An overview over PhD Projects 2019

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 40 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, 6 adjunct professors, 4 lecturers, and 5 researchers. The number of Postdocs has increased the last few years from four to seven. 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, October 2019

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PhD Summary 2019 Contents

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Master Degree: MSc Applied Physics and Mathematics
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Graduation Year: 2013

Supervisor: Erling Ildstad
Research Group: Electric Power Technology
Co-Supervisor(s): Sverre Hvidsten and Arne Nysveen
Project: Hydrogenerator Stator Winding Insulation Assessment

Partial Discharges in Voids at a Variable Voltage Frequency

Description of the research

Voids in hydropower generators can be a symptom of insulation degradation. The main part of my work is related to creating a theoretical model that describes partial discharge (PD) activity in voids embedded in a dielectric material and investigating its validity by experimental methods in the laboratory. A typical simulated void voltage for two voltage periods is shown in Figure 1.

The partial discharge inception voltage, total PD magnitude, maximum PD magnitude and number of PDs are studied experimentally as function of voltage frequency and temperature and compared to the theoretical model to justify its validity.

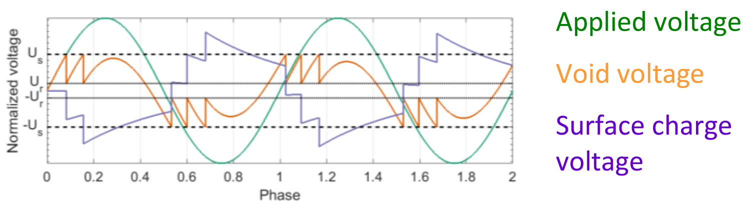

Figure 1: Voltage as function of time. A PD is initiated when the void voltage exceeds the initiation voltage U_{s}. The void voltage is then reduced to the remanent voltage U_{r}. The PD events establish a surface charge voltage to oppose the applied voltage. These surface charges are assumed to decay with time.

Experiments show, in accordance with the model, that these parameters have a temperature and frequency dependency. Important mechanisms that can explain this behavior are void surface conductivity change with time, residual charge relaxation, time lag, dielectric response and a limited discharge area.

Innovation potential and possible applications

The experimentally validated models describing the frequency and temperature dependency of PD activity in voids can be used to improve the interpretation of condition assessment tests. Additionally, this research has discovered the benefits of testing insulation systems in a voltage frequency range to discover important void parameters.

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Research Group: Power System Operation and Analysis
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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, and if grid expansions can be avoided or reduced. It is also possible to compare different expansion strategies compared to increasing flexibility. The methods should be useful as a decision support tool for both transmission and distribution system operators, and aggregators of flexibility.

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Project: Current interruption in supercritical nitrogen

Current interruption in supercritical nitrogen

An increasing trend of wind farms and mining operations located far off the coast will lead to development of offshore substations. To avoid the large cost of platforms and floaters, power switching equipment and other components of such an offshore substation will be placed on the seabed and be remotely controlled. The conventional solution is to use thick-walled pressure-proof vessel to provide an environment for the power components like that of onshore installations. Power cable feed-through or penetrators from the high-pressure water environment and into the more normal ambient inside are also required. These features add substantial technical complexity and cost, in particular at large sea depths. A novel concept is developed by filling the interrupting chamber of switchgear with high-pressure gas to reduce the differential pressure at seabed. Reducing the differential pressure will reduce the cost of the encapsulations and feedthroughs.

Due to the need of extremely high pressure, characteristics of very high pressure arc discharge is not a well explored area. Main goal of this PhD research is to investigate the characteristics of switching arc in extremely high pressure nitrogen (N_2). Objective includes designing and realization of ultra-high pressure test chamber and experimentally investigate the arc characteristics of ultra high pressure nitrogen arc.

Ultra-high pressure free-burning arcs, arcs burning inside cylindrical tubes, thermal interruption performance and post arc dielectric recovery characteristics of high-pressure nitrogen have been investigated recently in collaboration with SINTEF Energy Research. Based on the experimental results, it has been observed that without the forced gas flow high filling pressure deteriorates the interruption performance, while with the help of forced gas flow high pressure can improve the current interruption performance in comparison to atmospheric pressure.

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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

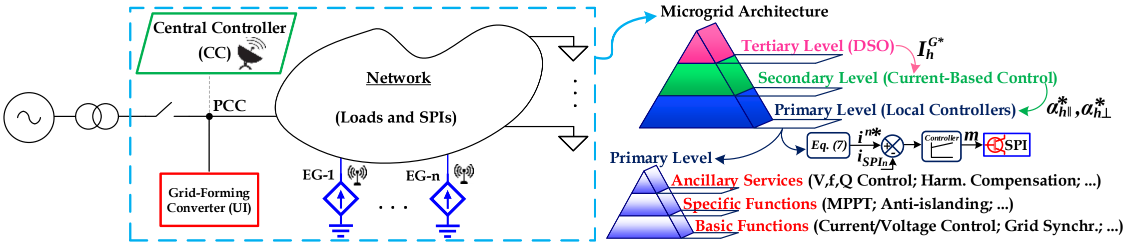
Dense penetration of distributed generators (DGs) in electrical grids, particularly at the distribution level, is increasing and it has been playing a key role in enhancing the performance of power systems by reducing energy losses and by supplying ancillary services that support the network under critical 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. Reduction of neutral currents is also inherently achieved for applications in four-wire systems:
- The GCBC allows to balance the thermal stress among DGs within the microgrid or low-voltage system, also respecting their nominal current capabilities;
- 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, offering power support to the distribution system;
- By taking advantage of definitions within the Conservative Power Theory, the GCBC is able to distributedly compensate unbalance currents. Additionally, being able to damp voltage resonances by driving DGs to synthesize resistive loads.

At last, incorporation of optimization algorithms to the cooperative strategy aims at managing the compliance with these multiple operational objectives, while accounting for diverse constraints of the network.



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.

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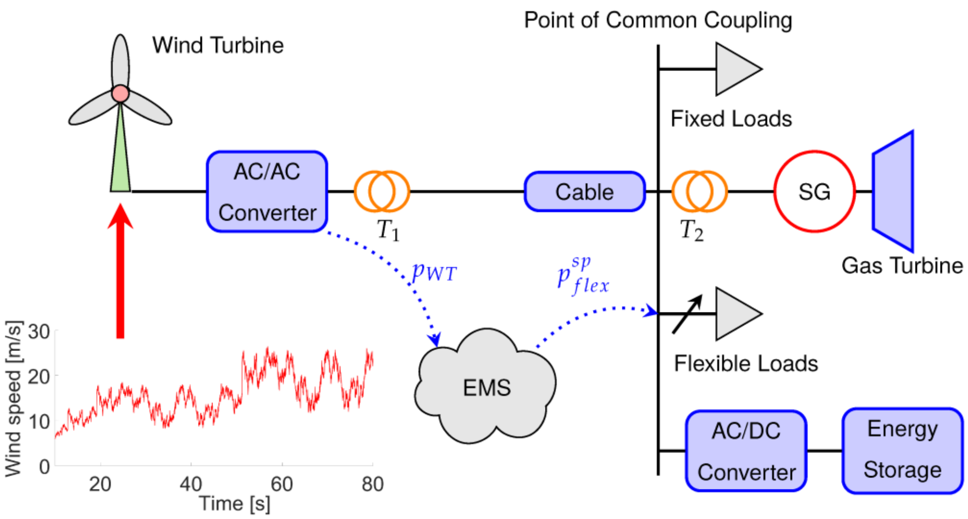
Project: HES-OFF - Innovative Hybrid Energy System for Stable Power and Heat Supply in Offshore Oil & Gas Installations

Power quality and system stability in islanded hybrid energy systems with energy storage

Description of the research

Offshore oil and gas platforms (OOGPs) 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 (GHGs). For instance, the petroleum sector was responsible for 27.8% of the Norwegian GHG emissions in 2017.

This fact led to an increased interest in the integration of wind power (WP) into OOGPs in parallel to gas turbines (GTs), especially where power from shore is not feasible, either technically or economically. The industry is already driving this concept further, and pilot installations in the Norwegian Continental Shelf are planned for as early as 2022.



From an electrical point of view, intermittent wind resources introduce challenges for the stable and efficient operation of this hybrid energy system (HES). In an OOGP, load variations can be sharp and represent a significant part of the total generation capacity. On top of that, stochastic variations are added on the generation side when WP is integrated. This raises concerns not only about insufficient amount of inertia, but also excessive frequency and voltage variations during operation that might negatively affect power quality and the GT operation. Hence, during the design phase of a wind-powered OOGP, it is important not only to meet the power balance between generation and loads, but also consider system dynamics that may affect voltage and frequency in the electrical grid.

From this perspective, energy storage is an enabling technology that can provide proper frequency and voltage regulation, and increase stability in such HES. The literature provides several approaches to the problem of optimally designing an energy storage system (ESS) for an HES, the majority based on solving the unit commitment and economic dispatch problems associating a cost function to the ESS.

However, a common simplification when solving the unit commitment problem is assuming steady-state equations to obtain the active power balance in the system. While valid for an HES connected to a strong grid, this assumption becomes questionable in islanded mode operation or when connected to a weak grid. In those conditions, the ESS is expected to contribute to frequency regulation, and considerable amounts of energy during a short period of time might be used for this purpose. Furthermore, previous works demonstrated that control and energy management strategies might affect substantially the ESS sizing in a stand-alone system.

Within this context, this PhD research aims to pinpoint power quality and system stability (PQSS) issues in HES operating in island mode with high penetration of power electronics-based converters. The main objectives are:

- Quantify the PQSS issues induced by the variability of loads and WP in a reference OOGP and identify how they affect the ESS required size;
- Develop control strategies to mitigate the identified PQSS issues;
- Validate methods and algorithms through hardware-in-the-loop testing.

Innovation potential and possible applications

Results will contribute to implement HES in OOGP where the cost-benefit of power from shore is questionable. From a broader perspective, the topics explored are general and other types of HES, such as electric ships or remote communities, can benefit from this research.

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Research Group: Electricity Markets and Energy System Planning
Co-Supervisor(s): Ove Wolfgang and Karen Byskov Lindberg
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 will consist of development of and analyses with mathematical models. The main model that will be 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 play in the energy system and how regulations should be designed so that the desired outcome is realized by market participants.

The model development will focus on building a mixed complementarity problem (MCP) representative of the market setting under consideration. The 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 two-level Stackelberg games where e.g. a policy maker (the leader) wants to achieve some objective by implementing a policy. An overview of complementarity models is provided in Figure 1.

