Masteroppgaver 2022

NTNU
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Summary of Master's Theses 2022

Department of Electric Power Engineering

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Summary of Master Theses 2022

Another year has passed, and a new class of Master students have completed their education at the Department of Electric Power Engineering here at NTNU. Also for these students lockdowns have been a part of the master period.

With this backdrop it is very satisfactory to be able present this summary of Master Theses from our 2022 class. I would like to take the opportunity to congratulate each and every student with completing the Master thesis and by that also the educational journey at NTNU.

In this pamphlet you will find short summaries of all the good work that our Master students have performed under the supervision of our academic staff. The set of theses give a good picture of the different research areas covered by the department, taking us towards our vision of being in the center of the green, digital transformation. I am sure that our students with their knowledge and skills will continue to drive society in the right direction.

If you by reading get inspired and would like to know more about the department feel free to contact us for discussions around education and research areas. You can find more information about the department here: https://www.ntnu.edu/iel.

Enjoy the reading!

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Head of Department

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PI Passivity-based Droop Control of Modular Multilevel Converter (MMC)

Students: **Ahmed Abbas, Muhammad Mazhar Saeed Butt**
Supervisor: **Gilbert Bergna-Diaz**

Problem description

PI-Passivity-based control implemented on many applications, including the MMC, its performance, robustness and stability are not yet thoroughly investigated in detail theoretically. The operation of PI-PBC requires knowledge of the equilibrium point. If the equilibrium point of the system is not known, which is the case in practical applications, then this controller stabilizes the MMC at a new equilibrium which risks being far from the desired one.

The task

In this thesis, we have used an appropriately modified version of the PI-PBC where leakage in the integral channel of the PI-PBC guarantees good dynamic performance, a tuneable steady-state, robustness in case of perturbations, and large-signal stability of the system even equilibrium point of the system is disturbed.

We further show the droop characteristics of passive outputs and control variables of MMC, which are liable for enhanced system performance and robustness. Furthermore, global exponential stability (GES) is proved for the proposed closed-loop PLI-PBC with MMC-HVDC system. MMC has seven control variables, each with its own leakage gain. Therefore, lastly, the simplified analysis of the MMC is presented, which deduces interesting facts.

Model

PLI-PBC is mathematically represented by the following equations. Here, subscript c represents the controller.

$$\dot{x_c} = -g^\top(x^*)Qx - K_L K_I(x_c - x_c^*) \tag{1}$$

$$m = -K_P g^\top(x^*)Qx + K_I x_c \tag{2}$$

where, $\lim_{t\to\infty} x(t) = x^*$, $x^* \in \hat{\mathcal{E}}$ is the reference state vector at equilibrium, $x_c^* \coloneqq K_I^{-1} m(x^*) \in \mathbb{R}^7$ is the state, $m^* = m(x^*) \in \mathbb{R}^7$ are seven control variables and $y = g^\top(x^*)Qx \in \mathbb{R}^7$ are the passive outputs. Moreover, gains matrices are the diagonal matrices as follows $K_P \in \mathbb{R}^{7\times7}$, $K_I \in \mathbb{R}^{7\times7}$and $K_L \in \mathbb{R}^{7\times7}$. The term $K_L K_I(x_c - x_c^*)$ defines the leakage in the controller. It depends on the leakage gain (K_L). It provides the compensation between desired and actual equilibrium. Moreover, the system will be more damped by increasing the leakage gain. Figure 1 shows the block diagram of system.

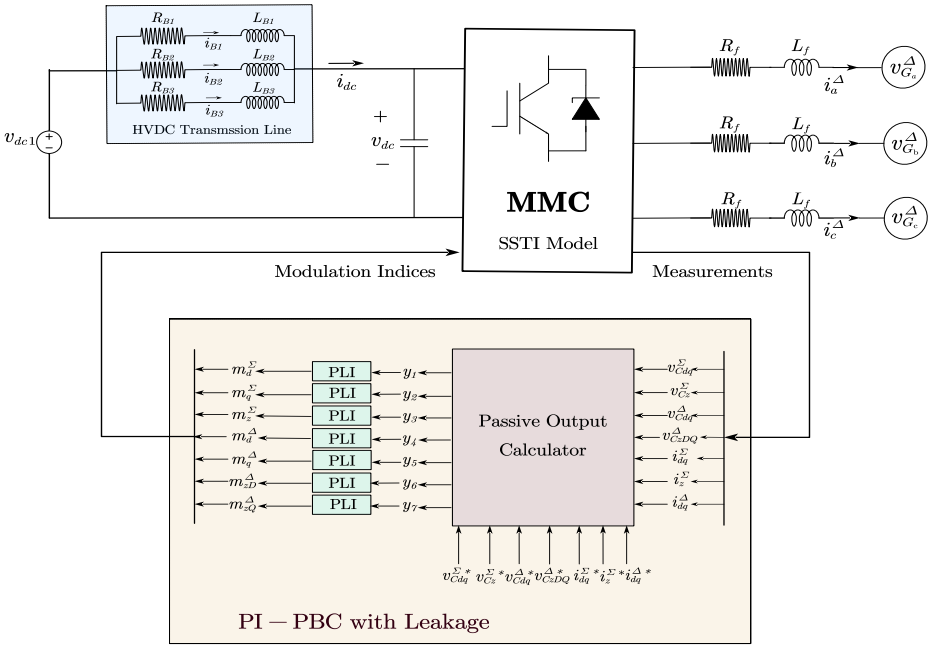


Figure 1. Schematic diagram of MMC-HVDC system under study.

Results

Overall, the results validate the performance of PLI-PBC under the imperfect knowledge of equilibrium. Not only the controller keeps the system stable, but it also compensates the steady-state error caused by inaccurate equilibrium. Practically, the leakage ensures the system stability and provide performance guarantees by regulating the voltage and currents to the valid operational range of desired references. The controller effectively tracks the references by exhibiting a droop characteristic by adjusting the modulation indices dynamically to change in passive outputs. The simplified analysis identifies m'^{Σ}_{z} and m^{Δ}_{d} as two most significant modulating indices in the system and provides the opportunity to tune only leakage gains corresponds to these control variables to get the desired response.

Conclusion

The simulation results demonstrate that the PLI-PBC controller on the MMC-HVDC system improves the dynamic and steady-state performance over PI-PBC control and open-loop control. With appropriate tuning of leakage, the controller regulates the voltage and currents to the desired level even with high uncertainty in equilibrium which is explained by the droop characteristics of the PLI-PBC controller, where leakage acts as a droop coefficient between modulation indices and passive outputs. Additionally, to reduce the complexity of tuning all the leakages, a simplified model of MMC is developed by neglecting the terms of small or no contribution in dynamic equations.

All in all, the PLI-PBC controller offers a viable substitute for the conventional controller in power converters. The controller guarantees system stability and safe operation even in the event of large-signal disturbances.

