Project: LowEmission

Control Strategies for Stability Guarantee in Oil and Gas Platforms with Significant Renewable Energy Integration

Description of the research

The aim of this PhD is to investigate and propose new control strategies for guaranteeing the stability in oil and gas platforms with significant renewable energy integration.

Norway produced 214 million standard cubic meters of oil equivalents of marketable petroleum in 2019. Slightly more than a half of this production was comprised by natural gas. Current trends point to a steady replacement of oil and coal by gas. Oil represented 29% and coal 25% of the world's total primary energy source in 2017. Natural gas amounted to approximately 25%, but it is expected to surpass oil and become the world's main primary energy source before 2030.

However, not all gas extracted from the Norwegian Continental Shelf is sold. Natural gas is used for heat and electricity generation on an impressive scale by oil and gas platforms. The petroleum sector was responsible for more than one quarter of the Norwegian aggregate greenhouse gas (GHG) emissions in 2018. Offshore gas turbines alone account for roughly 20% of the total GHG emissions of Norway.

In electrical engineering terms, in 2008, the total installed capacity of the 167 gas turbines on the NCS summed up to approximately 3GW. The total electrical energy consumption on the NCS in 2008 was on the range of 15TWh. To put that into perspective, the hydropower plants owned by the second largest Norwegian power utility produce 17TWh per year and can supply more than 2.2 million people, 40% of the Norwegian population.

Offshore wind farms represent an extraordinary opportunity for reducing the Norwegian GHG emissions. However, there are still significant technological barriers on the way to the partial or total replacement by renewables of the 3GW of gas-powered generators in operation in the Norwegian Continental Shelf.

Against this background, NTNU and SINTEF together with Norwegian and international industrial players joined forces at the LowEmission Research Center which aims to develop technologies and solutions necessary for reducing the offshore GHG emissions on the Norwegian Continental Shelf within 2030 and move towards zero emissions in 2050. This PhD is a part of the LowEmission Sub-Project 5 Energy Systems and Digital Solutions.

Within this context, the following research questions arise:

- The electrical grid of an oil and gas platform is considerably larger than a microgrid but still much smaller than a country-wide power system. How can the emerging techniques for the analysis of the stability of microgrids and the ones for large grids dominated by solar and wind be applied to this specific platform scenario?
- Will the analysis of the stability of an oil and gas platform with significant contribution of wind energy demand a hybrid approach combining different aspects of microgrids and large grids?
- Which are the root causes of instabilities in a platform's electrical grid with significant contribution of renewables?
- Is it possible to properly discern rotor angle, voltage, frequency, and harmonic instabilities? Which tools are appropriate for analysis and assessment of each type of instability?
- Which cooperative strategies for energy storage, virtual inertia, flexible loads, and multifunctional inverters can be explored for avoiding or mitigating instabilities?
- How to investigate the causes for instabilities and assess the applicable mitigating strategies with the help of practical experiments performed at the National Smart Grid Laboratory (hosted by the Faculty of Information Technology and Electrical Engineering in cooperation with other NTNU faculties)?

Innovation potential and possible applications

The aim of this PhD is to investigate and propose new control strategies for guaranteeing the stability in oil and gas platforms with significant renewable energy integration. These strategies are applicable to other isolated grids, as for example island communities, which nowadays rely on fossil fuels as primary energy sources.

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Project:

Development of methods for element-wise assessment of oscillatory rotor-angle stability

Description of the research

Electric power systems are facing a major structural change in the upcoming decades. The global agreements on reducing the emission of carbon dioxide has led to numerous countries aiming at replacing conventional power plants, fueled by fossil energy sources, with renewable energy sources (RES) as e.g. wind and solar energy. The European Union and Denmark in particular have issued ambitious targets regarding the share of renewables on the total energy production for the years 2020 and 2050 respectively.

In the past power system operators were able to plan their power flow scenarios offline several hours ahead as power production and consumption were plannable except for a limited number of severe fault scenarios and only minor balancing actions were required. Most renewable energy sources, however, are subject to prevailing weather condition, which can cause rapid and unpredictable changes in the system operating conditions. To be able to guarantee stable and secure operation under these circumstances new smart-grid solutions which provide real-time monitoring of the system state and information about the security and stability margins as well as coordinated controls to maintain or re-establish safe operation are needed.

The PhD project is part of a joint collaboration project between DTU and NTNU titled “Smart Wide Area Monitoring and Control for Secure Operation of Systems with High Penetration of Renewable Energy Sources”. It aims to complement the real-time stability assessment methods developed in earlier research at DTU within the Security Assessment of Renewable

Power Systems (SARP) and Secure Operation of Sustainable Power Systems (SOSPO) projects by addressing low frequency power system oscillations.

The objective is to provide an online estimation of the security margin in terms of oscillatory rotor-angle stability by relating the loading of one generator, or a group of coherent generators, to the loading, where the damping of the oscillations is considered critical.

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Project: FME CINELDI at SINTEF Energy Research

Reliability of electricity supply in the future smart distribution system

Description of the research

The electrical distribution system is expected to experience large changes in the upcoming years, both in relation to the integration of smart grid and through the implementation of new components such as distributed energy, flexible resources, and microgrids. This will make the system smarter, but also make the distribution system more similar to the transmission system. This will result in a changed behavior of the distribution system and will require the system operator to act in order to ensure safe operation of the network. Through the desire to postpone or reduce the cost associated with grid investments, the network will be pushed to operate closer to its limits which requires the system to use the components in the system in a more active and smarter way. It will therefore be necessary to create new ways to analyze and measure the reliability of electricity supply in the future distribution system.

This PhD is a part of CINELDI which is a project led by SINTEF. The purpose of their research is to develop a cost-efficient realization of the future flexible, smart, and robust electrical energy systems. In this sense, the PhD project will focus on analyzing the impact microgrids, flexible resources, switches, and relays have on the reliability of electricity supply in the future distribution system. The methods for calculating the reliability in the distribution system need to be modified in order to meet the changes at the distribution level. This PhD will therefore include finding new solutions for modeling and calculating the reliability of electricity supply in the changing distribution system.

Innovation potential and possible applications

The research developed in this PhD project can serve as a basis for how to model and calculate reliability indicators in the future distribution system with smarter components and flexible resources. This research will also help to reveal potential impacts microgrids, flexible resources, switches, and relays might serve on the reliability of the electricity supply. In the end, the goal of this research is to give the system operator a basis for understanding, analyzing, and calculating the reliability in the future distribution system.

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Project: Pricing Balancing Services in the Future Nordic Power Market (PRIBAS)

Pricing Balancing Services in the Future Nordic Power Market

Description of the research

The large increase in wind and solar power generation in continental Europe have increased the need for balancing energy and capacity in the European power system. The flexible and cheap Nordic hydropower is well suited to participate in providing these crucial balancing services. However, the day-ahead energy market has been the main source of income for Nordic hydropower producers since the liberalization of the electricity market in the early 1990s. The decision support tools that are in operational use today reflect this. The current optimization models that can capture the unique dynamics of a cascaded hydropower system fail to include balancing markets in a satisfactory way.

This PhD project is part of the KPN project PRIBAS[1], managed by SINTEF Energy Research. In the PRIBAS project as a whole, a fundamental multi-market modelling approach will be used to produce price forecasts for all physical electricity products in the Nordic market. Some interesting topics that I have explored in this PhD work are:

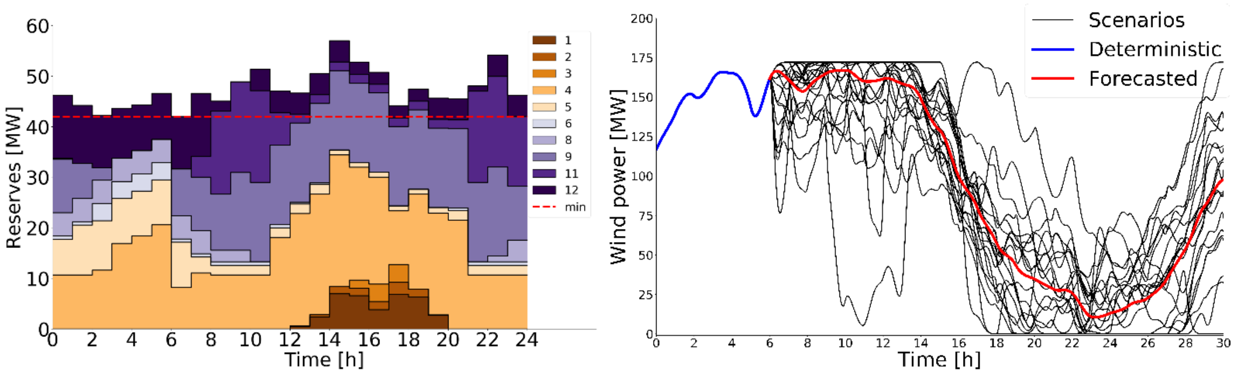
1. Reserve capacity activation in hydropower systems: Energy constraints are usually not considered when capacity is reserved for balancing on hydropower units. This means that the reserved capacity cannot be fully activated if there is insufficient energy or energy storage capacity available. Another complicating factor is the cascaded topology of the hydropower units, which means that activating reserved capacity on a single unit will have an impact on the rest of the system. We have

[1] https://www.sintef.no/en/projects/pribas-pricing-balancing-services-in-the-future-no/
NFR project number 268014

addressed this topic in a paper[2], by explicitly modelling the activation step in the reserve procurement phase.