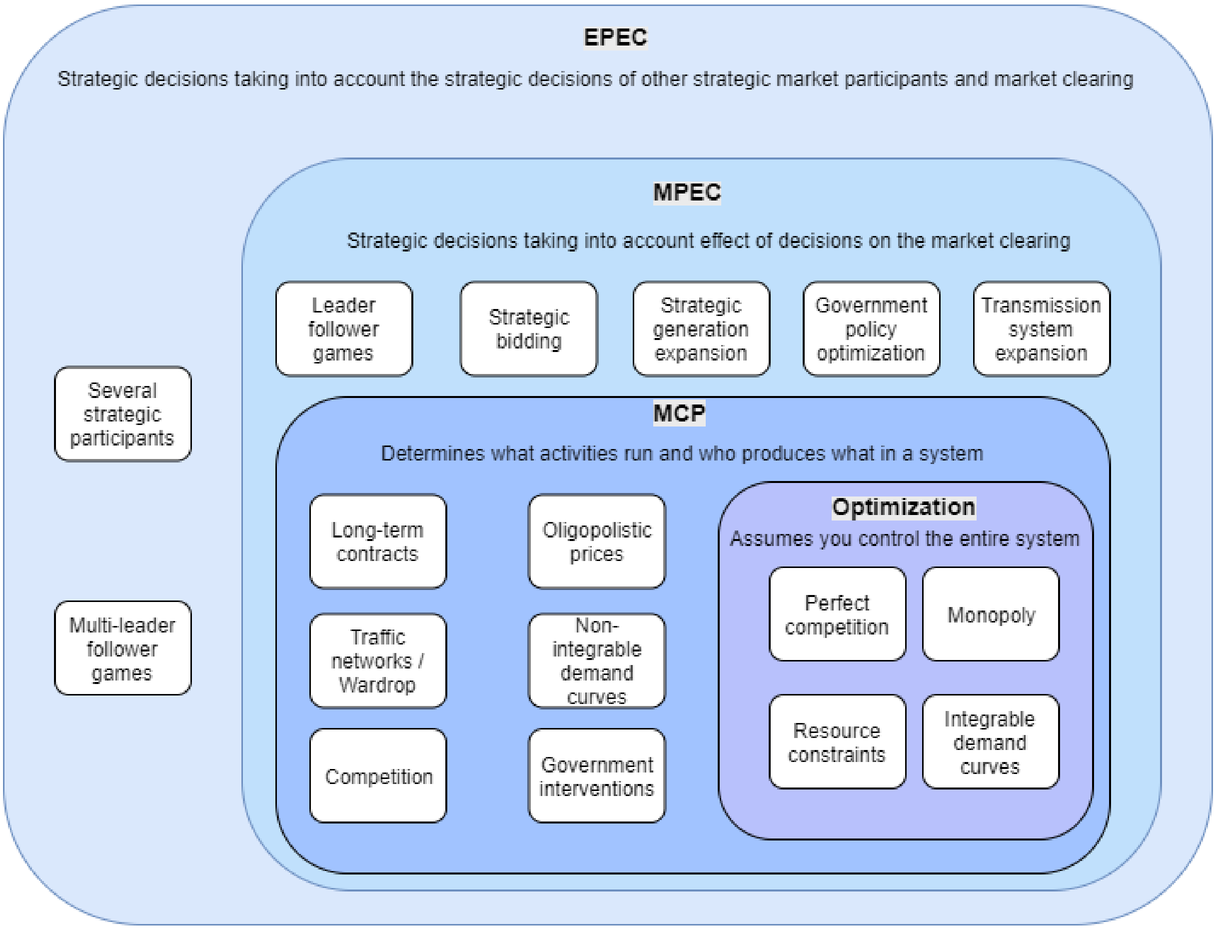

Figure 1: Complementarity model types

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. In this regard, boundary conditions for ZEN and policy instruments will be evaluated to provide information on the performance of these.

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Research Group: Power Systems
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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.

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Co-Supervisor(s): Dimosthenis Peftitsis
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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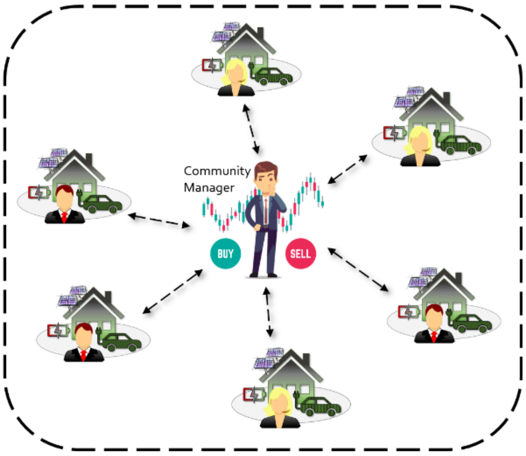
Project: Digital Economy

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.

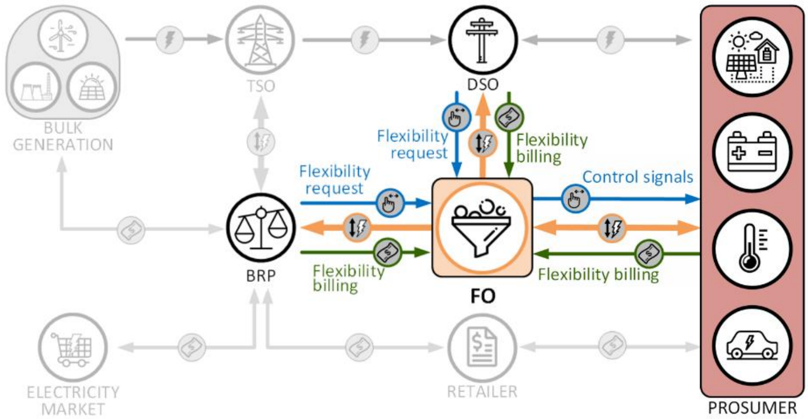
In order to fully integrate end-users, a consumer-centric market design is required in order to incentivize efficient use of distributed energy resources. In addition, the prosumer era market design must allow participation in flexibility markets such as distribution grid congestion management, reserve and imbalance 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 peer-to-peer 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 internal and external flexibility markets. The optimization problem can be used by aggregators, DSOs, community managers and smart energy service providers in order to coordinate flexibility from prosumers in order to increase the revenue from flexibility provision. In addition, we formulate optimization problems to handle completely decentralized electricity markets where peer-to-peer trading is done between all agents in the system.



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Project: Hyper

Hydrogen Production from Wind- and Hydro Power

My PhD is a part of the Hyper-project led by SINTEF that investigates large-scale hydrogen production. My PhD are focusing on the electric power system part of the project, including electrolyser, hydrogen gas storage, transmission grid, wind- and hydro power. We use mathematical modelling of the power system and the electrolysis plant to optimize investment and operational decisions so we can study the physical impact and costs of large-scale hydrogen production on the power system.

We have developed models for component sizing and operation as well as studying the regional effects of variable hydrogen production on the power system. This far, we have developed a deterministic model for component sizing and a stochastic rolling horizon model for simulation of power system operation, including short-term uncertainty in wind power. We have also created a model for investments that consider short-term uncertainty by combining the investment and the stochastic operation model.

The models are used in case studies on the power system in Finnmark in Northern Norway and Texas. In the Finnmark case study, 500 tons of hydrogen is assumed to be produced each day, whereof 90% from natural gas and 10% from electrolysis using electricity from wind and hydro power. The electrolysis plant is assumed to be located in Hammerfest where they already have facilities for liquefied natural gas (LNG) production, thus it is also a good cite for producing liquefied hydrogen in a similar way. In the case studies, we have investigated the optimal size of electrolyser capacity and storage as well as how the hydro power flexibility effects the hydrogen production.

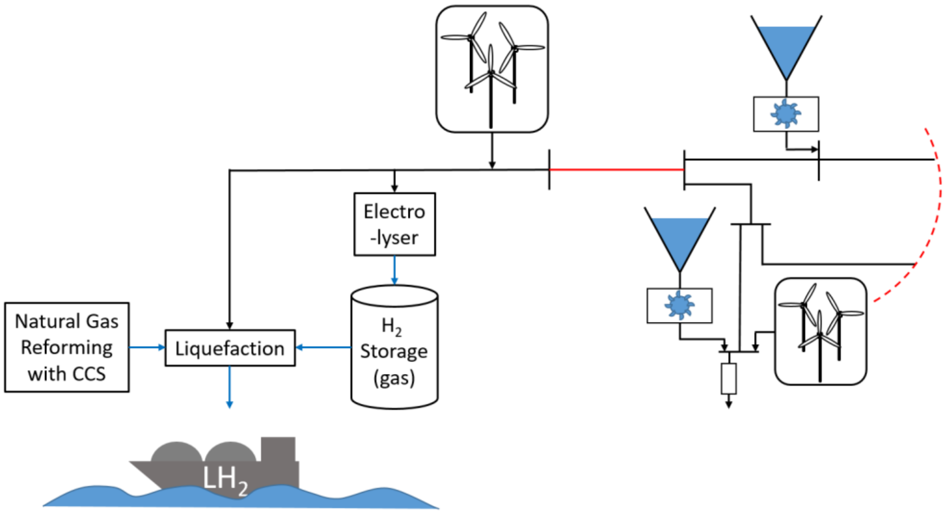

Figure 1: Illustration of a system with hydrogen production from natural gas and wind- and hydro power, including a regional representation of the power system with constrained transmission- lines(red).

The results from the case studies show that hydrogen storage is important to avoid rationing of power, especially when the transmission grid is weak. Hydrogen storage is also important to integrate more wind power without excessive curtailment as it allows for more flexibility in power consumption. Preliminary results show that the operational cost of producing hydrogen from electricity is increased by about 10 % when hydro power is considered inflexible.

Innovation potential and possible applications

This research can be used to decide on the best way of producing large amounts of hydrogen for mitigating CO2-emissions. Hydrogen can be used for mitigating emissions in many sectors, from transport to industry, in applications such as fuel for ships and trucks or replacing coal in the metallurgic industry. The models developed by us enables actors in the electric power sector to make investments that are more accurate by directly considering the operational uncertainty in the investment model.