Energy storage solutions integrated into HVDC-connected offshore wind power plants for providing grid services

Student: **Andrew Smith, Chiagoro Ahaotu**
Supervisor: **Elisabetta Tedeschi**
Contact: **Salvatore D'Arco**
Collaboration with: **SINTEF Energy**

Problem description

Increasing participation of renewable energy resources, in particular offshore wind energy, leads to technical challenges in the existing power grid systems. The majority of renewable energy sources use power electronic converters to connect to the grid, the properties and control of which are inherently different to classical synchronous generators. In conjunction with the increase of offshore wind generation, there is also an increase in High Voltage Direct Current (HVDC) transmission due to the higher efficiency of transmission over long distances. To improve reliability and energy security, offshore point-to-point HVDCs are expected to be interlinked, leading to the creation of a 'supergrid', based on the topology of a Multi-terminal HVDC (MTDC) network. It is expected that MTDC grids will in the future require the provision of certain ancillary services to keep the DC network operating in a reliable, stable manner.

MTDC grids require reserve power control on time-scales much faster than normal grids as there is very little restricting voltage changes other than capacitances in the transmission cables and converter stations. This fast action can be provided by control mechanisms such as droop control, although they necessitate a certain reserve power from the onshore AC grids.

The task

Energy Storage Systems (ESS) are a good source for balancing out power requirements and stabilizing the grid. In this thesis, the suitability of offshore-located energy storage technologies are considered for providing these services, given that these MTDC networks are expected to be built offshore (the North Sea). An analysis of storage technologies is carried out based on their possible specific offshore locations, and likely AC and DC ancillary services that they can provide. These are quantified in several tables based on a literature review.

Battery Energy Storage Systems (BESS) situated offshore are identified as the most suitable technology for supporting the DC network for the specified duration based on factors such as feasibility for offshore location, possible ancillary services to be provided (such as DC voltage regulation for less than 15 minutes), response time, and E/P (Energy-to-Power) ratio. This work examines provision of DC voltage regulation from a BESS co-located with an offshore wind farm. Three case studies are examined to compare providing DC voltage regulation and power control from a BESS offshore to an onshore BESS or AC grids.

Model/ measurements

The system model for one of the three case studies examined is provided below.

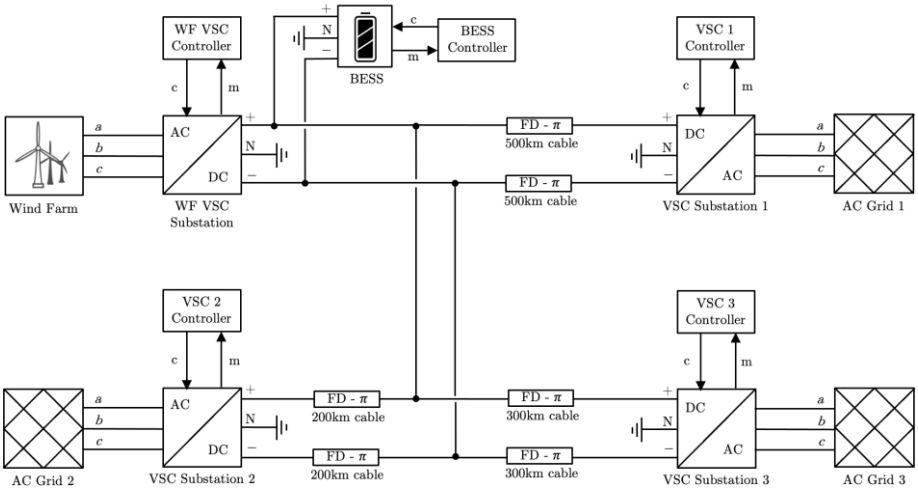


Figure 1: Case Study 1 model

Calculation

Each case study examines the power losses, DC voltage levels, and power losses.

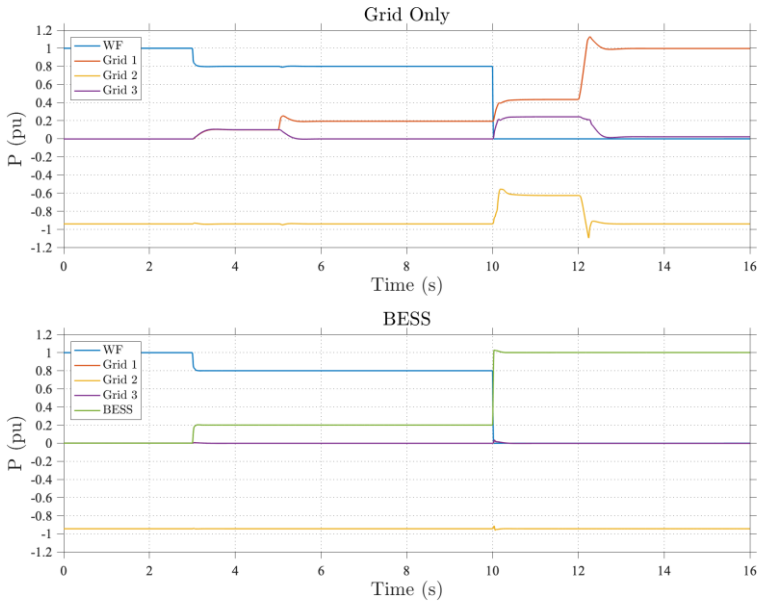


Figure 2: Case Study 1 power injections, using only an onshore grid vs. using an offshore BESS

Conclusion

By examining the power injections, DC voltage levels, and power losses in each case, the results show that BESS in coordination with a wind farm is best able to provide voltage regulation and mitigate power fluctuations, but in many circumstances will be accompanied by an increase in power losses due to the inefficiency of energy storage. This power loss may become a necessary sacrifice with increasingly complex MTDC grids, which require accurate DC voltage control.