2. Structural imbalances: The hourly resolution of the day-ahead energy market does not accurately represent the continuous behaviour of the actual load. The mismatch of hourly scheduled production and load causes structural imbalances that must be balanced using reserved capacity. Applying a continuous-time optimization framework to the Nordic power system could greatly reduce the structural imbalances since time-dependent variables are approximated as polynomials in time. We recently published the formulation of the operational hydropower constraints in continuous-time[3].

Left: Reserve capacity allocation for 12 hydropower plants when activation is considered.
Right: Wind power forecast and scenarios as a continuous-time splines.



Innovation potential and possible applications

The research is largely focused on a fundamental level where new techniques are applied to the standard modelling approaches. Work related to activation of reserves are of potential interest to all hydropower producers participating in the balancing markets, while minimizing imbalances are important to reduce costs for system operators. Both hydropower producers and the Norwegian transmission system operator Statnett are represented in the PRIBAS project.

[2] https://doi.org/10.1016/j.ijepes.2020.105864
[3] https://doi.org/10.1016/j.epsr.2020.106787

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Co-Supervisor(s): Associate Professor Dimosthenis Peftitsis
Project: NTNU Oceans Pilot Program on Deep-Sea Mining

Adaptive and Sensorless Control of Multiphase Electric Drives for Seabed Mineral Mining

Background & Motivation

Extraction of seabed minerals is steadily becoming indispensable due to the exponential demand growth, geopolitics and the depletion of easily accessible terrestrial mineral reserves.

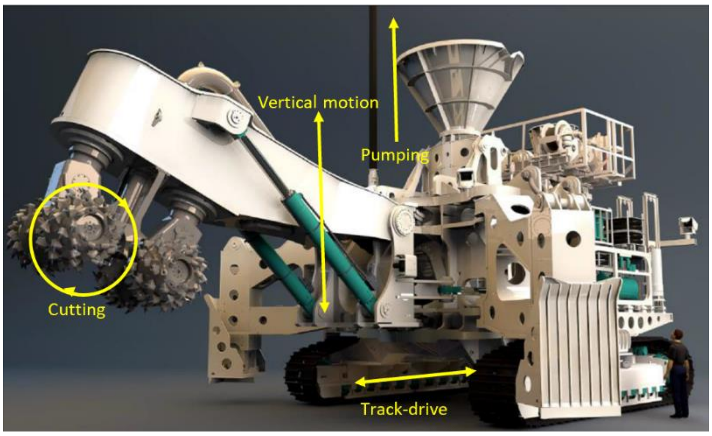

Fig. 1. Multi-motor, Mega Watt ROV for seafloor mining developed by SMD for Nautilus Minerals

The state-of-the-art seafloor mineral mining machines are high power, multi-motor remotely operated vehicles (ROV) in the likes of the mammoth machines in Fig. 1. These ROVs are equipped with multiple submersible variable speed drives (VSD) for various purposes as such as cutting and pumping. The VSD can experience high levels of shock, vibration and temperatures. However, the seabed mining operators cannot afford unprecedented interruptions because their repercussions can be highly detrimental. In the same time, longer the mean-time-to-repair, larger the profitability of the mining site becomes. Additionally, the compact and high power dense VSDs are easier to cool, transport and deploy, thus will offer economic advantages. The high efficiency, too, will incur low operational costs, heat emissions and alleviate the cooling complexities. In essence, the reliability, high power density and the operating efficiency become the figures of merit for the subsea VSDs which eventually determine the sustainability of the industry.

Proposed Solutions & Research Directions

6-phase electric machines with two isolated star-points offer increased availability over the 3-phase machines in the event of power device- or dc-link capacitor- failure in one of the PWM-inverters, the most vulnerable components in subsea VSDs. Interior permanent magnet synchronous machines (IPMSM) offer higher efficiency, torque density and capability for fault tolerant design over its counterparts.

The stall-torque and highly fluctuating load dynamics are some of characteristics of certain mining motor-drives. Thus, 6-phase IPMSM drives are investigated in the following research directions to ensure accurate torque control and increased reliability; 1) methods to track machine parameters that are affected by temperature (adaptive control). See Fig. 2., 2) concepts for position-sensorless control of electric machines in a wide speed range (sensorless control). See Fig. 3. for the proposed adaptive sensorless solution.

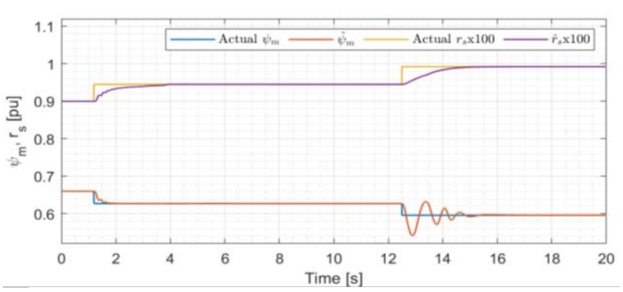

Fig. 2. Online adaptation of estimated permanent magnet flux linkage, ψ_m and stator resistance, r_s when the respective physical quantities in the motor vary

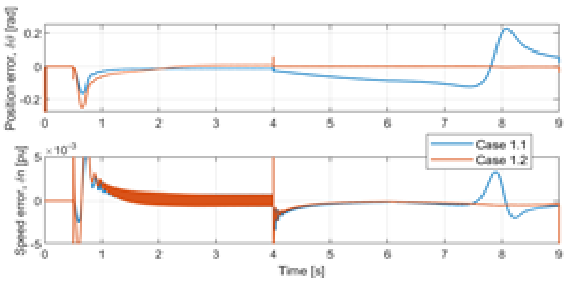

Fig. 3. Position- and speed- error when position sensorless control is implemented; Case 1.1: without parameter adaptation, Case 1.2 With parameter adaptation

Proof of concepts

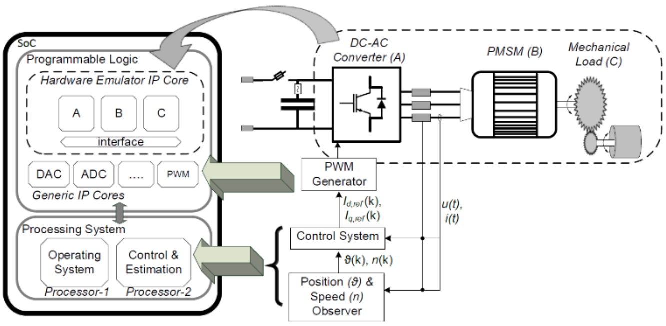

Fig. 4. Embedded Real-Time Emulator for Electric Drives

The concepts are to be proven with a laboratory scale 6-phase IPMSM drive. Si IGBT based, two sets of 2-level, 3-phase PWM-inverters shall be used in the prototype. The embedded real-time simulator (ERTS) as shown in the Fig. 4. is developed which contains dynamic models of the hardware in the FPGA and the control and estimation algorithms in the on-chip processor. ERTS can also be used to validate the concepts.

Innovation potential and possible applications

The concepts developed under this research are applicable not only in seabed mineral mining, but also in any safety-critical industrial drive as such as offshore oil & gas, aerospace, electric vehicles and marine propulsion. The ERTS is another interesting innovative approach that can enable rapid prototyping, hardware-in-the-loop (HIL) and software-in-the-loop (SIL) testing for many power electronic related applications.

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Research Group: PESC
Co-Supervisor(s): Roy Nilsen
Project: ASiCC (Adaptive Silicon Carbide Electrical Energy Conversion Technologies for Medium Voltage Direct Current Grids)

Digitally Adaptive Active Gate Driver for state-of-the-art Silicon Carbide (SiC) Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) used in Medium Voltage Direct Current (MVDC) Applications

Description of the research

Due to recent advances in the field of Power Electronic Converters (PECs) especially involving devices based on Silicon Carbide (SiC) as a wide-band gap material, Medium Voltage Direct Current (MVDC) grids are becoming an interesting alternative to their currently mostly used Medium Voltage Alternating Current (MVAC) counterparts. In the MVAC grids of today, voluminous, heavy and material-intensive low-frequency transformers comprise the main conversion units. Due to superior material characteristics compared to Silicon (Si), SiC-based devices enable the design of high-efficiency, high-power-density converters. In future, these aim at competing with low-frequency transformers of today both economically and ecologically.

To enable this substitution, the novel device characteristics must be exploited as efficiently as possible. Especially the dynamics of switching processes show optimization potential. Gate drive pulse shaping techniques applied to Si switches have improved Electro-Magnetic

Interference (EMI) and switching losses in the past. Also, it has been shown that it is possible to apply gate drive pulse control to SiC devices with beneficial influence on device behavior.