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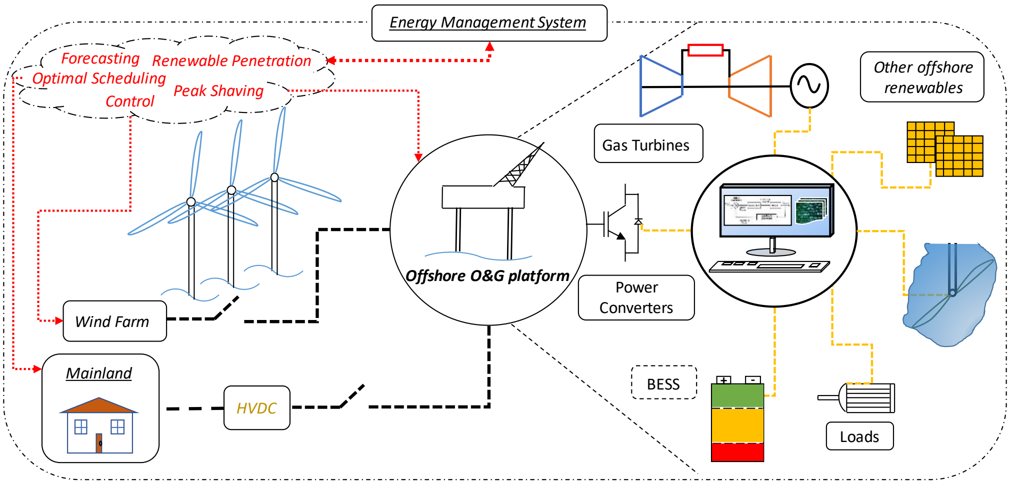
Research Group: PESC
Co-Supervisor(s): Damiano Varagnolo
Project: *EGO-OFF-STORE*

Energy management and control of offshore platforms integrating renewable energy

In order to achieve higher renewable penetration either in isolated or grid-connected O&G platforms, storage systems and appropriate energy management algorithms are essential. Regarding the storage systems, it is rational that battery energy storage systems (BESS) are primarily investigated, having proved their reliability in modern power systems and microgrids, also considering the constant decrease of their cost. On the other hand, data analytics and advances in machine learning have made huge steps in recent years, providing powerful tools that can help model the behavior of complex, highly non-linear systems, such as power systems, with high accuracy, and predict situations that might lead to cascading failures (ramp-up events, sudden renewable generation loss, load disconnection). Also, the forecasting capabilities provided by neural networks and other regression techniques can be used in conjunction with demand response algorithms to achieve reduced peak demand, optimized use of renewable power and smaller storage requirements to meet the tight space constraints of offshore applications.

The aim of this PhD project is the investigation of effective renewable power integration to the O&G offshore platforms, through advanced control, energy management algorithms and appropriately sized storage systems (i.e. Battery Energy Storage System-BESS). The impact of renewable energy sources (i.e. wind, but possibly also other offshore renewables) on the O&G microgrid operation will be examined, comparing the operation of both isolated and mainland-interconnected offshore O&G platforms. An overall conceptual representation of the project's main research areas and relevant technologies 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: Short-circuit current making of MV switching devices with environmentally friendly gas

Investigation on Fault Current Making Performance of Medium Voltage Switchgear

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. Regarding to the switches operation (break and conduct load current), there are numerous experimental results published so far in the field of contacts erosion in current interruption which are 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 contacts touch. Therefore, it is essential to put more effort into discovering the interaction process between arc and contacts during short-circuit making operation to *maintain* and *improve the reliability of MV-LBS*. In addition, using air-filled devices instead of SF_6 makes the switchgear more *environmentally friendly.* Unfortunately, this replacement leads to a more challenging making operation due to lower breakdown voltage and so higher arc duration, which leads to higher energy dissipation and increases melting and welding possibility.

This PhD thesis work is on experimental study relevant to contacts characterization during making operation (pre-strike and contacts touch) in MV-LBS with the main focus on how electrical test conditions are relevant to 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

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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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Project: IDeCON

Model Based Design for 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 realization of smart grid policy is extensively growing in recent years. Motivation for integration of renewables into global energy network is not only to meet the ever increasing energy demand but also to improve the energy availability, reliability, security and quality as well as to compensate the adverse impact of fossil fuels and nuclear energy on global warming. Among different renewables, offshore wind farm has attracted considerable attention mainly in Europe due to its geographical feasibility especially in the North Sea. HVDC grids are considered to be the best solution to transmit large amounts of wind power, in particular from offshore application to the land power system; in fact, HVDC networks are going to be an inevitable part of smart grids since they are the most reasonable alternative where long distance transmission networks or submarine cable routes are required.

This PhD project as a part of IDeCON research project is intended to focus on design and control of offshore HVDC networks, and the main aim is to provide a comprehensive guideline for 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 design and development of new HVDC grids from scratch but also it needs to cover strategies for expansion of currently existing networks. Besides, it is intended to extend the model from point-to-point topology to radial and multi-terminal configuration and further into meshed networks. The most significant challenge through 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. In fact, the topology optimization should not only be limited to equipment level, and it needs to be so comprehensive to embrace the entire system.

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Co-Supervisor(s): Prof. Danilo I. Brandão (UFMG) and Prof. Elisabetta Tedeschi (NTNU)
Project: NB_POCCREI

Consensus Power-Based Control for Low-Voltage Microgrids

Description of the research

The electrical power systems, which have operated longer than a century in a centralized manner, have been experiencing a decentralization process in the last years with the insertion of small generation units. These distributed generators, normally based on renewable sources close to the loads, are a way to meet the increasing energy demand towards reliability, flexibility, efficiency and sustainability. In this process, however, distributed generators have been inserted especially at the distribution level, changing its characteristics, without a structure previously prepared to receive these changes and to provide a coordinated operation and integration with the other existing system components, creating the need for evolution of these systems. In this context, the so-called *microgrids* resurge as a system model able to establish this desired integration between generation and load in a controlled structure, either connected to the preexisting network or isolated from it. To make this possible, an appropriate control system must be developed. This is a key part of such microgrids and the main focus of this PhD project, whose goal is to provide the conditions for the microgrid to perform its main functions satisfactorily. For the development of this control system, a distributed architecture was chosen in order to minimize the use of the necessary communication structure, without losing the possibility of reaching macro objectives, increasing the reliability, scalability and contributing to the economic viability in geographically-wide networks, since the communication structure is established only among neighbor generation units and with the common coupling point.

For the coordination of this system, as contribution of this project, it is expected, therefore, to develop a strategy for a cooperative control, based on the *power-based control*, originally developed with a fully centralized communication network, in a distributed communication structure, by applying the c*onsensus protocol*. This new strategy, called *consensus power-based control*, must be able to regulate the power exchange with the system, to promote the active and reactive power sharing among the generation units, in both operation modes, connected to the grid and isolated, keeping satisfactory standards of power quality.

Innovation potential and possible applications

- Application in low-voltage microgrids;
- Increase of scalability and flexibility in the microgrids;
- Potential to extend the principle to smart grids in general.

(Use max 1-2 pages)

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Co-Supervisor(s): Marta Molinas
Project:

Time-frequency analysis to enhance and simplify stability assessment in Smart Grids

Dealing with the rapid increase of complex components in Smart Grids involves improving our means of stability assessment. Modelling and design 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

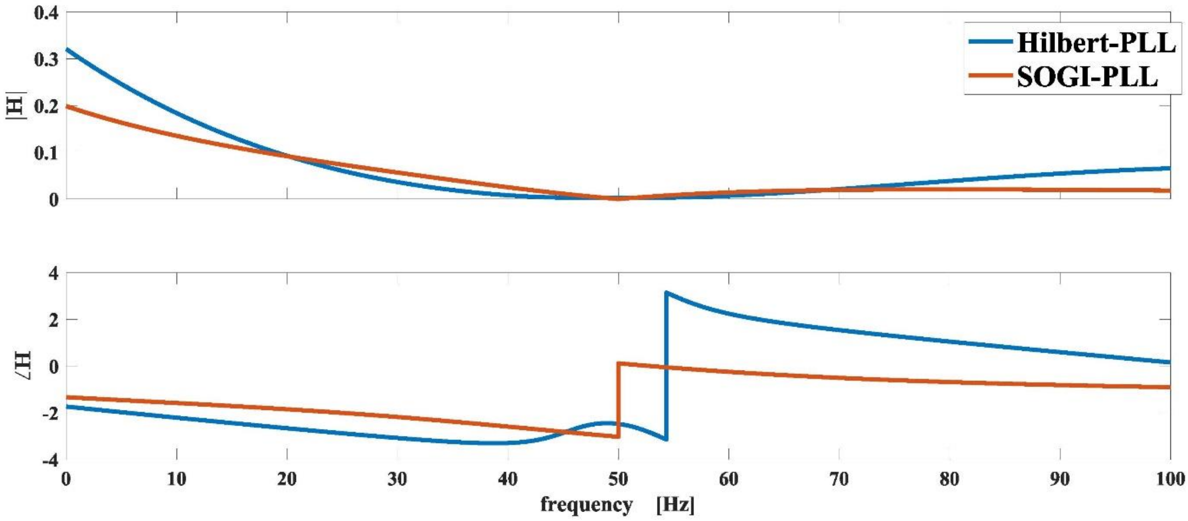

Figure 1: Harmonic transfer function for two synchronisation (Phase Locked Loop) units – this bode diagram relates a sinusoidal input with frequency f to a sinusoidal output with frequency f+50 Hz.

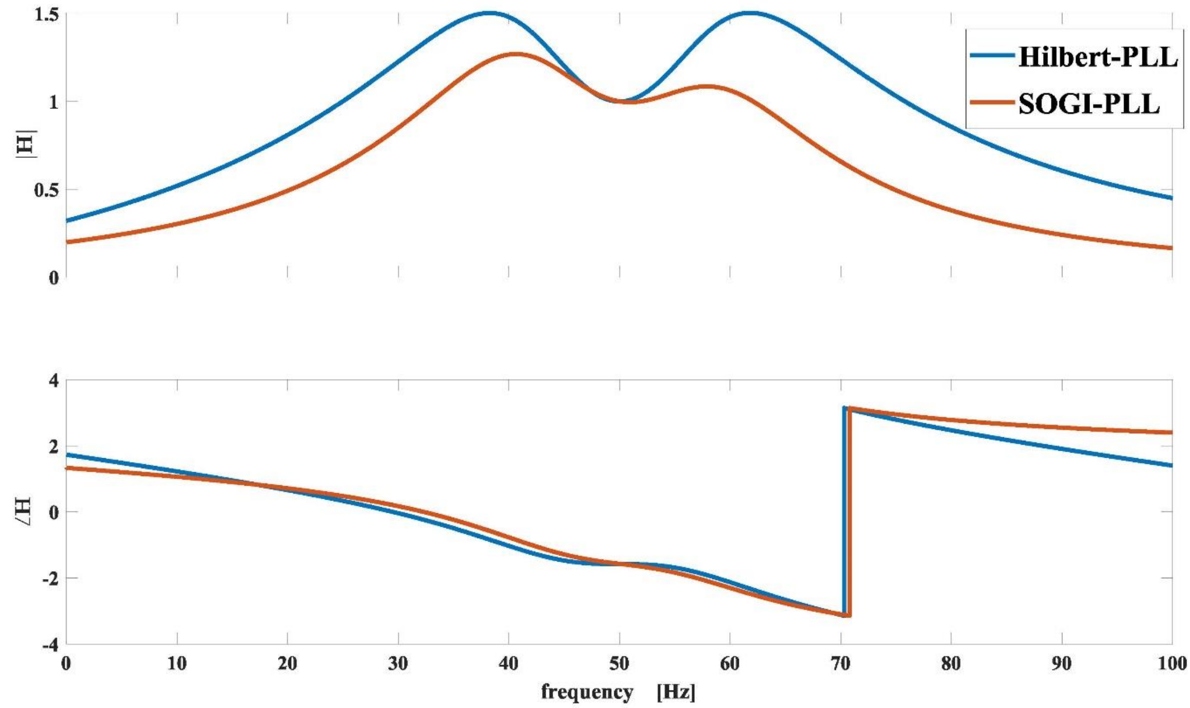

Figure 2: Harmonic transfer function for two synchronisation (Phase Locked Loop) units – this bode diagram relates a sinusoidal input with frequency f to a sinusoidal output with frequency f – 50 Hz

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

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Co-Supervisor(s): Jacek Rabkowski
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.