Powertrain Sizing of an All-Electric Commuter Aircraft for the Norwegian Short-Haul Network

Student: **Markus Anker**
Supervisor: **Jonas Nøland, Kieran Duncan**

Problem description

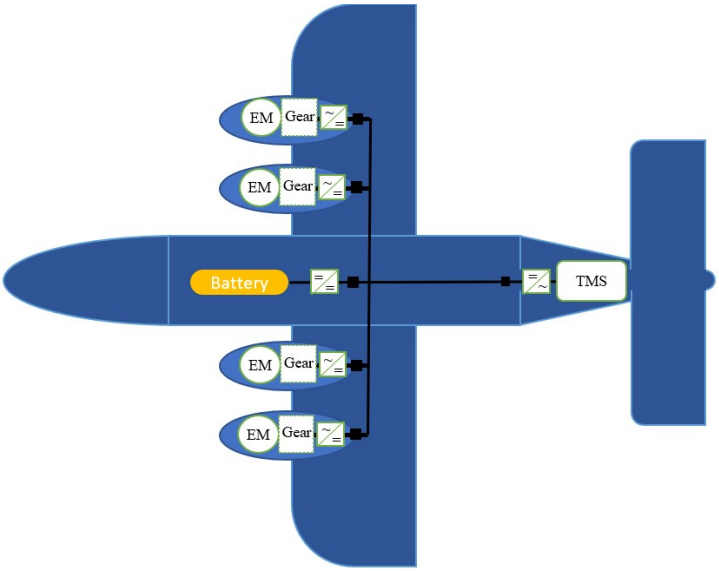
The emissions caused by the aviation sector are growing and the need to transition from fossil fuels to more sustainable energy sources is vital. This transition includes the implementation of electric drivetrains. However, the specific energy in batteries is low, while the weight attributed to the electric propulsors are high. These weight issues will initially enable short-haul travel, with the Norwegian short-haul network being one of the most promising markets. This thesis will perform a sizing of the electrical drivetrain of a 9- and 19-passenger all-electric aircraft based on real-world data.

The task

This thesis consists of three main parts. The first contains a thorough analysis of the Norwegian short-haul network. The routes and flight patterns are examined by using real-world data from Flightradar. In total, data on 1500 flights were collected and analysed to generate a standard power profile based on flight distance. Secondly, a thorough literature study was conducted to find state-of-the-art components for the electric drivetrain. This study included battery, electric motors, gear, circuit breakers, power electronic converters, thermal management circuit and the distribution grid. It resulted in a potential electric architecture for the aircraft. Finally, an iterative sizing procedure was programmed in Matlab, outputting the aircraft weight and power consumption. Through various scenarios, the effect of different technological and regulatory aspects on the aircraft weight was tested.

Model

The figure shows a model for the electric powertrain onboard the aircraft. The black boxes are DC circuit breakers. The rest of the components are also present. This model was used as a basis for the sizing procedure by using the downstream losses in each component. It led to an iterative process where the power and weight were recalculated until convergence was established. The TMS circuit was sized in an iterative process within the main sizing algorithm. Power and time estimations based on the data from the short-haul network were used as input data, and four reference cases were chosen. These consisted of Norwegian routes were the longest between Tromsø and Hammerfest was 211 km long.



Calculation
The results of the short-haul analysis were a normalized power curve that showed that the relation between peak and cruise power was 0.43. It also showed that shorter trips consist of more time spent in climb and descent, and less in cruise.
The calculations in the sizing procedure are mainly based on the efficiency and the specific power of the components. Additionally, during five scenarios made small alterations on the sizing algorithm. It included the addition of gears, a voltage level sensitivity analysis and adding battery losses. Additionally, it tested regulations as redundancy issues and the need for energy reserves.

Conclusion
The conclusion gives a bleak outlook on the prospects of electrifying the Norwegian short-haul network. Even the shortest routes ended in overdimensioned electric aircraft. Both references exceeded their maximum takeoff weight and additional requirements further increased the discrepancy. However, as the sizing procedure is very interconnected, small component improvements would yield significant weight improvement which could result in electric aircraft operating on certain routes by 2026.

DEVELOPMENT AND PROTOTYPING OF TWO-AXIS SOLAR TRACKER ARRAYS WITH A DECENTRALIZED DRIVE SYSTEM

Student: **Bañuls Ramírez, Víctor Andreu**
Supervisor: **Völler, Steve**

Summary

Solar trackers are a technology that improves the efficiency of solar farms. This is due to the fact that they allow for an increase in the peak power and the temporary spacing of the production. The main drawback of these types of trackers is their high manufacturing cost compared to fixed solar trackers. The disadvantages of these devices and their high cost make it pertinent to design an improvement proposal.

Existing two-axis solar trackers behave as mobile supports incorporating all the necessary components to work as complete units in themselves. Its components can be divided into three categories, control system, drive system and structure. If you have all the trackers in the same location they should move synchronously. This allows you to centralize the control and drive systems. It is by centralizing these systems that the manufacturing costs of the trackers are intended to be reduced.

A small-scale prototype was fabricated to prove that such a concept of centralizing systems is possible. For this purpose, a CAD software and a 3d printer were used to manufacture the structural parts. For the movement system it was used a system based on 4 stepper motors that transmit their motion to the structure through the use of cables and pulleys. An Arduino Mega was used for receiving and sending commands or data to sensors, web servers and motors. For the control and monitoring of the prototype a web platform was established. In the design process different tools and methods were used, among which are: sensor characterizations, vector simulations in Matlab, and programming of motion algorithms.

Performance tests were carried out on the prototype and on the web platforms. From these it was possible to demonstrate the functionality of the design as well as to obtain the maximum rotation angles. These turn angles were of has 360º of azimuth turn and 80º of elevation turn. The functionality of the web platforms was also successfully tested.

Once the design concept was demonstrated, it was necessary to prove that centralizing systems resulted in a cost reduction. To this end, a full-scale manufacturing cost model was created. For this purpose it was used a CFD and structural software. This allowed him to obtain the load and stress data needed for sizing. With this study it was possible to determine the relationships of the variables on which the cost estimation depended. Among the relationships it was able to determinate the impact of selecting an operating wind speed limit, or the relationship of the number of trackers in series with the relative improvement in manufacturing costs. Finally, in order to verify that these costs were reduced, the model created was compared with the manufacturing costs of the ST2408PH tracker model. Financially, this comparison yielded a 23.5% actual cost reduction.

Accessing Flexibility in Batteries Through a Local Flexibility Market

Student: **Berge, Renate Høvik**
Supervisor: **Rajasekharan, Jayaprakash**

Summary

The power quality regulation states that the distribution system operator is responsible for maintaining the power quality in the grid and ensuring that the voltage quality is within statutory limits. Due to environmental issues and a demand for more efficient energy generation the power system is transforming into a more decentralized system resulting in more intermittent power generation and distributed generation. This results in challenges in the distribution grid, such as under-voltage issues. The use of battery energy storage in the distribution grid provides a reliable energy source to be used for e.g. voltage control. The flexibility in battery energy storage systems can be made accessible for the distribution system operator through local flexibility markets.

This master thesis therefore presents the network model of a case study network with under-voltage issues. The under-voltage issues are evaluated for three load profile scenarios and the results are used to procure the flexibility demand for the load profile scenarios, consider two set voltage limits at 0.95 pu and 0.9 pu. These voltage limits reflect the DSO responsibility for ensuring the power quality in the distribution grid and the responsibility for ensuring that the voltage quality is within statutory limits. A two-stage stochastic optimization model was created with goal of obtaining enough flexibility, through a battery, to cover the flexibility demands procured, and thereby avoid violating the set voltage limits. The objective of the model is to minimize the total cost for the distribution system operator considering the cost of booking and activating flexibility through two flexibility options, LongFlex and ShortFlex, and also considering the cost of battery degradation.