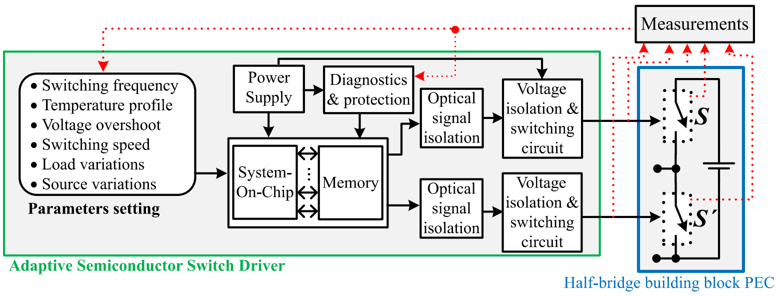

Figure 1 - A possible DAAGD Concept

The final goal of the Ph.D. project is the development of a Digitally Adaptive Active Gate Driver (DAAGD). A possible concept of a DAAGD is visualized in Figure 1.

The DAAGD developed in the Ph.D. project shall be applicable to SiC MOSFETs used in MVDC applications and feature

1. ability to exploit the characteristics of modern SiC MOSFETs,
2. online measurements of key entities in the converter circuit,
3. access to these measurements outside of the gate driver and
4. their usage in a closed-loop control.

A DAAGD offering such features enables to steer the controlled switch within a converter much more precisely. It is presumed that applying a suitable control strategy that fits both the converter- and system-level control instances can greatly improve both the performance and reliability of DC to DC conversion both within, between and at the fringes of MVDC grids.

The PhD project includes work on the following aspects:

- Electrical and thermal SiC MOSFET characterization.
- Electrical and thermal SiC MOSFET simulation.
- Study on the influence of operational conditions of MOSFETs on their short- and long-term behavior.
- Study on the manipulation of the dynamic switching processes in SiC MOSFETs.
- The final step will be to investigate interfacing techniques (since the final goal is to have a digitally adaptive gate driver), sensor choice and integration methods as well as embedded control design.

Innovation potential and possible applications

MVDC grids are widespread in off-grid solutions like oil-platforms or marine systems. In future, also grid-connected systems like residential electricity distribution, coupling of distributed renewable energy sources (wind and photovoltaics) in the low megawatt range or on- and offshore wind energy plants as well as energy storage systems are potential candidates for the use of MVDC grids (see Figure 2).

As mentioned earlier, an AAGD can shape switching processes of the controlled switches. Since with SiC based devices, the operational conditions are more and more shifted towards high switching frequency, making switching processes central to efficiency and device stress considerations. That is why for any type of MVDC grid application, this technology can increase converter efficiency and therefore both the economic and ecological balance of energy conversion.

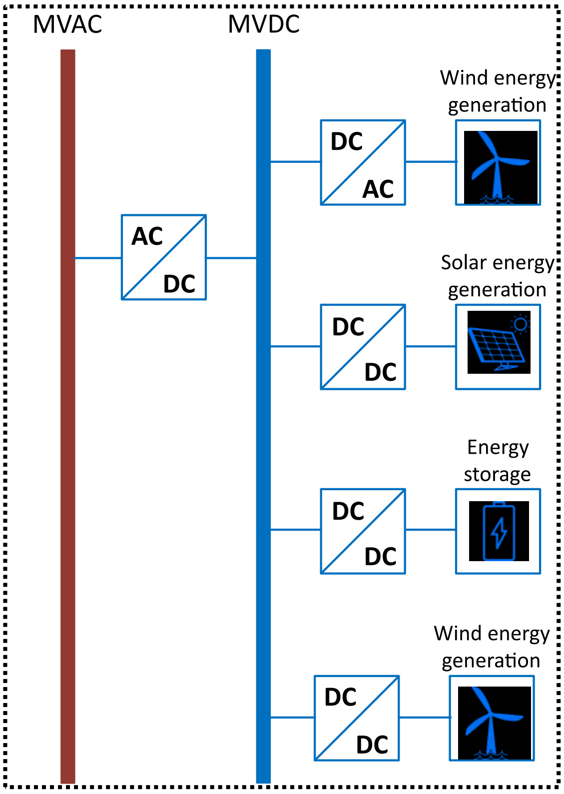

Figure 2 - Exemplary Layout of Power Conversion Units in a MVDC Power System

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Project: FME ZEN

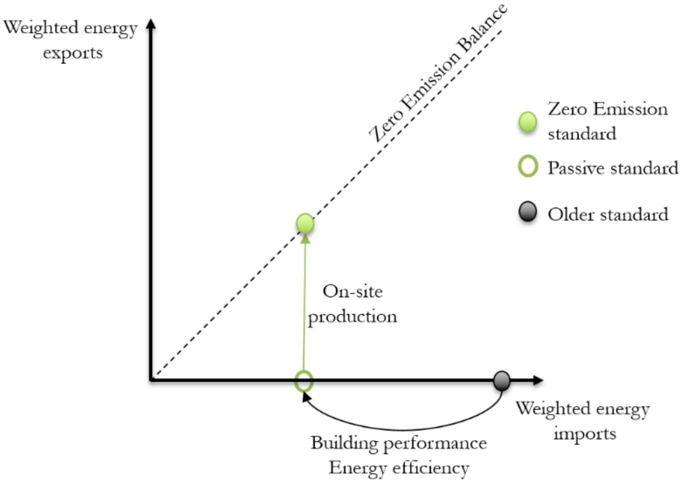
Models for Optimal Investments in the Energy System of Zero Emission Neighborhoods (ZEN)

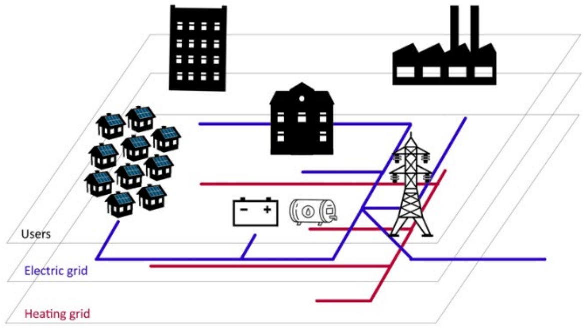
Description of the research

Building and cities are major contributor to global emissions of CO_2. In order to study and promote more sustainable buildings, the research center for Zero Emission Neighborhoods (ZEN) investigates this concept in a multi-disciplinary project. Architecture, materials, user acceptance, heating technology and optimization of the energy system among others are studied. Different phase of the lifetime of the buildings can be considered: construction, material, operation and deconstruction for example.

For the neighborhoods to be zero emission, several approaches can be combined. The first approach targets the emissions embedded in the materials by choosing them carefully. Then on the energy side, another approach is reducing the demand by acting on the performance of the buildings (insolation of walls, roof and window). The last approach is to have a local energy system with its own renewable production that compensate the emissions that could not be avoided in order to reach a “zero emission balance”. The figure below (left) shows those two steps.

My PhD takes place in this context. It aims at investigating investment models in the energy system of zero emission neighborhoods. The models that are investigated are based on optimization to find the cost-optimal design. They handle the investments in the heat and electricity system of the neighborhoods while considering its operation. The figure below (right) is a schematic representation of the neighborhoods we are optimizing. Different technologies are considered, both at the building scale and at the neighborhood scale, including batteries and heat storages.





The goal of the PhD is to have an optimization model for investment in the energy system of ZEN and that represents all the important dynamics of a neighborhood in order to have good investment and insightful results. The challenges lie in having a good representation of the dynamics of the system, a good representation of the constraints of each technology and a good representation of the relation between the heat and the electric part while containing the computational time. The long lifetime of buildings also makes it important to capture uncertainties in the development of technologies and is an additional challenge when planning neighborhoods.

The outcome of the PhD, along with the different models developed, is to answer several questions about designing the energy system of ZENs. For instance, we want to investigate the methods allowing to obtain cost optimal energy system designs, and how to obtain those result in a computational time that is acceptable. Then, another aspect that is researched is the transition between the design of the ZENs and their operation, and in particular how to make sure that the neighborhoods that were designed to be zero emission actually meet those targets during their operation. Another important research question is the role of the CO_2 factors for electricity on the technologies chosen in the resulting energy system. The correct factor to use in this application can be hard to select. Our models can help identify the impact of this choice on the results. Finally, combining this model with a European expansion planning model can give insight into the attractivity and impact of the introduction of such neighborhoods into the European power system and this is also a research question that is investigated in this PhD.

Innovation potential and possible applications

The results of this PhD and the investment model can be used first for helping pilot projects in the ZEN research center to design the energy system of their neighborhoods and to make informed decisions. If the concept of ZEN gets a broader audience, it could also be useful to a wider spectrum of stakeholders, in municipalities or from the industry.

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Project: Adaptive Silicon Carbide Electrical Energy Conversion Technologies for Medium Voltage Direct Current Grids (ASiCC)

Impact of Load and Source Variations on the Performance of Silicon Carbide (SiC) MOSFETs in the Dual Active Bridge (DAB) Converter for MVDC applications

Description of the research

Until the late 20th century, most of the electricity was produced by conventional power plants (coal/natural gas/petroleum/nuclear/hydroelectric). In the last two decades, there is a gradual rise in the use of renewable energy all around the world to generate electricity with a motive to phase out fossil fuels. In addition, electrification of transportation is also becoming increasingly popular creating additional electricity demand. Consequently, it is essential to have a stable grid to provide reliable power that meets the demand, but the power generation is generally fluctuating in the case of wind and solar renewable energy technologies. To solve this issue, energy storage systems such as batteries, fuel cells, supercapacitors, pumped-storage hydroelectricity, etc. are employed. To handle such a sophisticated power system, a smart grid technology with two-way data and power transmission is required.