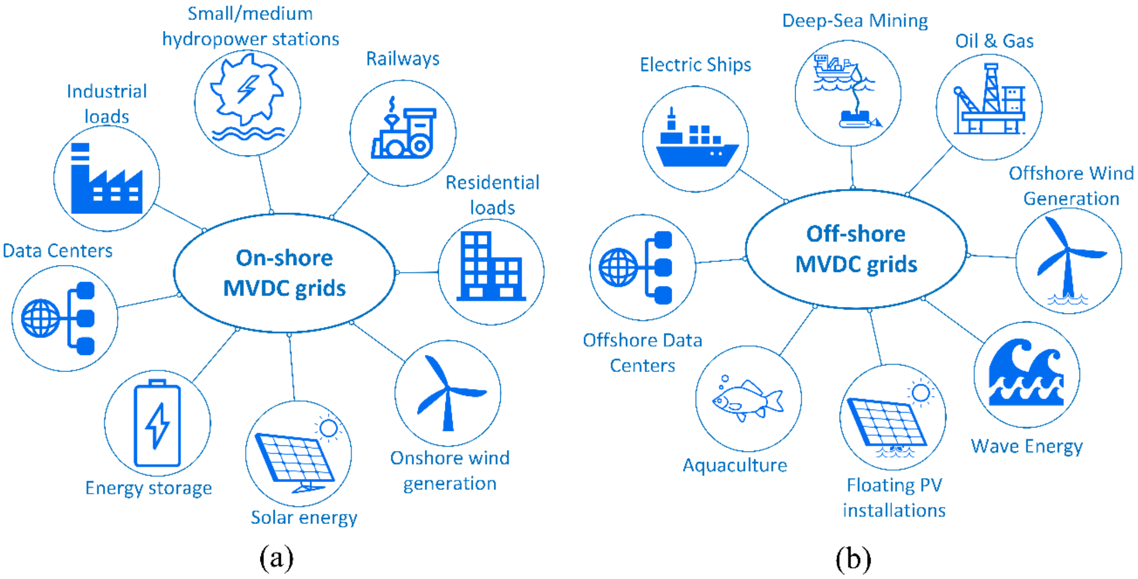

Fig. 1: Potential a) on-shore and b) off-shore applications of MVDC grids.

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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Co-Supervisor(s): Hans Kristian Høidalen, Bruce A. Mork
Project: ProSmart

Power system protection in microgrids

Description of the research

Entities called microgrids is believed to be building blocks of the future resilient distribution networks. However, there are certain technical difficulties to overcome, which are not observed in common medium voltage (MV) and low voltage (LV) distribution networks. Traditional distribution network protection schemes were designed to work from the perspective of radial power flow and introduction of power generation into distribution networks will affect the existing schemes. Non directional overcurrent protection and fuses commonly utilized in these networks are unable to provide higher amount of sensitivity and selectivity [1]. Inverters are the best candidate for an interface for the network interconnection of distributed generators due to their flexibility in control. This flexibility however can be problematic for protection, since behavior of the inverter during fault event is strongly dependent on the applied control method. Additionally, magnitude of the current provided by the inverter during faults is considerably lower compared to the traditional generators. Hence, new protection schemes are required in order to make microgrids concept possible to realize from power system protection point of view.

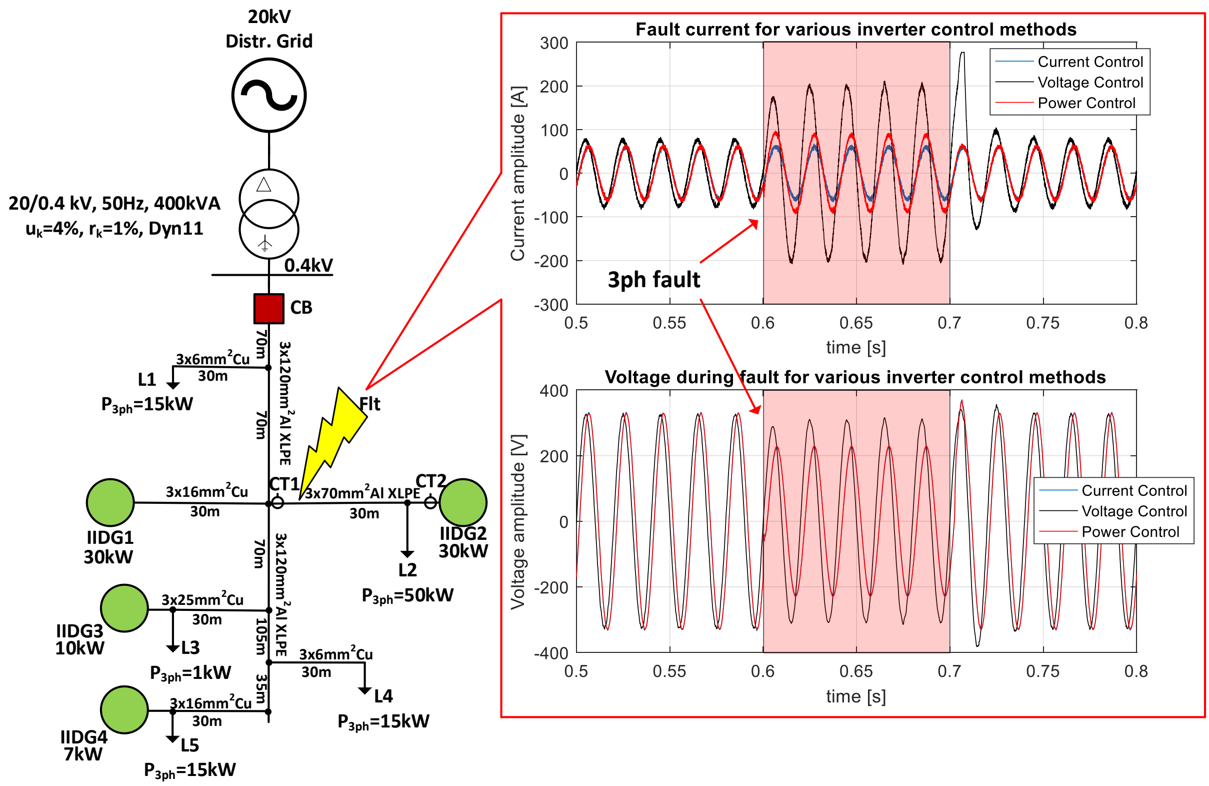

Figure 1 Benchmark LV microgrid topology [2] with current and voltage signals before and during three phase fault in the network for different inverter control methods

[1] S. Conti, “Protection issues and state of the art for microgrids with inverter-interfaced distributed generators”, Presented on International Conference on Clean Electrical Power, Ischia, Italy, 14-16 June 2011

[2] S. Papathanassiou, N. Hatziargyriu and K. Strunz, “A benchmark low voltage microgrid network”, Proceedings of the CIGRE symposium: power systems with dispersed generation, pp 1-8, 2005

Innovation potential and possible applications

Aim of the work is to improve protection schemes in future smart grids. Outcome of this research can be an innovative protection scheme suited for microgrids characterized with low inertia, low fault current levels and possibility to work both grid-connected and islanded.

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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.

Microgrids can be controlled in a centralized or de-centralized manner. In the centralized scheme, a central controller issues the reference signals for the other inverters in the grid. This yields excellent behavior, yet compromises the reliability as it is dependent on communication and the proper functioning of the central controller. In the decentralized scheme, enhanced reliability is ensured since all inverters only depend on local measurements. However, this control compromises power sharing and power quality in the presence of unbalanced and non-linear loads and differing line impedances.

The following are the main objectives of the project:

- Contribute to deepening the knowledge on how power sharing can be done in microgrids. This should be done without the means of communication between DG units in order to ensure reliability and modularity of the system.
- Investigate how virtual impedances can be utilized in the control of microgrid inverters.
- Contribute to an improved understanding of how power quality can be ensured in microgrids.
- Find a general way of evaluating robustness of a microgrid, in order to ensure stability and performance in the event of a change in the topology or under different operating points.
- The proposed solutions shall be validated both analytically and experimentally.

The current work is revolved around a synchronous reference frame controller, which utilizes the conventional droop method to control inverters operating in island mode. The power sharing is improved by application of virtual impedances.

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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

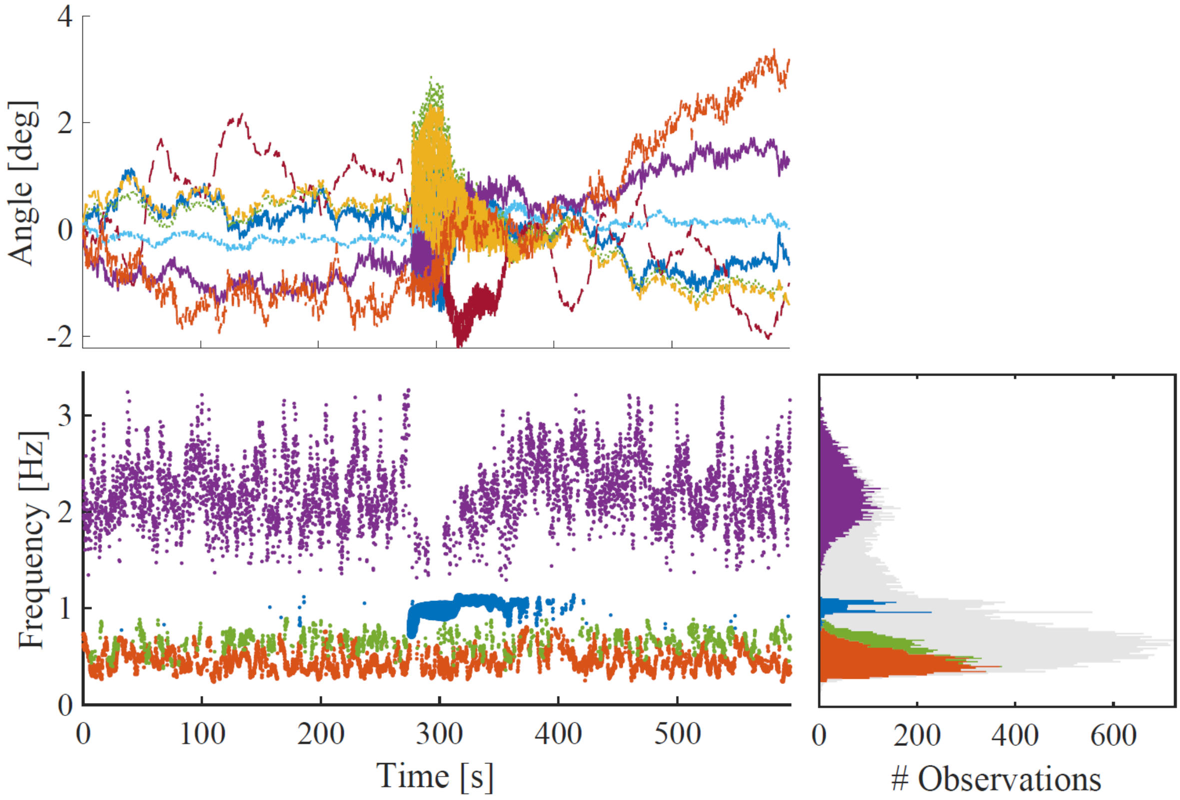
Description of the research

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.