The use of various load profile scenarios in the network model resulted in varying degree of under-voltage issues, considering voltage magnitude and the duration of the issues. The use of the flexibility demands procured, by the use of the under-voltage limit, in the optimization model verified that the model booked and activated enough flexibility to cover the demands. The use of ShortFlex and LongFlex varied with the cost of booking and activation, for both of the cost profiles. The battery discharged enough power to cover the demand and various segments in battery are activated. However, the model resulted in low cost for the distribution system operator as a result of operating with small amount of power and a overdimensioned battery. The use of the power quality limit resulted in a very high flexibility demand for each scenario, and the use of these demands in the optimization model resulted in an infeasible model. This was a result of the constant flexibility demands, which did not allow for any battery charging. In situations with a great demand more batteries must be considered or other options for reinforcing the grid.

Design and Manufacturing of a Twin Harmonic Machine with Counter-rotating Rotors

Student: **Samson Bergesen**
Supervisor: **Robert Nilssen**
Contact: **Arne Nysveen**
Collaboration with: **HydroCen**

Problem description

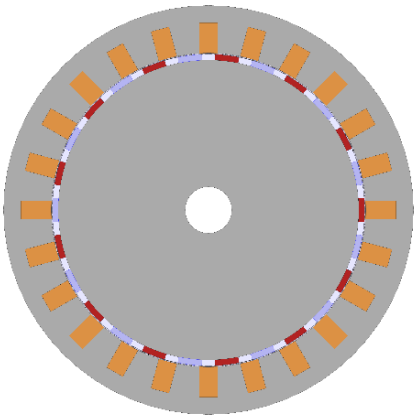
The capacity of installed renewable energy sources such as wind- and solar power is increasing globally, and these sources are highly uncontrollable with fluctuation in available energy. Norway relies heavily on hydropower to power its electrical demand, and the total installed capacity in Norway is 33 GW per 2021. It accounts for 50% of the capacity for hydropower in Europe. The installed PSH is per 2019 at a capacity of 1.4 GW which is around 5% of the total installed capacity in Norway. However, it is estimated that there are 86 hydropower plants with a combined capacity of 10.8 GW that are well suited to be built into PSH Converting these hydropower plants into a PSH will lead to high cavitation on the turbines as the pressure in the tailrace will be too low in pump mode. HydroCen is currently looking at booster pump solutions to overcome the cavitation problem during pump mode of the hydropower plants. The booster pump solution involves having a booster pump in the tailrace tube to increase the pressure on the suction side of the main turbine, therefore negating the cavitation and waterway losses. Counter-rotating turbines and propellers are considered as they have a hydrodynamic advantage of being able to recover some of the rotational slipstream energy. The background for this project is based on a phenomenon that Prof. Robert Nilssen has observed in his many years of working with fractional slot concentrated wound motors which will be described as twin harmonics in this project. The twin harmonics are two harmonics in the magnetic field with different pole numbers and opposite rotations. The twin harmonics often have a much larger magnitude than the other harmonics, sometimes almost as large as the fundamental. Using two rotors with the same number of poles as the two twin harmonics will lead to the rotors having the rotational direction as their respective harmonic. This project aims to build and investigate such a counter-rotating machine.

The task

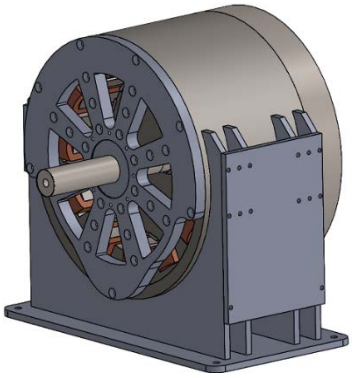
This thesis aims to simulate, design, build and test a prototype motor with two counter-rotating rotors, where the counter-rotation will be achieved by using the twin harmonics in the stator. The design for the prototype made in the specialization project “Design of a counter-rotating twin-rotor machine prototype” will be used as the basis for the finished design. Drawings for further improvements and additions to the motor setup will be made using SOLIDWORKS. COMSOL models previously made during the project will also be improved and used to give motor characteristics that will be used during lab testing of the finished prototype. The report will neither include different types of losses nor discuss the general efficiency of the designed prototype as the main goal is to end up with a finished prototype that proves the concept of counter-rotation using magnetic field harmonics. The motor design will not be optimized. Programs such as COMSOL, SOLIDWORKS and MATLAB will be used to simplify the design and simulation process.

Model/ measurements

To verify the design of the prototype, two cross-sections models were built in COMSOL, one for each rotor. The models were made to analyze and verify the counter-rotation of the motor. Each model includes one of the rotors, where the interaction between the rotor and stator can be investigated. As the rotors only can be analyzed separately, the interaction between the rotors, such as cogging between the rotors, cannot be investigated.

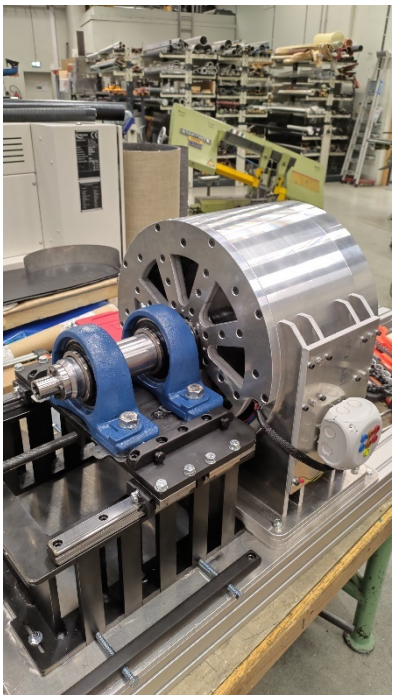


The designed motor was drawn and modeled using SOLIDWORKS.
One rotor shaft will be mounted with ball bearings in the cover of the stator housing, while the other rotor shaft will be mounted on an adjustable table with pillow block bearings. The rotor shaft mounted with pillow block bearings will be movable, allowing the distance between the rotors to be adjusted. Therefore, it is possible to investigate the rotors' influence on each other.



Results

The main results from the project were a functioning prototype, that can be seen below.



Conclusion

The main conclusion from the project is that the twin harmonic counter-rotation drive works as theorized. The concept of driving two counter-rotating rotors in one stator using magnetic field harmonics was proven during this project by designing, manufacturing, and testing a prototype motor, where basic testing proved the concept.
The COMSOL simulations that were done to confirm the counter-rotation were to some degree verified through no-load tests; however, further verification is needed. Back emf measured in the no-load test on the prototype deviated about 10\% from the simulated values from COMSOL. The design topology of the prototype setup with two counter-rotating rotors made the manufacturing process especially difficult, as each shaft can only be supported on one side.