Medium voltage direct current (MVDC) grids form an essential part of the smart grid technology. MVDC grids require competent bidirectional DC/DC converters, so that the smart grid technology can work effectively. Dual Active Bridge (DAB) converter as given in Figure 1, exhibits several advantages such as galvanic isolation, bidirectional power flow capability, soft switching, higher power density, reduced number of power switches, etc. DAB converter establishes itself as the perfect fit for such applications and with the use of silicon carbide (SiC) power semiconductor devices, which exhibit superior characteristics in comparison to silicon power semiconductor devices, the efficiency of the DAB converters is close to 99%.

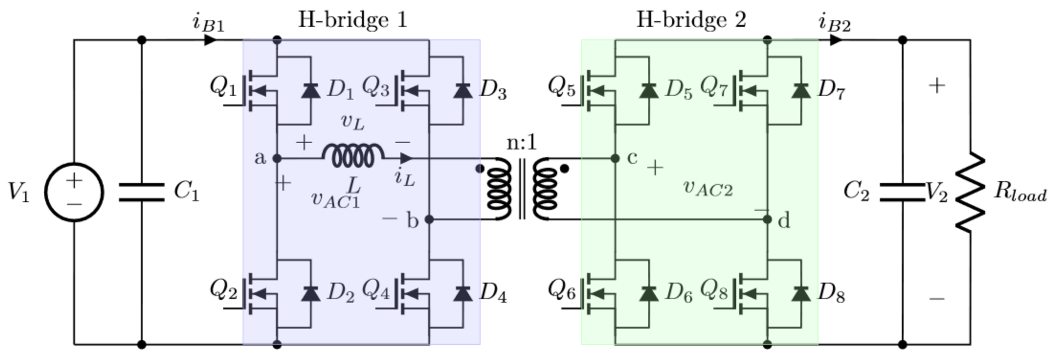

Figure 1: Schematic diagram of the DAB converter

This PhD project is part of the ASiCC project and focuses on the following:

- Investigation of the modulation and control strategies of the DAB converter using simulations in MATLAB/Simulink and PLECS.
- Modelling of load and source variations (load profile of electric vehicle charging, variable nature of the power generation from solar and wind, etc.) and analysis of the impact of these variations on the performance of the SiC MOSFETs in the DAB converter.
- Design of optimum control strategy in collaboration with the adaptive semiconductor switch driver (ASSD) obtained from the other PhD research of the ASiCC project to improve the reliability and performance of the SiC MOSFETs.
- Investigation of the operation of modular configuration of the DAB converter.

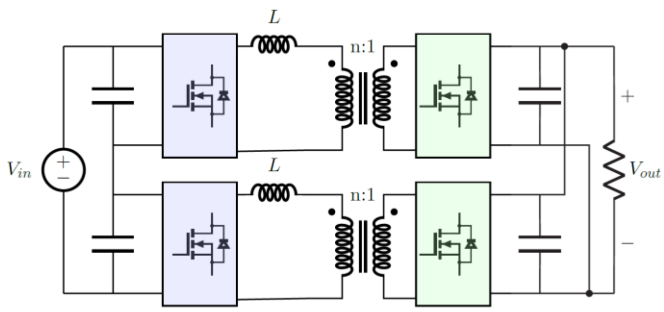

Figure 2: Basic input series output parallel (ISOP) configuration of the DAB converter

A prototype of the DAB converter will be built, and its bidirectional operation and performance of the SiC MOSFETs will be evaluated.

Innovation potential and possible applications

Design of DAB converter with a focus on reliability and better utilization of SiC MOSFETs will have a huge impact on the overall converter performance and the associated application. The results from this research can be used in applications such as charging infrastructure of electric vehicles, traction, marine systems, battery energy storage systems, etc.

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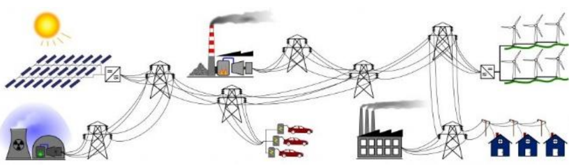
Project: HydroCen

Grid Integration of Variable Speed Hydro Power Plant

Background

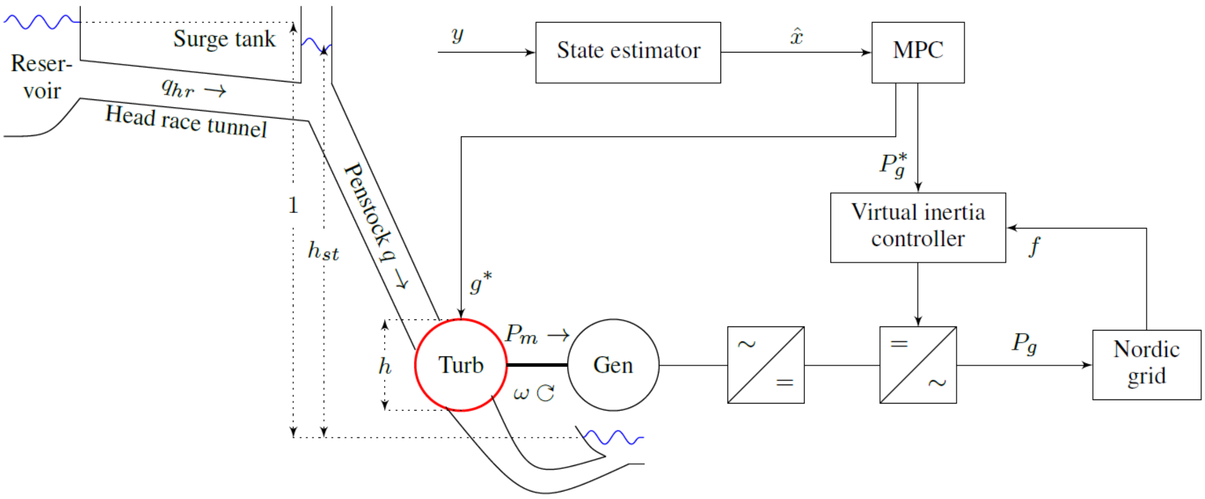
As the share of wind and solar energy production increases, more flexible production and loads are required to control the balance of the grid. A potential use of Variable Speed Hydro Power (VSHP) is to provide this flexibility and compensates the production of variable renewables. The hypothesis is that VSHP can offer additional ancillary services, contributing to the frequency regulation and improving the grid stability, allowing for higher penetration of renewables in the grid.



The advantages compare to conventional pumped-storage hydro power with constant rotational speed is better utilization of the rotation energy in the turbine and generator and improved power control in pumping mode. The efficiency and operating range of variable speed hydro power will also be higher and they can contribute in frequency control both in production and pumping mode.

Objective

The focus of the PhD work will be to investigate the interactions between the VSHP plant and the grid, and how variable speed operation can benefit the security and flexibility of the power system operation. The main research task will be to explore the control possibilities from a system perspective while considering the limitations given by the water/turbine system. This comprise development of non-linear time domain simulation models with limitations for water flows in the tunnel, turbine, governor, generator with magnetizing system, generator-side converter and grid-side converter, and a representatively test grid.



Different methods for virtual inertia control methods are investigated for increasing the total inertia in the grid and for damping of power fluctuation. New control schemes for control of VSHP utilizing model predictive control (MPC) and virtual inertia control are developed. The MPC coordinates the control of governor and grid converter considering limitations given by the water and turbine system and the control is optimized for a system perspective.

Innovation potential and possible applications

The virtual inertia control of the VSHP allows for the provision of fast frequency reserves (FFR) to the grid while the MPC controller maximizes the possible contribution of FFR. When an expected marked for FFR is introduced, the producers may increase their income from VSHP by utilizing the suggested controller. The MPC controller is also tuned to reduce the wear and tear of the power plant and thereby reducing operation cost and increasing lift time. Besides, it will also optimize the turbine rotational speed to maximize the efficiency of the power plant.

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Project: Industrial PhD

Automated short-term production planning for Hydro- and wind power

Background & Objective for PhD

Every day power is traded based on the estimated consumption, and the scheduled production on the Nord Pool Spot power exchange. On this exchange, power produced from different sources is bought and sold and is ready for delivery the next day. This is called the Day-ahead market.

Even though the marked is planned to be in balance, the system is continuously influenced by factors that could lead to imbalances. This could be changes in consumption as result of colder weather or unplanned outage in a Power Station. During the last decades Statnett have introduced market solutions to ensure sufficient supply of reserves.

To manage and plan for sales in an increasing number of markets, most power producers have engaged production planners. In production planning, the power producer attempts to optimize the value of the resources in a long and short-term perspective. This is done by applying a wide range of models and commercial competence

The complexity in the planning and nomination process is increasing. The time from when information is acquired to decisions are made is getting shorter, and the degree of details modelled in the power systems, and the amount of information processed, is continuously increasing. In addition, restrictions given by local, state-dependent, concessional and environmental conditions tend to introduce additional requirements to models that are applied in the planning process.