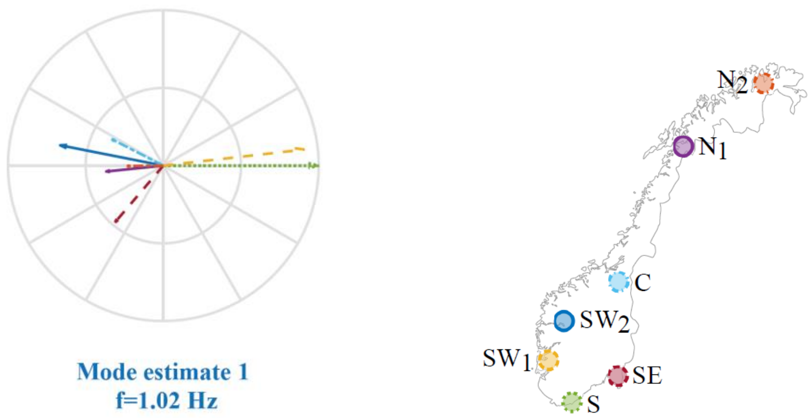
Currently the focus is on monitoring of power oscillations. In large power systems, the generated electric power often needs to be transported over wide areas to be consumed. Increasing the power transfer between weakly connected areas of generation generally causes poorer damping of inter-are oscillations. This motivates development of methods that increase our knowledge on oscillatory stability, as this allows us to operate the system closer to its stability limits, and also to take proper remedial action in case of problematic oscillations appearing due to a severe fault or disturbance.

This far the research has resulted in a method that monitors the frequency of power oscillations occurring in the system, and the amplitude and phase with which the oscillations are observed in the different parts of the system. An example of a result obtained when applying the method to measured data from Phasor Measurement Units deployed across Norway is shown on the next page.

A natural continuation of this work will be to develop efficient countermeasures that mitigate oscillations, for instance by modifying control signals of generators, HVDC-links or controllable loads.



The measured time series are shown in the upper plot, where problematic oscillations occur around $t = 280$ s and last until approximately $t = 400$ s. In the lower left plot, all the detected oscillations are shown, while in the lower right plot shows a histogram of the detected oscillation frequencies. The problematic oscillations of about 1 Hz are indicated in blue in both lower plots.



The final result is the phasor plot shown above to the left, which describes the amplitude and phase of the problematic oscillations at the different measurement locations. Studying the map to the right, showing the locations from where the measurements are obtained, reveals that the south and south-west of Norway swings against the east and more northern locations.

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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.

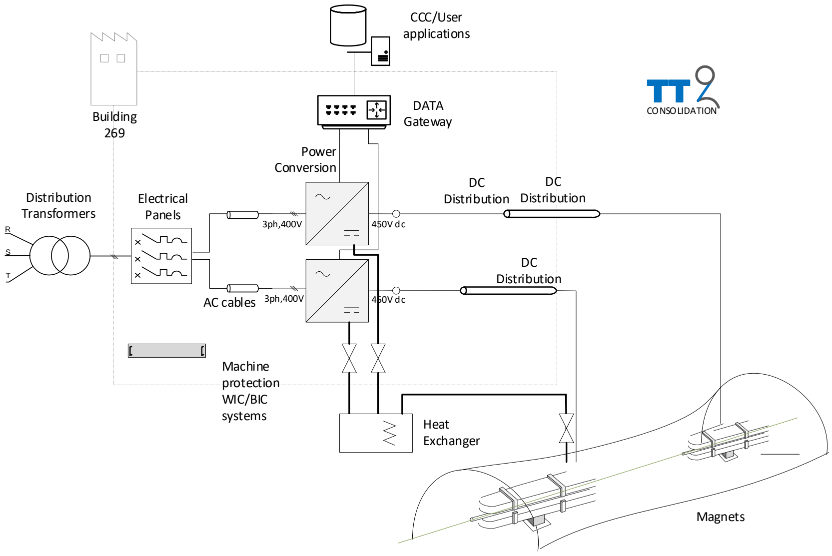

Figure 1 Functional diagram of the current delivery system for the accelerator magnets

The current converters are based on old technologies compared to the today's standards and are nearing the end of their lifetime. Therefore, a joint research project between NTNU and CERN will aim to find a suitable replacement using state of the art high efficiency power convert technology with regenerative properties. The application aims to use many different power sources, combining the local energy storage with the grid in a robust and efficient way.

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

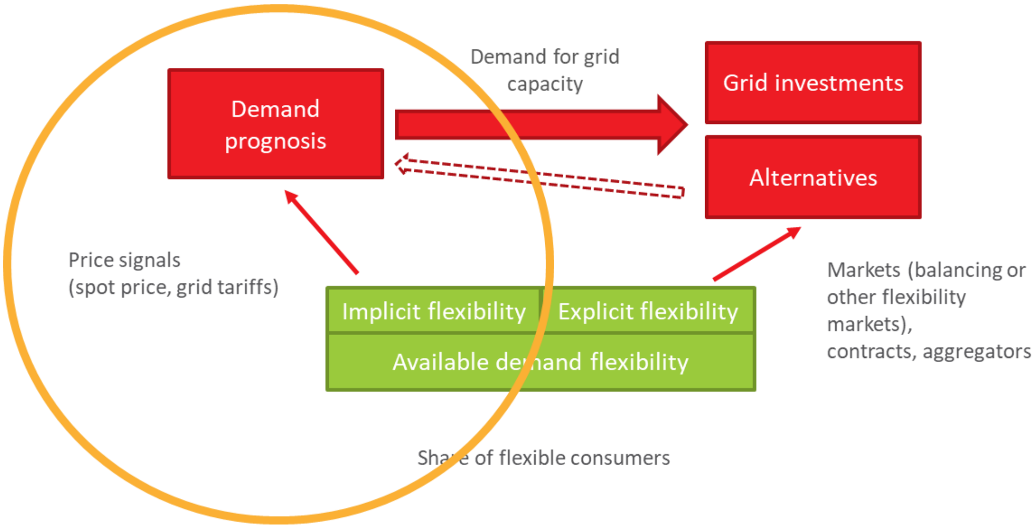
Description of the research

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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Co-Supervisor(s): Frank Mauseth (NTNU) and Knut Magne Furuheim (Nexans Norway AS)
Project: Mass impregnated non-draining HVDC submarine cables

Electric fields in mass-impregnated nondraining high voltage direct current cables

High voltage direct current (HVDC) cables transfer electric energy across large distances, particularly across straits and seas. HVDC cables are considered important to "the green shift", where large amounts of electric energy are to be consumed far away from where it is produced. The most mature type of HVDC cables is *mass impregnated non-draining* (MIND) cables. Such cables are insulated with paper that is impregnated with a highly viscous oil ("mass"). A sketch of the insulation is shown in Figure 1.

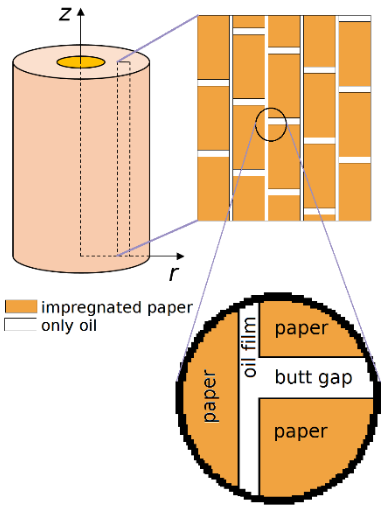

Figure 1: Sketch of MIND cable insulation. Figure from [1].

The aim of the PhD project is to improve the understanding of how the electric field is distributed within the insulation of MIND cables, considering the effect of time and temperature. Calculations are based on measured values of dielectric response and conductivity in impregnated paper and in oil gaps. (The oil gaps are the oil films and butt gaps shown in Figure 1.)

Innovation potential and possible applications

The research results may be a basis for for improved design, test regimes or operational requirements for MIND cables. Hence the knowledge is beneficial for both cable manufacturers and operators.

The PhD candidate is employed by Nexans Norway AS.

Publications

[1] G. Håkonseth, E. Ildstad, and K. M. Furuheim, "Local Electric Field in Mass-Impregnated HVDC Cables," in Proceedings of the Nordic Insulation Symposium, vol. 25, 2017.

[2] G. Håkonseth and E. Ildstad, "Steady-State Electric Field and Conductivity in Mass-Impregnated HVDC Cable Insulation," in 2018 IEEE 2nd International Conference on Dielectrics (ICD), 2018.

[3] G. Håkonseth and E. Ildstad, "Time-Dependent Electric Field Distribution in Layered Paper–Oil Insulation," in Proceedings of the Nordic Insulation Symposium, vol. 26, 2019.

[4] G. Håkonseth, K. M. Furuheim, and E. Ildstad, "Structure of Paper–Oil Insulation for Mass-Impregnated HVDC Cables, accepted for presentation at *Conference on Electrical Insulation and Dielectric Phenomena*, Richland, Washington, USA, October 20–23, 2019.

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Co-Supervisor(s): Kjetil Uhlen
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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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Supervisor: Jonas Kristiansen Nøland
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Project: Optimal Utilisation of Smart Generators

Temporary title: Optimal Utilisation of Smart Generators

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 at 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 thermal modeling of the machine and the ‘digital twin’ identification of the whole system, represent the main cornerstones of the project. Different other challenges may arise when specific case studies are to be considered. 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 optimising the final operation of the machine itself.