New Environmentally-friendly Insulation Gases - Pre-breakdown Mechanisms under Impulse Voltage in Synthetic Air and AirPlus

Student: **Fredrik Leonardie Bratland**
Supervisor: **Frank Mauseth**
Contact: **Frank Mauseth**
Collaboration with: **SINTEF Energy**

Problem description

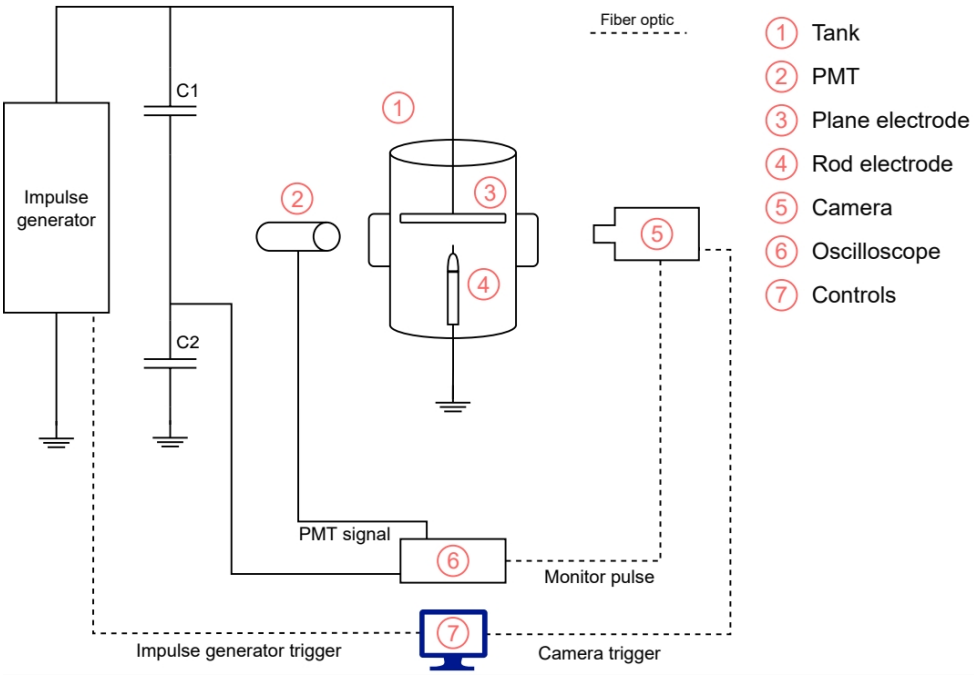
SF_6 is a widely used gas in MV and HV systems today. This gas is a very potent greenhouse gas, with a global warming potential of approximately 23.000 times that of CO_2. New gases are being developed, but before these gases can fully replace SF_6, more research is required to understand more about how the gases behave in different conditions.

The task

The main task of the project is to create a visual understanding of how streamers and other pre-breakdown mechanisms act in AirPlus in different pressures and polarities, compared to synthetic air.

Model/ measurements

A lab-setup with a marx impulse generator A lab-setup with a marx impulse generator was used to apply fast impulse voltage to a rod-plane gap inside a tank. A PMT was used to measure light emitted during the impulse, and a high speed camera was used to capture images of the pre-breakdown mechanisms inside the tank.



Conclusion

•The goal of this project was to better understand how pre-breakdown mechanisms, specifically streamers, act in different pressures and polarities in AirPlus compared to

synthetic air. This was done by applying a lightning impulse to a very inhomogeneous plane-rod gap and capturing images of it using high-speed cameras. The motivation for the project was to get a broader understanding of how AirPlus acts as an insulation gas and if it is suited for replacing SF6 in MV and HV applications in the near future.

• The results from the up-and-down tests are not to be trusted, as most likely 180 seconds is not enough waiting time between shots to be completely independent of each other. From the images captured, it can be seen that in all cases, the streamers are shorter in AirPlus than in synthetic air, even though the images from AirPlus are captured at higher voltages. None of the streamers or leaders in this setup reached the plane without a following breakdown, contrary to the tests in synthetic air, where almost all configurations propagated streamers over the whole gap. Negative streamers in 1.5 bar were the only exception to this. The images also show that increasing the pressure of synthetic air doesn't significantly change the visual appearance of the positive streamers, except for an increase in the number of smaller branches, and discharges from the rod and the needle. For negative streamers in synthetic air, the increased pressure to 1.5 bar resulted in shorter branches, where none of the streamers reached the plane.

• Increasing the pressure of AirPlus resulted in discharges more similar to leaders than streamers, for both polarities on 1.5 bar and the negative discharges in 1.3 bar. Visually, it's hard to differentiate between the positive and negative streamers/leaders in 1.5 bar, and the negative discharges were captured at a higher voltage than the positive. For 1.0 and 1.3 bar AirPlus, the positive streamer branches are short and straight. The negative streamers in 1.0 bar are cloudy and diffuse, but these images were also shot at a lower voltage than the positive streamers. When comparing synthetic air and AirPlus, all images show that AirPlus performs better when it comes to restraining streamer discharges.

PSCAD Simulations of Distance Protection Performance in a Grid with high Wind Power Penetration

Student: **Lars Thaulow Bremnes**
Supervisor: **Hans Kristian Høidalen**
Collaboration with: **Statnett and SINTEF**

Problem description

Distance relays are considered to be the most reliable protection for transmission lines. This may not be the case anymore, as the share of renewable energy sources (RES) becomes a more substantial part of the power system. By introducing a large amount of RES there are expected problems to arise for distance relays ability to measure the correct fault impedance, which will lead to faulty operations.

The task

This master thesis uses PSCAD to simulate the performance of the distance protection function in distance relays, for high penetration of wind power. It is developed a system model in cooperation with Statnett and SINTEF, to make a representable model of a system at Fosen, where there are wind farms connected to the 420kV grid. Statnett has raised concerns that their distance relays in Fosen may experience faulty operations, where multiple wind farms were finalized in 2020. The main objective is to answer these questions:

1. How does fault resistance impact distance relays fault detection capability?

2. How does the increased penetration level of wind power influence protection performance?

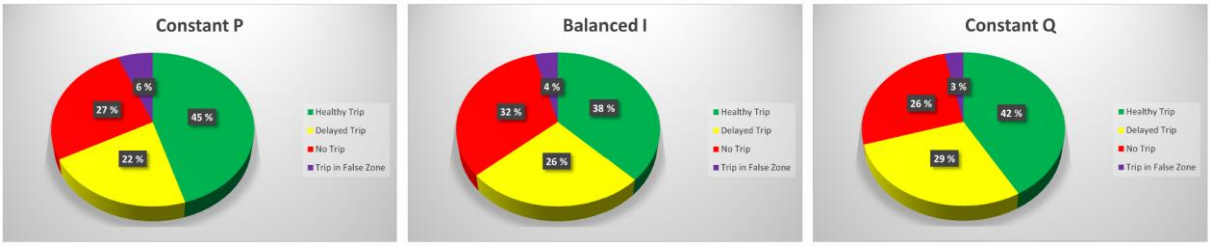
3. What wind farm control strategies are the most reliable, and which has the most negative impact on protection performance?