The objective of this project is to develop new methods for applied decision support for hydro- and windpower production planning. The long-term target is automatization of the nomination process using a combination of fundamental models, and deep reinforced learning methods.

Published research

Optimal pricing of production changes in cascaded river systems with limited storage: A new method, using marginal cost curves for individual powerplants to generate an overall marginal cost curve for interlinked power stations has been developed. Results based on a real-world case study demonstrate the advantage of the proposed method in terms of solution quality, in addition to significant insight into how optimal load distribution should be executed in daily operations.

Rolling Horizon Simulator for Evaluation of Bidding Strategies for Reservoir Hydro: A rolling horizon simulation framework is developed and closely integrated in the daily operations of a hydropower producer. The power producer's existing framework of decision support models and data for prices and inflow has been used to simulate the use of alternative strategies on a real-life case. Results from the case study show that one single strategy not necessarily will be the optimal one under all conditions, because the optimal strategy will depend on the state of the system.

A supervised learning approach for optimal selection of bidding strategies in reservoir hydro: Power producers use a wide range of decision support systems to manage and plan for sales in the day-ahead electricity market. The available tools have advantages and disadvantages and the operators are often faced with the challenge of choosing the most advantageous bidding strategy for any given day. Access to an increasing amount of data opens for the application of machine learning models to predict the best combination of models and strategy for any given day. In this article, historical performance of two given bidding strategies over several years have been analyzed with a combination of domain knowledge and machine learning techniques. A wide range of model variables accessible prior to bidding have been evaluated to predict the optimal strategy for a given day. Results indicate that a machine learning model can learn to slightly outperform a static strategy where one bidding method is chosen based on overall historic performance.

Ongoing research

Coordinated Hydro- and wind balancing: With the increasing penetration of wind in the Nordic market, power producers are in large extent managing combined portfolios of wind and hydro power. In this context it is interesting to evaluate the value of internal coordination for planning and balancing of combined portfolios.

Innovation potential and possible applications

Even though the complexity in the planning and bidding process is increasing. Still, most companies have placed people in the center of this process. The main question is if the bidding-process in a much larger extent could be managed by computers and algorithms. There are two main challenges in relation to transforming from a manual to an automatized process: One is technical, the second is organizational. How to ensure that the new process is safe and robust, and how to make sure existing resources support the implementation and are given more relevant and interesting tasks.

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Co-Supervisor(s): Roy Nilsen
Project: High-efficiency all-electric DC supply systems for subsea work-class remotely operated vehicles - HEROVs

Power Electronics for Fully-Electric Work-Class Remotely Operated Vehicles (WROVs)

Description of the research

HEROVs is a joint research project between NTNU and the two industrial partners: Argus Remote Systems AS based in Bergen, Norway, and Ingeteam Power Technologies SA based in Bilbao, Spain. The goal of the research project is to design and optimize a high-power DC/DC converter suitable to perform electrical energy conversion from medium-voltage direct-current (MVDC, e.g.5-15 kV) to low-voltage direct-current (LVDC, e.g. 500-1000 V) for the future, fully-electric work-class remotely operated vehicles (WROV). The targeted WROV power level range exceeds 200 kVA with operating water depths exceeding 3000m. Today, WROVs mostly use hydraulic systems on board in order to meet the high power demands of their manipulators and propulsion systems. However, a trend towards modernizing WROV by making them fully electric is clearly observed.

Fig. 1 – Argus Worker WROV rated at 175 hp (≈ $130\ kVA$*).*

The conducted research will focus on proposing approaches and solution for high-efficiency, pressure-tolerant and reliable power supplies which may lead to breakthroughs in the ROV industry. Design aspects of DC/DC converters utilizing wide-bandgap (WBG) power semiconductors (e.g. SiC, GaN) to obtain enhanced power density as well as

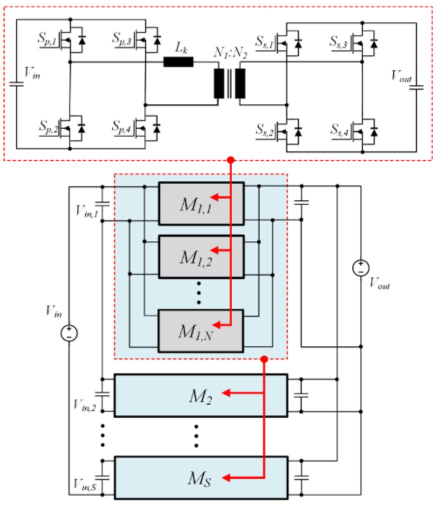
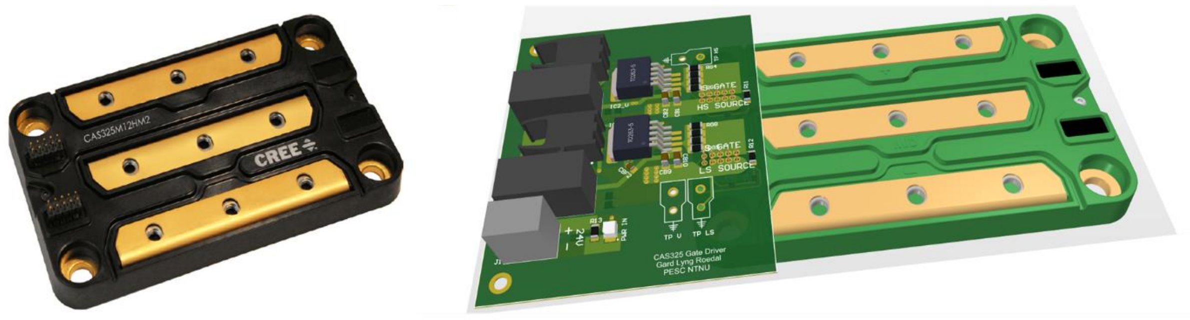


Fig. 2 - Schematic diagrams of the Serial-Input-Parallel-Input-Parallel-Output (SIPIPO) DC/DC isolated converter configuration.

operational behavior of power electronic system under high pressure are key results areas expected from this project. Obtaining a light weight of the WROV is highly preferable, a challenge strongly associated with increased power density of the electric supply system. Variations of the Dual Active Bridge DC/DC converter topology, as seen in **Error! Reference source not found.**, are reviewed as the most promising topology for this application and will be prioritized for further investigations. It is highly advantageous in its inherent galvanic isolation, bi-directional power flow capabilities, zero-voltage switching capabilities and modularity. Using WBG devices enable higher switching frequency and semiconductor operating temperature and will play a key role in the design of the power supply.

Due to the fast rise and fall time of WBG devices currents and voltages, significant challenges exist in driving complete converter system reliably. Highlighted challenges which is currently investigated within this project relates to very high dv/dt and di/dt, with focus on gate driver topologies (i.e. current source vs. voltage source gate drivers), Miller effects in SiC MOSFETS and oscillations in gate and power paths. Furthermore, since the ROVs are required to operate at immense depths (up to 11000m), they may be exposed to high pressures. Current solutions rely on housing pressure-sensitive equipment (such as power electronics) in heavy pressure chambers with the pressure of around 1 atmosphere which the equipment is rated for from the manufacturer. These chambers are heavy, exceeding several tons for the required volume. To avoid these chambers, the power electronics with its auxiliary circuits should be submerged in dielectric fluid at ambient pressure. The pressure will transfer from the ambient sea to the chambers through pressure-compensation techniques.

Current research focuses on developing a high-power DAB converter capable of handling an input voltage of 5 kV, output voltage of 500 V with a power level of 1MW, using elements of Fig. 3



a) *b)*

Fig. 3 - a) CAS325M12HM2 1.2 kV, 444 A Silicon Carbide (SiC) MOSFET half-bridge module, b) its accompanying gate-driver PCB.

Innovation potential and possible applications

WROVs are needed in the oil and gas sector (e.g. for intervention, trenching, umbilical and power cable-laying, repair and maintenance tasks), renewable energy sector (e.g. offshore wind- or solar-farm installations) and other niche applications requiring subsea operations (e.g. military, forensics deep-sea exploring). Besides the WROV industry, high-power-density, medium-voltage DC/DC converters are key technology within electric mobility industry (e.g. electric vehicles, railway traction, aerospace) and renewable energy sector, with heavy interests invested in increasing power density while maintaining adequate system efficiency. Research innovations possibilities are large within the area of high-efficiency high-power MV DC/DC converters using WBG devices, as well as pressure-tolerant power electronics.

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Research Group: High current / circuit breaker laboratory
Co-Supervisor(s): Magne Runde
Project: Innovation Project for the Industrial Sector, Cost-effective Rotational Switch for SF6-free Gas Insulated Switchgears

Temporary title: Ablation-assisted load current interruption in SF_6 free medium voltage switchgear

Medium voltage (MV) load breaking switch (LBS) technologies are today dominated by SF_6 solutions. SF_6 is a gas with 23900 the 100-year global warming power of CO_2. As such, there is a desire from the industry to phase out the use of this gas, without losing the compact format of today's switches, while being cost competitive.