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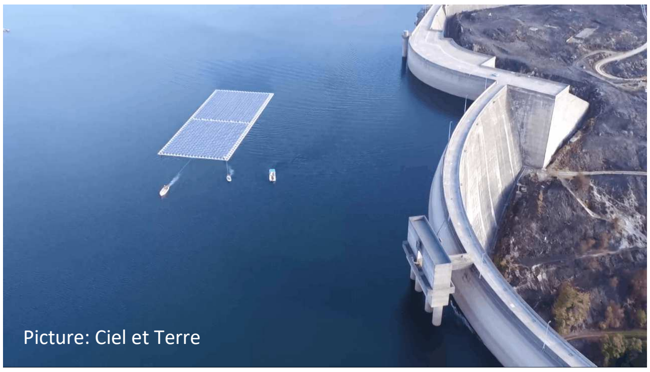
Project: Industrial Ph.D. with Multiconsult

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 overcomes 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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Graduation Year: 2017

Supervisor: Arne Hejde Nielsen
Research Group: Power Systems
Co-Supervisor(s): Hjörtur Jóhannsson, Kjetil Uhlen
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

Risk and vulnerability in the future intelligent electricity distribution system

The increasing uncertainties in the future distribution system call for a high level, top down approach to be applied by the DSOs in order to assess the risks. At the same time, new components and technologies will provide new information for enhanced accuracy in the risk models, and new possibilities will be provided by automation, self-healing and islanding of microgrids in interplay with the distribution system. To control the effect of interdependencies and new threats and vulnerabilities on the uninterrupted power supply, methods to monitor and manage the risks are needed.

This candidate will work with development of indicators for continuous management of risks and vulnerabilities in future smart distribution grids, taking the large number of uncertainties into account in the decision making. In this respect, interdependencies between the power distribution system and the ICT solutions with respect to reliability, vulnerability, cyber security, and robust communication solutions, are expected to be of high importance.

This PhD is a part of WP1, smart grid development and asset management, in the FME CINELDI project lead by SINTEF Energy Research in cooperation with NTNU. The purpose of the research in WP1 is to develop decision support methodologies and tools needed for the optimal planning and asset management of the future robust, flexible and intelligent distribution system[1].

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Co-Supervisor(s): Arild Helseth, SINTEF Energy Research
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 want to explore in this PhD work are:

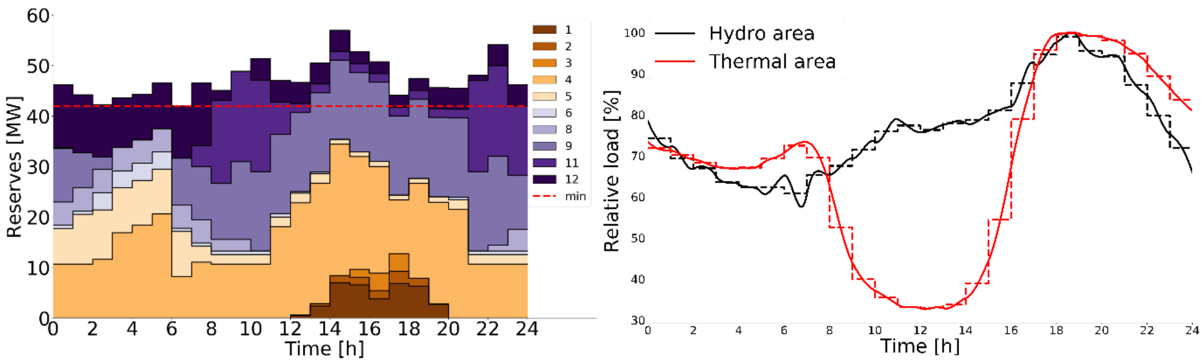
1. <u>Reserve capacity activation in hydropower systems:</u> Energy constraints are usually not considered when capacity is reserved for balancing on hydropower units. This means that the reserved capacity cannot be fully activated if there is insufficient energy or energy storage capacity available. 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 currently under review, by explicitly modelling the activation step in the reserve procurement phase. An older version of the paper can be accessed at https://arxiv.org/abs/1903.04805.

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.

3. Reserve capacity sharing across bidding zones: Sharing reserve capacity between different bidding zones is cost-efficient but requires available transmission capacity between the zones. A way of modelling the reservation of transmission capacity for balancing purposes is to extend the methodology of 1) to a multi-area model with activation scenarios. There is also potential to incorporate the framework used in 2) to simultaneously tackle structural imbalances.



Left: Reserve capacity allocation for 12 hydropower plants when activation is considered.
Right: Load represented as a continuous-time spline and piece-wise constant function (dashed line).

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 and sharing reserve capacity between zones are important tools to reduce costs for TSO's. Both hydropower producers and a TSO are represented in the PRIBAS project.

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Project: NTNU Oceans Pilot Program on Deep-Sea Mining

A more productive motor drive system for sea-floor mineral mining

Motivation

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

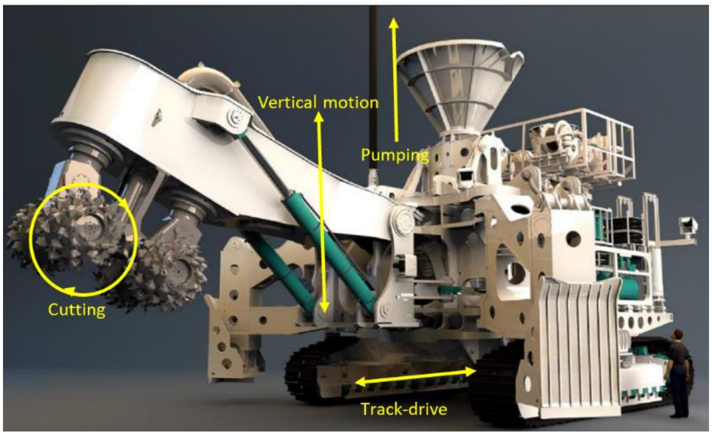

Figure 1: Multi-motor, Mega Watt ROV for seafloor mining developed by SMD for Nautilus Minerals

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 Figure 1. These machines demand their variable speed drives (VSD) to be submersible in deep waters in harsh environmental conditions. Thus, the reliability, high power density and the operating efficiency become the figures of merit for the subsea VSDs which will determine the commercial viability of the seafloor mining.

Problem description

In the subsea VSDs, the power electronics and dc-link capacitor bank have the highest failure rate. However, an unscheduled interruption in seafloor mining due to VSD failure would cause devastating consequences in terms of profitability and sustainability. The highest challenge is to ensure longer periods of uninterrupted VSD operational times.

Another challenge that the motors in the seafloor mining machines sometimes experience zero speeds when the load needs high torque. At the absence of speed/position sensor (to increase the reliability), it becomes a necessity to estimate the motor states accurately at very low speeds. The system parameters too, are bound to be uncertain in the remote, harsh underwater environments, thus, the robustness and fault tolerance in the control system would be beneficial in the subsea environments.

It is also interesting to investigate methods to reduce the required amount of capacitance at the dc-link, again, to reinforce the VSD reliability.

Research directions

Position sensor-less, 6-phase motor drive system shall be investigated in the PhD research, mainly due to its inherent power-stage redundancy. In looking at the superior operating efficiency, torque density and control convenience, interior permanent magnet synchronous machine (IPMSM) based VSD has been the preferred choice.

Novel position estimation techniques shall be investigated to advance the state-of-the-art for reasonably accurate torque production around zero speed. In addition, model predictive control methods over the classical linear (PI) control methods are interesting research directions due to the achievable high control dynamics and control robustness against parameter uncertainty.

Proof of concept

The concepts shall be proven with a laboratory scale prototype encompassing a 6-phase IPMSM of the ratings of 20 kVA. Si IGBT based, two sets of 2-level, 3-phase PWM-inverters shall be used in the prototype.

The state-estimation and control will be implemented in PicoZed system-on-module (SOM) which contains a powerful, all programmable Xilinx Zynq system-on-chip (SOC). Its FPGA fabric will contain the PWM, ADC, digital filters etc., while its ARM processor shall contain the state-machines and most of the control algorithms.

Innovation potential and possible applications

The research concepts are applicable for applications that are particularly concerned about the mission-criticality. For example, subsea (oil and gas) motor drives, motor drives in offshore platforms, aerospace motor drives, medical instrumentation. The novel design flow with SOM can be very attractive when it comes to the R&D cost & time reduction. The Norwegian offshore, subsea oil & gas and aerospace industries can benefit profoundly, if the concepts can be extended towards a product.

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Research Group: Power Systems
Co-Supervisor(s): Karen Byskov Lindberg
Project: FME ZEN

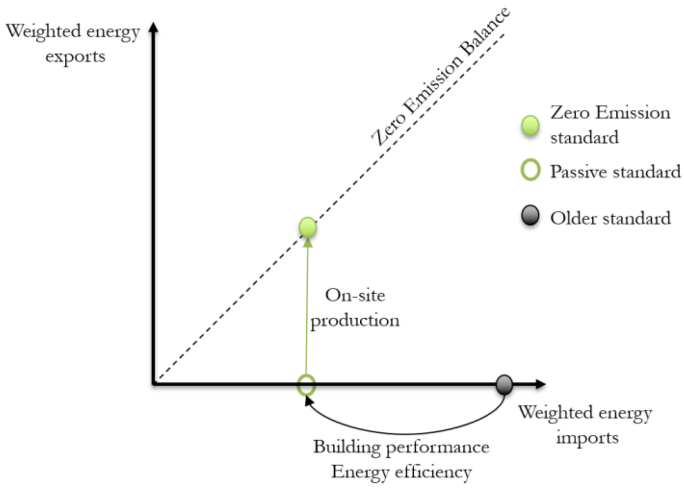
Models for Optimal Investments in the Energy System of Zero Emission Neighborhoods (ZEN)

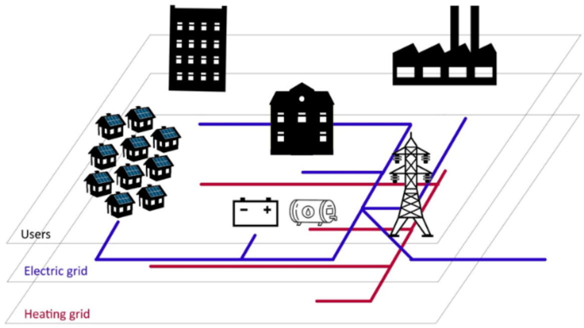
Description of the research

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 Buildings (ZEB) have investigated for 9 years the concept of zero emission/energy buildings in a multi-disciplinary project. Architecture, materials, user acceptance, heating technology and optimization of the energy system were studied. Zero Emission Neighborhoods (ZEN) are an extension of this concept to the neighborhood scale which are now studied in the ZEN research center.