Model/ measurements

To investigate this, there are performed multiple simulations where different parameters are used to observe their impact on distance protection performance. There are used five changeable parameters, fault type, fault resistance, fault distance, wind farm control strategy, and wind power penetration level, bringing out a total of 1080 simulations.

Calculation

The concluding results from the simulations are presented below.



(a) (b) (c)

Figure 1: Concluded results of the three different control strategies, a) Constant P, b) Balanced I, and c) Constant Q.

Figure 2: Impact of fault resistance on DR32, including simulations for unsymmetrical faults only, all control strategies, and divided between all penetration levels. a) $Rf = 0.1\Omega$, b) $Rf = 1\Omega$, c) $Rf = 5\Omega$ and d) $Rf = 10\Omega$.

Conclusion

Question 1: The increase in fault resistance has a great impact on distance relays fault detection capability. This is due to the unpredictable current from wind farms compared to the main grid which is dominated by synchronous generators. This will lead to an under-or overreach situation for the relay. It is especially the relay closest to the wind farm that suffers the most, the other relays have either none or very few misoperations.

Question 2: With increasing wind power penetration levels, distance relay performance is greatly impacted. There have been performed simulations for extreme future scenarios, with penetration levels of 50\% - 100\%, where it is a clear indication, that the higher the penetration level, the more misoperations the relays encounter.

Question 3: The three wind farm control strategies tested in the thesis are; Constant active power, Constant reactive power, and Balanced currents. It is concluded that the Constant reactive power strategy is the most reliable for distance performance, and the Balanced currents strategy has the most negative impact.

Direct Drive PMSM Characteristics for Retrofit in Regional Turboprops Using a Design Space Approach

Student: **Håkon Broch**
Supervisor: **Jonas Kristiansen Nøland**
Contact: **Andrea Bocchese**
Collaboration with: **Rolls-Royce Electrical Norway**

Problem description

This thesis aims to map the design characteristics of direct drive motors with high power ratings and densities based on current aircraft power requirements. This mapping includes identifying the motor performance requirements of modern turboprop aircraft and using these as the basis for motor design. A general impression of motor performance compared to existing aircraft can indicate which types of aircraft are more relevant for electric motor retrofit. It is also possible to gain knowledge of the performance of the electric motors, as direct drive propulsion in aircraft requires relatively high power and low rpm compared to automotive motors. Lastly, it may be possible to draw conclusions regarding how future electrical aircraft can be designed based on which motor designs are more viable. This is especially relevant regarding the viability of distributed propulsion.

The task

This thesis will use turboprop aircraft data as a basis for a design space of different performance parameters. Using an analytical dimensioning approach, PMSM designs corresponding to these performance requirements are generated.
These results will then by verified by numerical means and attempted to be further optimized to ensure viable and well-performing electric motors are presented.
The performances of the designed electric motors are then compared to aircraft performance demands, to investigate the possibility for retrofit in the contemporary turboprop regional aircraft.

Model/ measurements

Firstly, a wide selection of turboprop-aircraft data is gathered to act as input performance demands for the electric motors later design in the thesis. An analytical design algorithm (fig. 2) is adapted and used to quickly generate a large amount of motor designs. This algorithm is based on pre-selected parameters selected to ensure designs that maximize efficiency and specific power. A small selection of the finalized motor geometries is then input into FEM-analysis software and simulated in order to verify the analytically calculated expected performance. By using a manual optimization algorithm (fig. 3), certain geometric parameters are further attempted improved to verify the analytical algorithm's ability to create optimal designs.

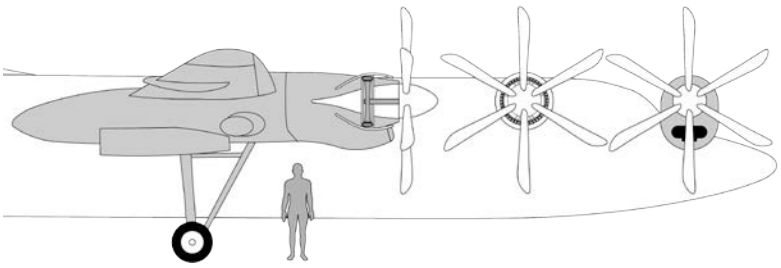


Figure 1—EM design compared to aircraft of similar performance.

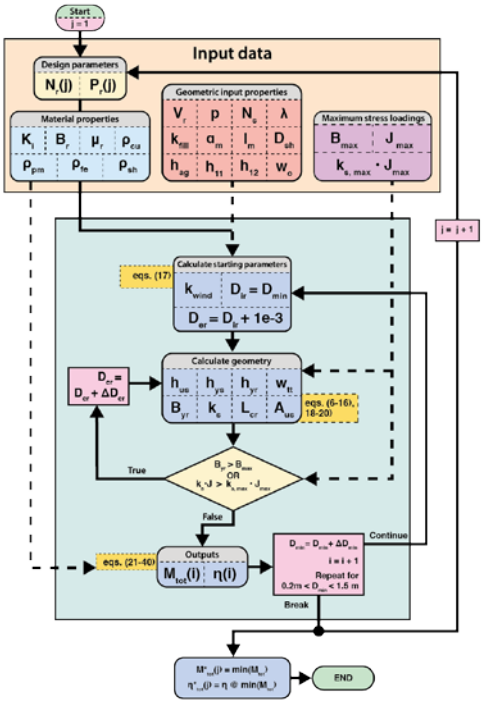


Figure 2 — Analytical design algorithm.

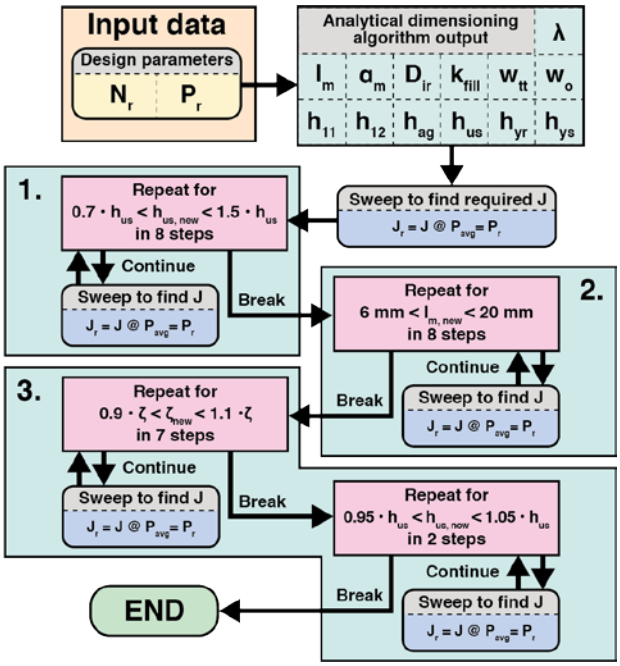


Figure 3—Manual optimization algorithm

Calculation

A selection of outputs from the analytical design algorithm is presented in fig. 4 and 6. An example of a finalized design of 1.8 MW and 1100 rpm is compared to a turboprop aircraft of similar performance in fig. 1.