This PhD is at the centre of a cooperation between NTNU, SINTEF and ABB. The aim of the PhD is to further the knowledge around the use of polymer ablation to assist the current interruption in air and the proprietary gas of ABB, AirPlus™. Ablation is, in this case, the evaporation of the surface of a polymer in vicinity of the electrical arc generated during the current breaking process. The main objectives of the PhD can be summarized into the following points:

- Lay down the scientific and technological groundwork for a cost competitive alternative to SF_6 LBSs
- Understand the behaviour of the dielectric restrike in the ablated polymer gases in both air and AirPlus™
- Find nozzle geometries which increases current breaking success rates
- Develop a comprehensive empirical model on the effect of ablation on arcs in the MV range, using the relevant variables
- Apply what has been learned to rotational breakers

In short, the outcome of the research can be used to help design the next generation of climate friendly load breaking switches and will hopefully further the knowledge around the polymer-arc interactions.

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Project: FME HydroCen

Modelling of environmental constraints in hydropower scheduling

Description of the research

Hydropower can respond to fluctuations in load and intermittent renewable generation by rapidly adjusting the production when required. The integration of more wind and solar power into the European power system is increasing the variability and the need for flexibility in the system. Hydropower can play an important role in meeting the increasing need for flexibility. On the other side, rapidly changing operation of hydropower plants can have negative impacts on surrounding ecosystems. To limit such negative impacts, the operation of hydropower plants is regulated by constraints on operation defined in the license of the plant.

My PhD is a part of FME HydroCen Task 3.4 Environmental constraints and uncertainties – impacts on revenues[1]. The project is managed by SINTEF and aims to test new methods and tools for advanced operational scheduling that also includes environmental constraints. The ability to model and assess the impacts of environmental constraints have received increased attention over the last few years, as many hydropower plants face uncertainty in future licensing terms. Since many of the Nordic hydropower plants are old, a large share of the plants is going through revision of the licensing terms. In the revision processes new or stricter constraints on operations can be enforced. The purpose of the constraints is normally to improve environmental or recreational conditions, but the constraint will often also have an associated cost. The associated cost is a result of further restricted operation

[1] https://www.ntnu.edu/hydrocen/3.4-environmental-constraints-and-uncertainties-impact-on-revenues

and can take the form of reduced energy production or less flexible operational patterns. We find that there is a research need for improved modelling and knowledge of the implications of environmental constraints on operation of hydropower plants. In my research I want to explore:

- The impacts of (selected) complex environmental constraints on the operation and economics of Norwegian hydropower plants in cascaded hydro systems.
- The implications of simplified representation of environmental constraints in mid-term operational planning of hydropower plants. How important is it to include such constraints in hydropower scheduling models? What is the trade-off between improved performance and computational efficiency?
- How can we improve the modelling of environmental constraints? Can we find approaches to model environmental constraints which cannot be included in today's hydropower scheduling models?
- The implications of environmental constraints on system flexibility and security of supply in hydropower dominated systems. I would like to assess the basic relationship between environmental constraints on hydropower operations and system flexibility under future market assumptions.

Innovation potential and possible applications

Improved modelling of environmental constraints in hydropower scheduling, and knowledge on when and how to incorporate such constraints in the scheduling, can be valuable for both the hydropower producers, the regulator and the TSO. Better representation of such constraints in the modelling can reduce the operational losses by providing closer to optimal production schedules. Furthermore, it can provide improved knowledge on the impact of such constraints on the overall system flexibility and potentially insights into how future regulation could be improved.

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Project: Industrial PhD for Statnett

Reinforcement learning in handling failures in the power systems

The role of Statnett is to plan, build and operate the transmission network for electricity in Norway. An important aspect of maintaining reliability is to compare the costs of investments in the grid to the socioeconomic costs of power outages. In short: What is the optimal level of resilience?

To do this comparison sensibly it is necessary to understand how failures in the power system occur and how they are dealt with. Ideally, preventive measures should be employed before a failure occurs in order to minimize the impacts. After a failure one should apply corrective actions in order to restore power supply to end users as fast as possible. And finally, restorative actions should be applied to bring the system back to a state where the level of resilience is as it was before the failure event occurred. Finding the most appropriate actions is therefore equal to making a rational evaluation of different measures considering the probability of failure events and the pool of measures available.

This is a huge optimization problem given the complexity of modern power systems. Traditional optimization methods will generally be time consuming for these kinds of problems. However, both in an operative setting and in planning there is a need to quickly compute the optimal solution of this problem. In an operational setting, the urgency of the situation demands fast actions. In planning one typically wants to simulate a large number of events within in a large number of different system states where the failure events occur and endure as realistically as possible. In order to do enough simulations, it is necessary to have fast methods.

The main idea in this project is to use machine learning in general and reinforcement learning in particular to quickly find the optimal actions when failure events occur in the power system. Reinforcement learning is an agent-based approach to machine learning. In such an approach one can imagine an agent modeling the system operator, iteratively learning and improving the operation of the grid in different power system states. This seems to be a promising approach to how one can operate an increasingly complex power system while simultaneously keeping the amount of calculations manageable.

Reinforcement learning is a subject in stark development, where the most relevant techniques and algorithms are improved rapidly on a year to year basis. Central to this development is deep learning where non-linear relations are modeled in layers of neural networks. Within power systems research the application of deep reinforcement learning are still in its infancy. Therefore, it is essential to explore and get an overview of which kind of algorithms are scalable to the Norwegian power system and not only applicable to relatively simple test cases.

The scalable methods developed in this project must find fast solutions to the optimal handling of failure events in the power system. Due to long training times for deep machine learning models, GPUs (graphics processing units) has become an essential part of the hardware being used when training such models. To this end, it will become an important research task to explore the use of GPUs and eventually make assessments on the pros and cons of the training times achieved compared to the speed of the final evaluations/predictions of the trained models.

It is also important that these methods are applicable by Statnett and could be integrated with the existing portfolio of tools. In order to achieve this, it is the intention to develop a programmable interface such that other tools can use the results from the deep reinforcement learning models when making calculations of reliability and analyzing the socioeconomic cost of power system failures.

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Projects: FME ZEN and FME CINELDI

Flexibility potential in the smart distributional grid and Zero-Emission Neighborhoods to cope with imbalances and CO_{2eq} compensation

Description of the research

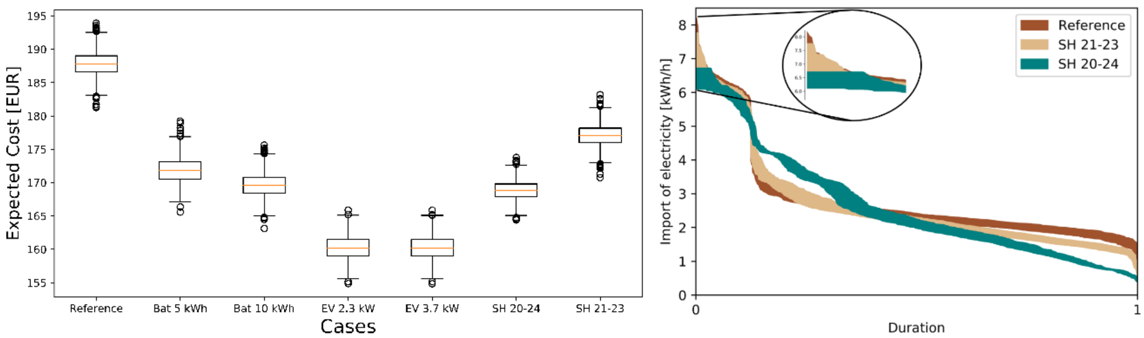
To create a smart future grid, there is potential and a need to include the flexible resources that are existing within the grid. Therefore, the flexible units, especially from the end-user side, needs to be investigated to find their value and contribution to the total distributional grid. Some of the possible contributors to this is the Zero Emission Neighbhorhoods (ZEN) that FME ZEN is working on. However, the level of flexibility and their value for flexibility is something that must be found, both in the long-term and short-term setting during operation.

The goal of this research is to find new smart ways to get an accurate plan of the operational phase of the ZEN network and for the distributional grid. To have an optimal operation of a building in short-term setting, it is vital that the future consequence of the decision-making is represented so the operation takes that into consideration. Inspired by the methods and techniques commonly found in hydropower scheduling, the author is trying to incorporate the long-term impact of operation of buildings Especially using Stochastic Dynamic Programming (SDP), there is potential in the techniques that could be implemented here as well, which also helps finding the flexibility measures and the added value of that.

Regarding results, a detailed household including flexible assets and control of flexible load has been developed to study the scheduling impact. This has been combined with an SDP method for a case study where a measured-peak grid tariff has been included. The aim is to represent the future consequence of building scheduling, based on the cost-optimal peak power that is initialized early in the period. The results shows that the SDP method finds the cost-optimal peak power for the household based on the expected future cost for the period. The peak power level is based on the value of allowing more flexibility in electricity scheduling versus the added cost from the grid tariff.

Further, the work above has been extended to investigate the multiple flexible assets individually, to see how each of them contribute with flexibility to reduce peak import. The findings showcased that EV charging has high power demand if charged passively and can decrease the peak if smart EV charging is enabled. In addition, Space heating has increasingly flexibility based on the indoor temperature boundary it can operate within, where going from 21-23 $°C$ to 20-24 $°C$ saw a notable peak import decrease.