In order to be zero emission, several steps should be undertaken, and in a simple approach, they can be summed up to two steps. The first step is related to the performance of the buildings (insolation of walls, roof and window) and to the emissions embedded in the materials. The second step is to have a local energy system with its own renewable production in order to obtain a “zero emission balance”. The figure below (on the left) shows those two steps.

My PhD takes place in this context. It aims at optimizing the investments in the energy system of zero emission neighborhoods. The optimization handles the investments in the heat and electricity system of the neighborhoods and consider its operation for a representative year. The figure below (on the right) represents the neighborhood we are optimizing. It can consist of houses, apartments and neighborhood scale heat production technologies with a heating grid. It also includes 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 main objective is to identify what has an impact on the design of ZENs, which technologies are chosen and why. For example, one parameter that can play an important role is CO_2 factors for electricity and other energy carriers. However, defining those values is not trivial and using the investment model can provide helpful insights regarding its impact on the design of neighborhoods. Many other such insights can be gained and would be valuable in promoting and applying the concept of ZEN.

Another aspect that can be addressed in the PhD is investigating the effect of such neighborhoods, with a lot of production on site, on the national electric system. Examples of questions in this topic are: What are the impacts on existing lines and on the needs of new transmission lines? To what extent can the neighborhoods provide flexibility to the grid?

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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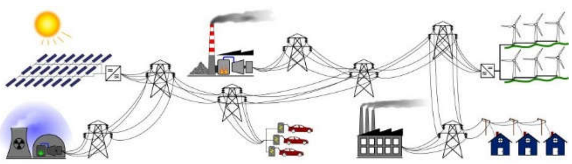
Supervisor/co-supervisor: Kjetil Uhlen, Arne Nysveen
Project: HydroCen

Grid Integration of Variable Speed Hydro Power Plant

Background

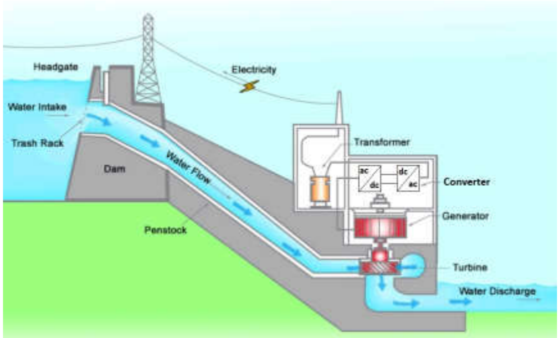
As the share of wind and solar energy production increases, more flexible production and loads are required to control the balance of the grid. A potential use of Variable Speed Hydro Power (VSHP) is to provide this flexibility and compensates the production of variable renewables. The hypothesis is 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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Research Group: Dept. of Electric Power Engineering
Co-Supervisor(s): Sigri Scott Bale / Lisa Haukaas (Hydro)
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.

<u>Published research</u>

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.

<u>Ongoing research</u>

Applied machined learning for optimal selection of bidding strategies in reservoir hydro: Access to an increasing amount of data opens up for applying machine learning for predicting the best combination of models and strategy for any given day. Historic performance of two given bidding strategies over several years have been analyzed with a combination of domain knowledge and machine learning. A wide range of parameters accessible to the models prior to bidding have been evaluated to predict the optimal strategy for a given day. Results indicate that a prediction model will outperform a static strategy where one bidding method is chosen based on overall historic performance.

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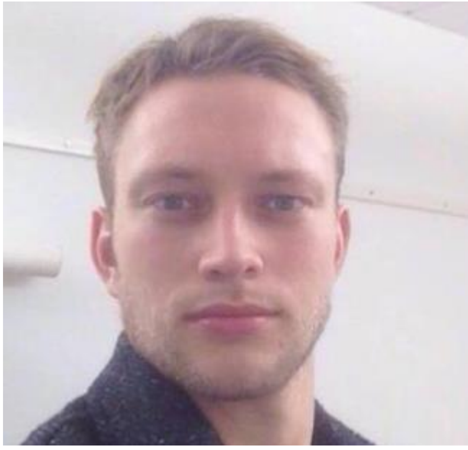


Master Degree:

University: NTNU

Graduation Year: 2017

Supervisor: Dimosthenis Peftitsis

Research Group: Power Electronic Systems and Components – PESC

Co-Supervisor(s): Roy Nilsen

Project: High-efficiency all-electric DC supply systems for subsea work-class remotely operated vehicles - HEROVs

Fill in the title of your thesis

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 operational behavior of

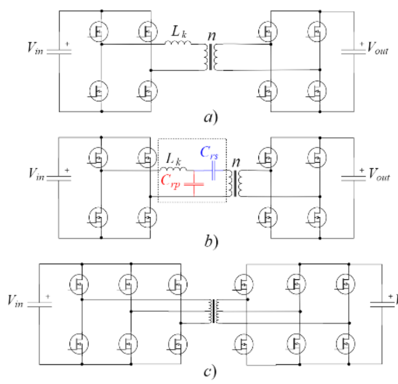
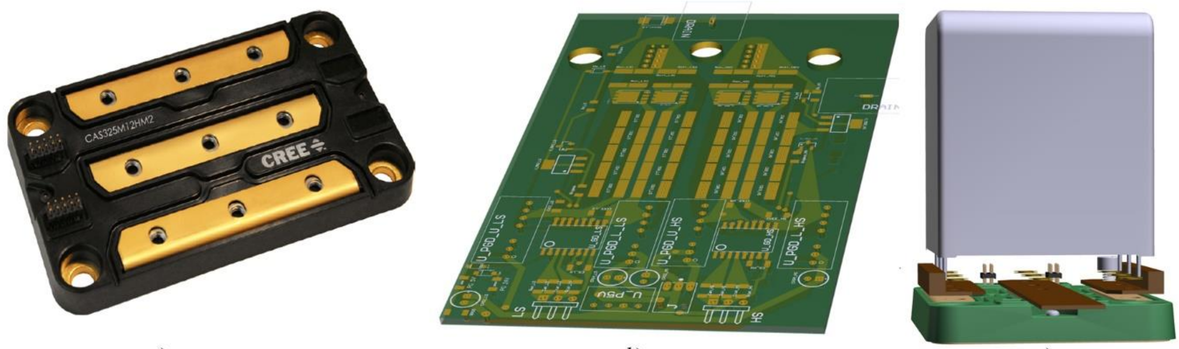


Fig. 2 a) Single-phase CDAB, b) Single-phase SRC (blue capacitor) or PRC DAB (red capacitor), c) 3-phase CDAB.

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 Fig. 2, 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- and zero-current-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. Research regarding power electronics utilizing SiC or GaN semiconductor devices is still in its infancy,

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 become extremely 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. Little known research has been conducted on pressure tolerance of active power electronic components, even though the application areas are large.

Current research focuses on developing a high-power DAB converter capable of handling an input voltage of 10 kV, output voltage of 500 V with a power level of 200 kVA, using elements of Fig. 3



a) b) c)

Fig. 3 - a) CAS325M12HM2 1.2 kV, 256 A Silicon Carbide (SiC) MOSFET half-bridge module, b) its accompanying gate-driver PCB, c) double-pulse hardware setup for the module.

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. The current open-source research is sparse with regards to pressure tolerance of power electronics. Breakthrough within this area can lead to solutions within the mentioned industries.

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Co-Supervisor(s): Ole-Morten Midtgård
Project: HiPPE

Design and optimization of GaN based auxiliary converter for medium voltage converters.

Description of the research

Recently, advances have been made in fabrication of semiconductors based on wide band gap materials. The most important materials for future power electronics are silicon carbide and gallium nitride (GaN). The material properties of GaN result in devices with superior characteristics to silicon devices. These characteristics result in devices that has lower on-state losses and lower characteristic capacitances. This gives new opportunities for further improvement of power electronic converters as well as new challenges.

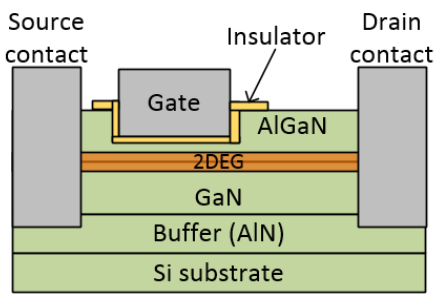


Figure 1. Device structure of a normally-off GaN high electron mobility transistor.

One of the applications which could benefit from for GaN based converter systems, is wireless power transfer (WPT). The density, transfer distance and efficiency of WPT systems are improved with high frequency power electronic converters. Due to the low parasitic components of GaN device, converters can operate at higher frequencies

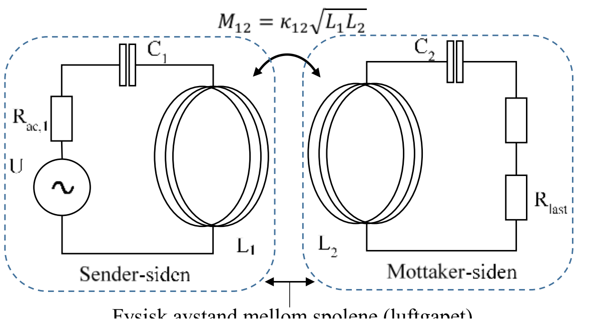
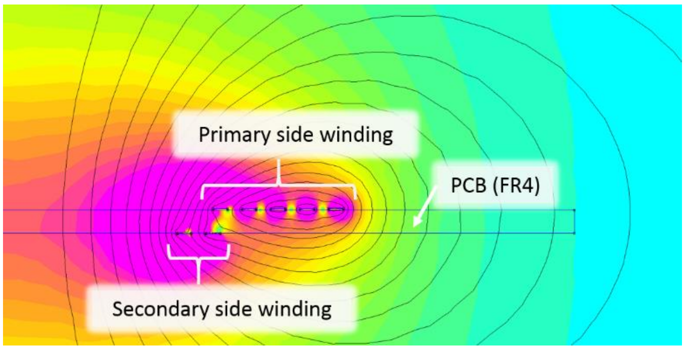


Figure 2. Wireless power transfer system using an inductively coupled system. Power is transferred from the primary (left) to the secondary side (right) where it is consumed by a load.

while at the same time increasing the converter efficiency.

In collaboration with G2Elab in Grenoble, France, and Stanford University, USA, an auxiliary power supply is developed, targeted to energize the auxiliary circuits of medium voltage converters (1 to 36 kV_{RMS}). The converter topology is based on WPT systems. The power supply must fulfill criteria of high insulation voltage, low coupling capacitance, high density and high efficiency. The low coupling capacitance is achieved by distancing coupled coils of the WPT system. By filling the space between the two inductors with a highly insulating material, a high insulation voltage can also be achieved. The high density and efficiency is achieved by a resonant GaN converter which is designed through detailed modelling and then optimized using a genetic algorithm. Future medium voltage drives or multilevel modular converters will benefit from the results of this work.