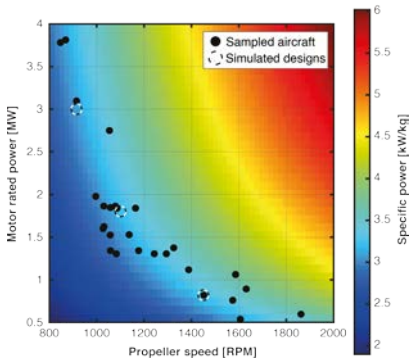


Figure 4—Specific power of designed EMs.

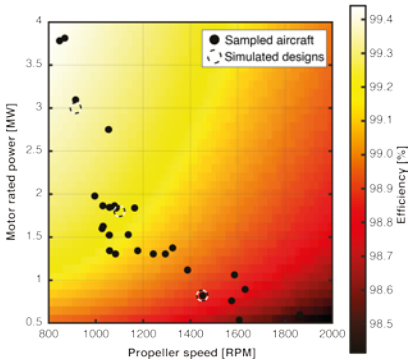


Figure 5—Efficiency of designed EMs.

Conclusion

It is found that specific power remains relatively constant in motor designs for turboprop aircraft across the entire performance range, with results in the range between 2.8–3.7 kW/kg. Specific torque and efficiency increase with motor size ranging between 18–34 Nm/kg and 98–98.7%. This indicates that retrofit designs for larger aircraft are more optimal in terms of efficiency, and similar in terms of specific power.

It is also found that larger electric motors are comparatively 30% heavier than their turbine driven counterparts, unlike smaller electric motors that can be up to 40% lighter.

Tidsdomene dielektrisk respons for tilstandskontroll av statorviklinger fra driftsaldret vannkraftgenerator

Student: **Nikolai Brodin**
Veileder: **Erling Ildstad**

Problemstilling

Flertallet av de norske vannkraftgeneratorene har vært i drift i mer enn 40 år, og flere har allerede passert forventet levetid. I tillegg utfordrer nye og tøffere driftsforhold, deriblant høyere belastning og hyppigere start og stopp. Dette betyr at isolasjonen utfordres utover det den opprinnelig var designet for. Slike faktorer øker usikkerheten rundt aldringshastigheten, samt estimering av gjenværende levetid.

For å avgjøre om generatoren fortsatt er trygg å benytte, selv etter forventet levetid kreves det at man diagnoserer generatoren. Den mest hyppige årsaken til at en generator havarerer er isolasjonssvikt i statorviklingen.

Oppgaven

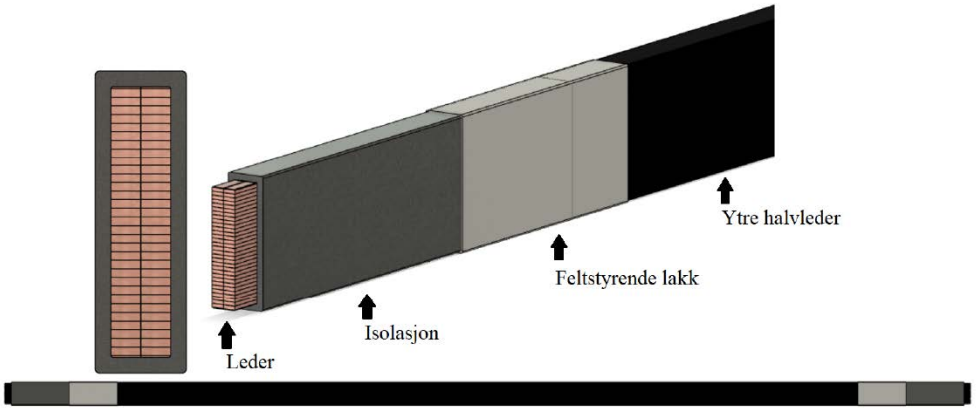
En generatorstav som er driftsaldret i 52 år, hentet fra Suldal I generator G2 blir undersøkt med dielektisk respons målinger i temperaturområdet 20℃ til 130℃, i spenningsområdet 1kV til 15kV. Målingene blir utført med Megger S1-1568: En likestrømsisolasjonstester som er enkel i bruk og portabel.

En påtrykt likespenning vil gi resultat i tidsplanet og for å regne om dette til frekvensplanet blir det benyttet Hamon approksimasjon.

Hovedformålet er å oppdage aldringstegn i isolasjonen, dette blir gjort ved å undersøke spenningsavhengihet, frekvensavhengighet og temperaturavhengigheten til dielektrisk respons.

Studien tar óg for seg om Megger S1-1568 kan benyttes til måling av tapsfaktor tan δ

Modell/målinger

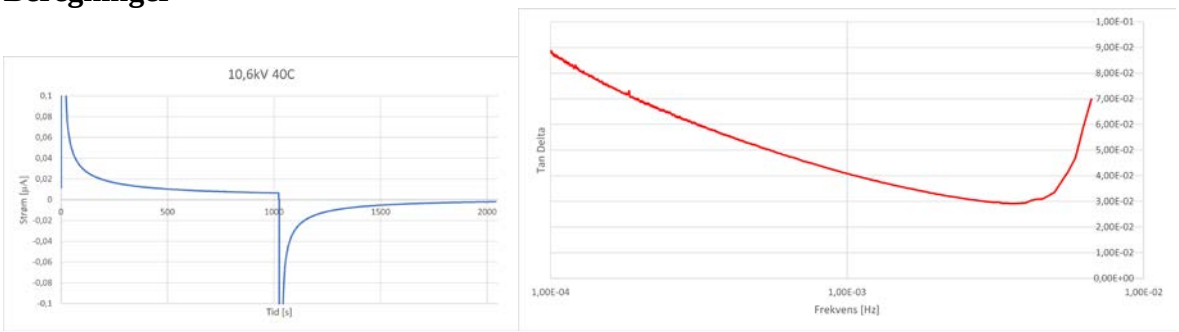


Figur 1: Oppbygning av generatorstaven

Figur 2: Megger S1-1568, som er benyttet til å utføre målinger i denne studien.