The findings show that the SDP approach is promising to integrate with households and is not only limited to the case study described above. Extending this to other parts in the grid or to a small distributional grid could give details of the flexibility need and the value of flexibility from internal scheduling, when considering other deciding factors.



Left: Boxplot of expected monthly cost for a building with different flexible assets activated for a measured-peak grid tariff

Right: Duration curve for import of electricity for flexible space heating with different temperature boundaries over a month with uncertainty

Innovation potential and possible applications

In terms of innovative potential, the most important part of this work lies in the algorithm used for the operational planning. As the SDP method, gives an indication of how to schedule, there lies potential in extending this to be part of a real-time operational strategy. If used as a guideline, the short-term operational model can schedule more detailed within the short-term horizon, while the future beyond the horizon is represented by the future cost curves provided by the long-term model. The application could be interesting for single households as a flexibility controller, or like the work described above, could be integrated for larger industries that already are charged by this measured power peak grid tariff.

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Project: HydroCen

Frequency converter solutions and control methods for variable speed operation of pumped storage plants

At present, the pump storage hydropower plants are realized with a reversible pump-turbine (RPT) and an AC machine (generator/motor) connected on the same shaft. In most of the pump storage plants, the AC machine is the synchronous machine directly connected to the grid and therefore, the set of machines run at almost constant speed depending upon the frequency of the grid regardless of the amount of water flow into the turbine/pump. However, it is a well-proven theory that the turbine/pump operates at optimal efficiency only if its speed is varied according to the variation in the water flow. This optimal efficiency operation of hydraulic machines is currently being achieved in several power plants around the world with help of Doubly Fed Induction Machine (DFIM) where a frequency converter of approximately 30 % capacity of the stator rating is required to achieve a speed variation of ± 10% of speed. Even though, the system is widely used for few decades, it cannot dynamically switch the operation from generation mode to pumping mode or vice versa which is going to be an important requirement in near future to balance the increasing amount of renewables being introduced to the grid. Such a dynamic mode switching from turbine to pump and vice versa can only be achieved by decoupling the turbine/generator sets from the AC grid using a full power back-to-back converter between the AC machine and the grid using converter fed synchronous machine (CFSM). This technology needs a converter of same rating as of the stator and therefore, the application can be limited by the size of the converter.

The research outcome of this PhD will be the proposition of an appropriate full-size converter topology which can enable the variable speed operation of pumped storage plants. In addition, the overall control strategy of the converter and machine will be tested in a lab setup of 100 kW capacity with 2-level back-to-back converter connected between the grid and the synchronous machine. The prime mover of the synchronous machine, which is an RPT in real application, will be emulated using an induction machine and the variable speed operation of turbine to track the maximum efficiency will be simulated using a motor inverter connected to the induction machine. As the converters decouple the physical inertia of the RPT and AC machine, emulating virtual inertia and damping in the control system will be also be one of the major requirements.

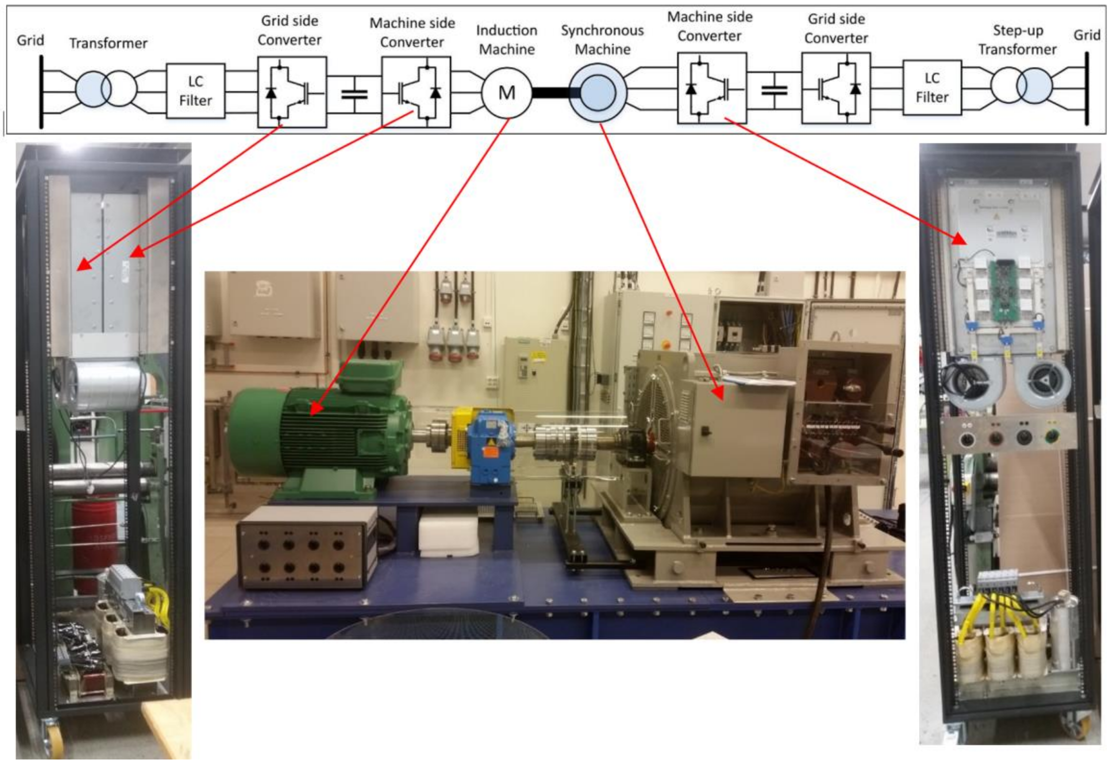

Figure 1: Lab Setup

The most relevant application of this project will be the retrofit of the exiting pumped storage hydropower projects where the synchronous machine and RPT are already installed, and a full-size converter to make CFSM could be a better alternative than the combination of a new Induction machine and a smaller converter. In addition, the dynamic transition between the pump and turbine mode will enable the power system to utilize the renewable energy sources (wind and solar) to the maximum.

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Co-Supervisors: Irina Oleinikova, Bjørn Gustavsen
Project: ProDig

Improvements in fault location in resonant grounded power systems

Description of the research

The focus of the ProDig[1] project is the protection and control in digital substations. This PhD work is linked to WP3 titled "Strategies for protection and fault location in digital substations". This work package aims at utilizing a digital substation and wide-area environment to improve protection and fault location schemes, particularly in complex, multiple-fault cases. A main focus of the work package is on the special challenges of ground faults in isolated or resonant grounded systems. The focus of this PhD will be on earth-faults occurring in resonant grounded systems, and the application of methods for fault location based on fault-generated transients. Transient-based algorithms for locating faults are considered a promising alternative to classical steady-state algorithms for fault location and protection, especially for handling and locating high-impedance and intermittent faults.

Innovation potential and possible applications

Results will contribute to a faster and more accurate location of earth faults, particularly in the HV regional networks, where the current requirement for locating earth faults is 2 hours. A long-term goal is the automatic clearing of earth faults without the need for performing manual switching operations in the network.

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[1] ProDig website: https://www.ntnu.edu/prodig/power-system-protection-and-control-in-digital-substations

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Advanced medium-voltage SiC-based power module designs with integrated gate drivers

Decentralized electricity generation (DEG) will play a crucial role in the decarbonization of the existing electric power grid infrastructure. The technology that will facilitate the expansion of DEG is the multi-terminal medium-voltage direct current (MVDC) grid, and one of its key components is the power electronic converter (PEC). Current MV PECs employ Silicon (Si) power semiconductors, such as the Insulated Gate Bipolar Transistor (IGBT). However, Si power semiconductor technology has reached the theoretical limits of the material. The recent development of Silicon Carbide (SiC) Metal-Oxide Field-Effect Transistors (MOSFETs) has lead to ways to design PECs with higher efficiencies due to the significantly lower losses for SiC compared to Si counterparts. However, commercially available SiC MOSFETs are only available at voltages from 0.65 kV to 1.7 kV, with 3.3 kV devices expected to enter the market in the next five years.