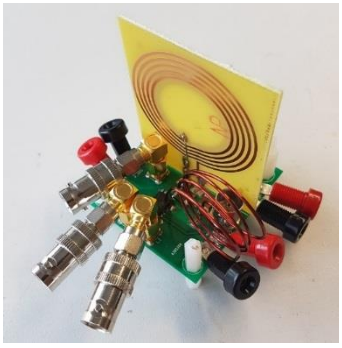


Figure 3.Left: example of FEM simulation of the planar transformer with isolation capabilities up to several tens of kilovolts. Right: photo of the prototype of the auxiliary power supply.

Innovation potential and possible applications

Several innovations are explored regarding the holistic design of the planar transformer with high voltage isolation. Power supplies with high insulation voltage criteria, e.g. auxiliary supply for medium voltage power converters. Possible user of such systems would be suppliers of medium voltage converter systems like ABB, Siemens and GE/Alstom. Other industrial applications have not been investigated.

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Co-Supervisor(s): Magnus Korpås, Karen Lindberg, Ove Wolfgang
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 that exist within 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.

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. Inspired by the methods and techniques commonly found in hydropower scheduling, the author is trying to incorporate these techniques within the given work plan. 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 components 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 monthly power tariff based on highest peak power has been included. The household demand is considered uncertain. The aim is to find the optimal peak power for the household to minimize total electricity cost. The results from this test shows that the SDP method finds the optimal peak power for the household based on the expected future cost for the period. The peak power level is set based on the value of allowing more flexibility in electricity scheduling versus the added cost from the power tariff.

The findings show that the SDP approach is promising to integrate with households. 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.

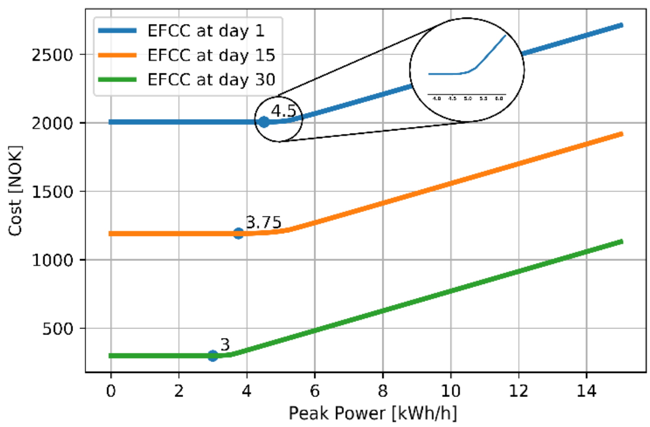

Figure 1: Illustration of expected cost based on peak power for a household with the measured peak grid tariff implemented

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, as used above, 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 model can then schedule hourly with hourly realization with flexibility reserved for this so that the household can schedule by using the flexibility to ensure that the operation goes smoothly without any extra cost. 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 pump storage plant

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 within this PhD will involve 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 will be 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. The decoupling will also limit the influence of grid dynamics on the hydraulic and civil structures.

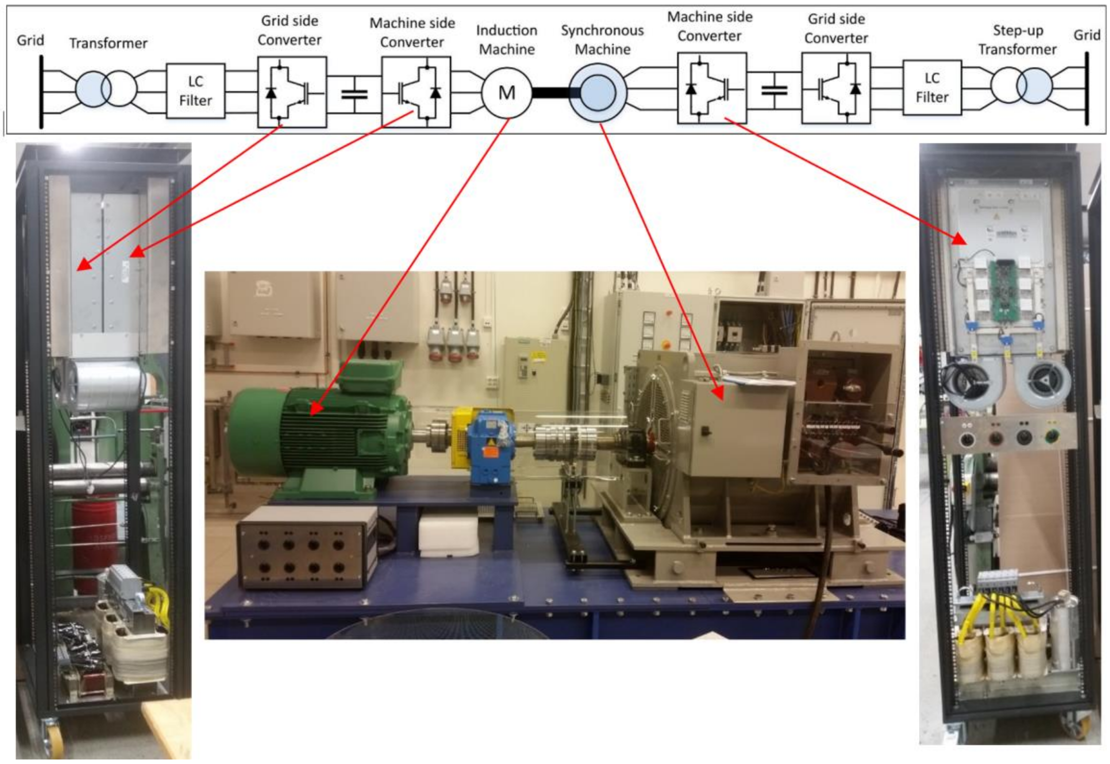

Figure 1: Lab Setup

The most relevant application of this project will be in the retrofitting of the exiting pump storage hydropower projects where the synchronous machine and RPT are already installed and buying a full-size converter to make CFSM could be a cheaper option than to buy 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 (wind and solar) to the maximum and can minimize the variations in operation of thermal power plants.

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Research Group: Electric Power Technology
Co-Supervisor(s): Robert Nilssen, Niklas Magnusson
Project: Thermal modelling of transformers

Investigation of power transformer core losses and stray losses under special conditions

This project is a part of the research project 'Thermal modelling of transformers', coordinated by SINTEF Energy Research. The objective of the main project is to develop thermal models that can be adapted to existing transformers to support reinvestment and maintenance decisions and allow safe upgrading and emergency overloading.

Geomagnetically induced currents (GIC) is another concern that can cause damage for transformers. Norway is among the countries at higher risk of GIC, with the largest GIC over a 100-year period being estimated to 400 A. GIC can saturate the magnetic core, hence assessing the risk of damage for transformers requires extensive calculations of magnetic fields and the associated stray losses which have yet to be performed.

The main goal of the project is to investigate the loss feature of the transformer under saturation condition. The results are the critical input to thermal modelling. The stray field distribution outside the transformer core is expected to deviate from what is observed during normal operation. Finite element model including the strong non-linearity of the materials shall be used. The losses in the windings, core and tank from the stray field need to be evaluated in detail. Besides FEM calculation, the experimental investigation is also critical in order to investigate (verify) various factors that affect core losses and stray losses.

Innovation potential and possible applications

The goal of the project is to gain the understanding of the performance of electric apparatus under 'extreme' conditions. The method, model and results are supposed to be different from the normal one. The knowledge explored would give a reference for industry when design, manufacture and operate the apparatus towards new boundary.

PhD graduated at Department of Electric Power Engineering, NTNU, from 2000

Year	Name	Title
2019	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
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	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
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	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

	Astrid Røkke	Permanent Magnet Generators for Marine current Tidal Turbines
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
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	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
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	Rene Alexander Barrera Cardenas	Meta-parametrised metamodeling approach for optimal design of power electronics conversion systems. Application to offshore wind energy conversion systems
	Gilbert Bergna Diaz	Modular Multilevel Converter - Control for HVDC Operation
	Santiago Sanchez Acevedo	Stability Investigation of Power Electronics Systems A Microgrid Case
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
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2013	Sverre Skalleberg Gjerde	Analysis and Control of a Modular Series Connected Converter for a Transformerless Offshore Wind Turbine
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	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
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	Jafar, Muhammad	Transformer-Less Series Compensation of Line-Commutated Converters for Integration of Offshore Wind Power
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2012	Yordanov, Georgi Hristov	Characterization and Analysis of Photovoltaic Modules and the Solar Resource Based on In-Situ Measurements in Southern Norway
	Haileselassie, Temesgen Mulugeta	Control, Dynamics and Operation of Multi-terminal VSC-HVDC Transmission Systems
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	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
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2006	Maribu, Karl Magnus	Modeling the Economics and Market Adoption of Distributed Power Generation
	Catrinu, Maria	Decision-Aid for Planning Local Energy Systems. Application of Multi-Criteria Decision Analysis
2005	Hellesø, Svein Magne	Dynamic analysis and monitoring of power transmission cables using fibre optic sensors
	Lund, Richard	Multilevel Power Electronic Converters for Electrical Motor Drives
	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
2004	Øvrebø, Sigurd	Sensorless control of Pemanent Magnet Synchronous Machines
	Kristiansen, Tarjei	Risk Management in Electricity Markets Emphasizing Transmission Congestion
	Korpås, Magnus	Distributed Energy Systems with Wind Power and Energy Storage
2003	Botterud, Audun	Long Term Planning in Restructured Power Systems: Dynamic Model- ling of Investments in New Power Generation under Uncertainty
	Ettestøl, Ingunn	Analysis and modelling of the dynamics of aggregate energy demand
2002	Kolstad, Helge	Control of an Adjustable Speed Hydro Utilizing Field Programmable Devices
	Norheim, Ian	Suggested Methods for Preventing Core Saturation Instability in HVDC Transmission Systems
	Warland, Leif	A Voltage Instability Predictor using Local Area Measurements. VIP++
	Ruppert, Christopher	Thermal Fatigue in Stationary Aluminium Contacts
2001	Larsen, Tellef Juell	Daily Scheduling of Thermal Power Production in a Deregulated Elec- tricity Market
	Kleveland, Frode	Optimum Utilization of Power Semiconductors in High-power High-frequency Resonant Converters for Induction Heating
	Myhre, Jørgen Chr.	Electrical Power Supply to Offshore Oil Installations by High Voltage Direct Current Transmission

2000	Oldervoll, Frøydis	Electrical and thermal ageing of extruded low density polyethylene insulation under HVDC conditions
	Doorman, Gerard	Peaking capacity in Restructured Power Systems
	Hystad, Jan	Transverse Flux Generators in Direct-driven Wind Energy converters
	Pleym, Anngjerd	EMC in Railway Systems. Coupling from Catenary System to Nearby Buried Metallic Structures.