The technology that is used to electrically connect and mechanically fasten power semiconductor chips is the power module. Generally, several individual chips are connected in parallel to increase the current rating of the module. The typical layout of a commercially available module is shown in Figure 1. However, to operate such modules at medium blocking voltages, the power modules are connected in series externally. Such an arrangement is not favorable for SiC devices, as they are especially sensitive to parasitic circuit elements that are present in the circuit and may lead to excessive voltage overshoots and oscillation during high switching speeds. However, one way to minimize the effect of the

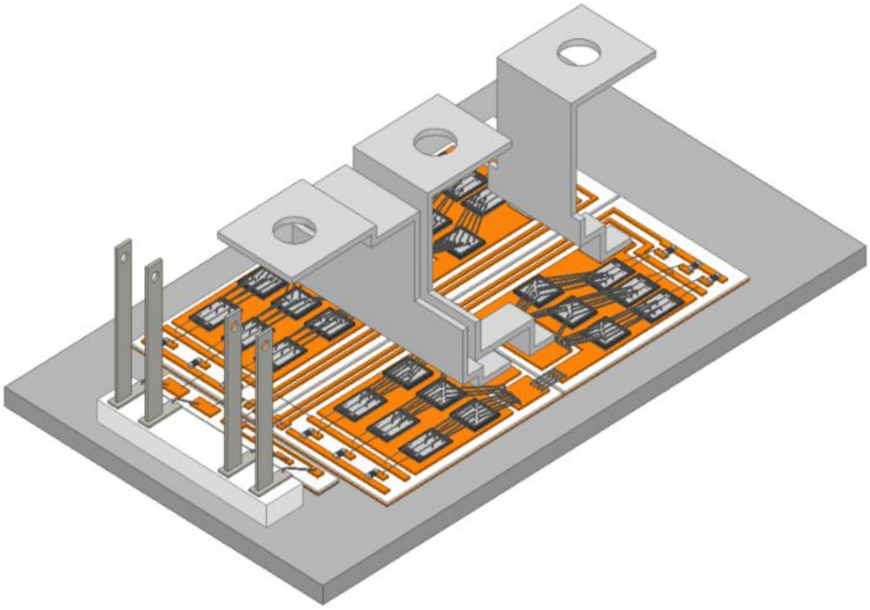

Figure 1: 3D model of the internal layout of a commercially available module.

parasitic elements is to series-connect the individual power SiC chips internally in the power module. For such designs one must determine the optimal layout for minimization of parasitic elements, as well as assess the thermal performance of the module so that the temperature is uniformly distributed among the devices. Moreover, the devices will experience unbalanced voltage sharing, which might lead to one device blocking more voltage than it is supposed to and drive the module to failure. Thus, voltage balancing techniques, such adaptive gate control or integration of gate driver inside the power module, will also have to be investigated.

The objective of the PhD is to develop novel power module layouts that will allow MV operation, at high switching speeds and high efficiencies.

Innovation potential and possible applications

The development of advanced SiC-based power module designs with integrated elements is a crucial step towards the development of proper PECs suited for the future electrical grid and will contribute to the green-shift in the electrification of large sectors in the economy by smoothening the integration of renewable energy sources.

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Year	Name	Title
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
	Salman Zaferanlouei	"Integration of Electric Vehicles into Power Distribution Systems - The Norwegian Case Study; Using High-Performance Multi-Period AC Optimal
	Pål Keim Olsen	Inertial Partial Discharges at High DC Voltage and the Effect of Superimposed AC Voltage
	Abid Fahim	Characteristics of Switching Arc in Ultrahigh-pressure Nitrogen
	Torstein Grav Aakre	Partial Discharges in voids at Variable Voltage Frequency and Temperature – Diagnostic Testing of Stator Mainwall Insulation
	Abbas Lotfi	Off-core magnetic flux paths in power transformers - Modeling ans applications
2019	Sigurd Hofsmo Jakobsen	Frequency control and stability requirement on Hydro plants
	Martin Håberg	Activation Optimization and Congestion Management in the European Balancing Energy Market
	Subhadra Tiwari	SiC MOSFETs and Diodes: Characterization, Applications and Low-Inductive Converter Design Considerations
	Hans Ivar Skjelbred	Unit-based Short-term Hydro Scheduling in Competitive Electricity Markets
	Anirudh Budnar Acharya	Evaluation Modeling and Control of Modular Multilevel Converter for Photovoltaic Applications
	Erlend Løklingholm Engevik	Design and Operation Investigations for large Converter-Fed Synchronous Machines in Hydropower Applications
	Markus Löschenbrand	Dynamic Electricity Market Games – Modeling Competition under Large-scale Storage
	Emre Kantar	Longitudinal AC Electric Breakdown Strength of polymer Interfaces
	Martin Kristiansen	Multinational transmission expansion planning: Exploring engineering-economic decision support for a future North Sea Offshore Grid
	Martin Hjelmeland	Medium-Term Hydro power scheduling in a Multi-Market Setting
	Hans Kristian Hygen Meyer	Dielectric barrier under lightning impulse stress: Breakdown and discharge – dielectric interaction in short non-uniform air gaps
	Henning Taxt	Ablation-assisted load current interruption in medium voltage switchgear
	Iromi Udumbara Ranaweera Kuruwe Mudiyanselage	Energy storage for Control of Distributed Photovoltaic Power Systems
2018	Konstantin Pandakov	Improvements in protection of medium voltage resonant grounded networks

		with distributed sources
	Ingeborg Graabak	Balancing og wind and solar power production in Northern Europe with Norwegian hydropower
2017	Erling Tønne	Planning of the Future Smart and Active Distribution Grids
	Atsede Gualu Endegnanew	Stability Analysis of High Voltage Hybrid AC/DC Power Systems
	Lester Kalemba	Multi-variable control systems and analysis Techniques applied to power systems
	Edris Agheb	Medium frequency high power transformer for All-DC wind parks – Design, modeling and optimization
	Amir Hayati Soloot	Resonant overvoltages in offshore wind farms. Analysis modeling and measurement
	Karen Byskov Lindberg	Impact of Zero Energy buildings on the Power System
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2016	Seyed Majid Hasheminezhad	Tangential electric breakdown strength and PD inception voltage of Solid-Solid interface
	Bjarte Hoff	Model predictive control of voltage source converter with LCL filter
	Ravindra Babu Ummaneni	Design and modelling of a linear permanent magnet actuator with gas springs for offshore application
	Dinh Thuc Duong	Online voltage stability monitoring and coordinated secondary voltage control
	Christian Skar	Modeling low emission scenarios for the European power sector
	Emil Hillberg	Perception, prediction and prevention of extraordinary events in the power system
	Traian Nicolae Preda	Modelling of active distribution grids for stability analysis
	Mehdi Karbalaye Zadeh	Stability analysis methods and tools for power-electronics based DC distribution systems, applicable to on-board electric power systems and smart microgrids
	Nathalie Holtsmark	Investigation of the matrix converter application in a DC series-connected wind farm modulation, control and efficiency
2015	Yonas Tesfay Gebrekiros	Analysis of Integrated Balancing Markets in Northern Europe under Different Market Design Options
	Mustafa Valavi	Magnetic Forces and Vibration in Wind Power Generators
	Nina Sasaki Støa-Aanensen	Air Load Break Switch Design Parameters

	Gro Klæboe	Stochastic Short-term Bidding Optimisation for Hydro Power Producers
	Zhaoqiang Zhang	Ironless Permanent Magnet Generators for Direct-Driven Offshore Wind Turbines
	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
2014	Bijan Zahedi	Shipboard DC Hybrid Power Systems - Modelling, Efficiency Analysis and Stability Control
	Chuen Ling Toh	Communication Network for Internal Monitoring and Control in Multilevel Power Electronics Converter
	Hamed Nademi	Advanced Control of Power Converters: Modular Multilevel Converter
	Håkon Kile	Evaluation and Grouping of Power Market Scenarios in Security of Electricity Supply Analysis
	Jonas Sjolte	Marine renewable energy conversion: Grid and off-grid modeling, design and operation
	Nadeem Jelani	Investigating the Role of Active Loads in the Future Electrical Grid Dominated by Power Electronics
	Erik Jonsson	Load Current Interruption in Air for Medium Voltage Ratings
2013	Sverre Skalleberg Gjerde	Analysis and Control of a Modular Series Connected Converter for a Transformerless Offshore Wind Turbine
	Vrana, Til Kristian	System Design and Balancing Control of the North Sea Super Grid
	Larsen, Pål Johannes	Energy Savings in Road Lighting Correct Lighting at all times and every condition
	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
	Abuishmais, Ibrahim	SiC Power Diodes and Juction Feild-Effect Transistors
	Zhang, Shujun	Percussive Drilling Application of Translation Motion Permanent Magnet Machine
	Ruiz, Alejandro Garces	Design, Operation and Control of Series-connected Power Converters for Offshore Wind Parks
	Jaehnert, Stefan	Integration of Regulating Power Markets in Northern Europe Offshore Wind
	Tesfahunegn, Samson G.	Fuel Cell Assisted Photo Voltaic Power Systems
	Farahmand, Hossein	Integrated Power System Balancing in Northern Europe Models and Case Studies
	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
	Kulka, Arkadiusz	Sensorless Digital Control of Grid Connected Three Phase Converters for Renewable sources
	Guidi, Giuseppe	Energy Management Systems on Board of Electric Vehicles, Based on Power Electronics
2008	Pedersen, Per Atle	Forces Acting on Water Droplets in Electrically Energized Oil Emul- sions; Observations and Modelling of Droplet Movement Leading to Electrocoalenscence
	Østrem, Trond	Reliable Electric Power Conversion for Connecting Renewables to the Distribution Network
	Skjellnes, Tore	Digital Control of Grid Connected Converters for Distributed Power Generation

	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
	Hoff, Erik Stjernholm	Status and Trends in Variable Speed Wind Generation Topologies
	Løken, Espen	Multi-Criteria Planning of Local Energy Systems with Multiple Energy Carriers
	Ericson, Torgeir	Short-term electricity demant response
	Mauseth, Frank	Charge accumulation in rod-plane air gap with covered rod
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
	Bjerkan, Eilert	High Frequency Modeling of Power Transformers - Stresses and Diagnostics
	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