Figur 3 Generatorstaven oppkoblet i varmeskapet.

Beregninger



Figur 4: T.V. Polariserings- og depolariseringsstrøm ved 40 grader og 10,6kV påtrykt likespenning. T.H. Tan δ approksimering ift. frekvens beregnet fra samme måling.

Konklusjon

Det er observert en tydelig ikkelineær endring i ledningsevne og dielektrisk tidskonstant ved omtrent 70℃ og 100℃.

Det er en ikkelineær spenningsavhengighet mellom 8kV og 9kV ved 40℃. Basert på de utførte målingene er det rimelig å anta at denne ikkelineariteten gjelder fra 20℃ til 60℃ og avtar et sted mellom 60℃ og 90℃.

Polarisasjonsindeksen tilsier at isolasjonen er i utmerket stand.

Tan δ verdi som diagnostiseringsparameter er ikke spesielt egnet uten å ha et velegnet sammenligningsgrunnlag.

Future Design of Subsea High Voltage Cables for Offshore Renewables - Effect of Static Mechanical Stresses on the Insulation Lifetime

Student: **Magnus Bøe**
Supervisor: **Frank Mauseth**
Contact: **Karl Magnus Bengtsson**
Collaboration with: **Nexans**

Problem description

High voltage subsea cables are essential e.g. to facilitate renewable offshore energy installations such as wind and solar farms. Today, polymeric AC subsea cables rated up to 36 kV are generally of a “wet design” type, while for higher voltages, “dry designs” are applied where the cable is equipped with an enclosing metallic water barrier. Lately, there has been a great interest in increasing the voltage rating of wet designed cables to be used for i.e. inter-array connections in offshore wind farms and floating installations. The main advantage of a “wet design” at higher voltage levels is cost savings as the metallic water barrier is eliminated. Wet designed high voltage cables are also a very attractive solution for dynamic cables, where the metallic water barrier of a dry design cable can be an issue due to mechanical fatigue. In addition to the dynamic mechanical stresses, cables can simultaneously be subjected to static mechanical stresses, e.g. stresses from 3 core lay-up and exit J-tube, where the side facing the center will be compressed while the other side will be stretched. The static mechanical stresses can be significant. Thus, it is important to investigate how the static mechanical stress with the combined effect of the electric field, humidity, and temperature influences the lifetime of XLPE cable insulation. The results will be an important input to the design criteria of the next generation of wet designed power cables for offshore renewables.

The task

The purpose of this project is to study water tree growth in a newly developed wet-design XLPE-insulated cables with static mechanical stresses applied.

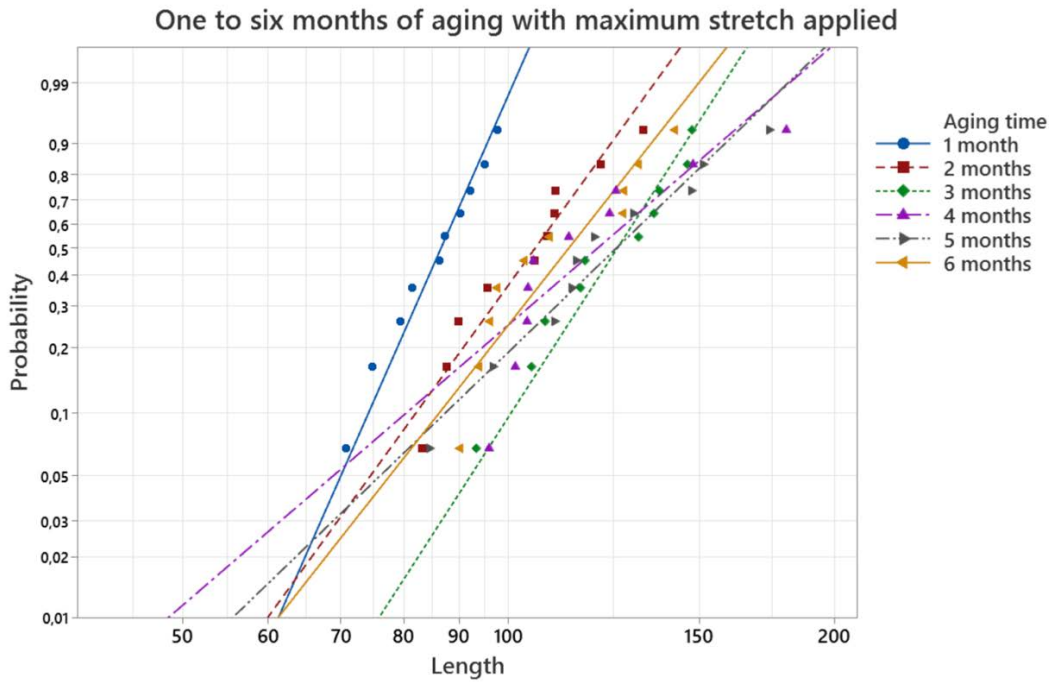
Model/ measurements

An aging rig was set up and confirmed functional in the autumn of 2022. Ten samples of 12 kV wet-design cables were aged with static mechanical stress. The mechanical stress was induced by bending the cables around three different pipes with different diameters, which gives a stretch of 4%, 6% and 12%, simultaneous the same amount in compression force was applied. These cables were then connected to the aging rig. The rig consists of a large waterbed that were heated to 40 °C. All cables were connected in parallel to a bus bar and energized with 30 kV 50 Hz AC. The cables were then aged in a total of six months, where the first cable was disconnected and inspected after one month, with the other cables following the same procedure with one-month intervals. After the aging period the insulation of the cable was cut into helicoids and dyed. During the microscope analysis the longest bow-

tie tree in stretch and compression zone was recorded, as well as length of vented trees if observed in the different zones. In addition, the two longest vented trees were examined in more detail to investigate the cause of initiation. This procedure was used for the three different mechanical stresses.

Conclusion

Static mechanical stresses influence the growth pattern of the bow-ties, where the average maximum length of the bow-ties is longer in the zone with stretch force applied than in the zone with compression force applied. The results also indicate that the most extreme lengths of the bow-ties are influenced by the stretch force applied, where the longest trees was mostly found in the samples with maximum stretch. By comparing the maximum stretch and minimum stretch samples, the results imply that the average maximum length of the bow-ties increase with approximately the same amount, as the increase in stretch, where an 8% increase in stretch yields an average of 7% increased length. By comparing maximum compression with minimum compression, there is also an increase in maximum average length, with an increase of 8% compression force yields an increase of 10% in length. The results show no difference between stretch and compression zone in the amount of vented water tree observed. The longest tree observed was a vented tree of 250 µm, initiated from the inner semi-conductor, which is 7% of the total thickness. The low number of vented trees in addition to the short lengths can indicate a good design that is very resistant to water tree growth.



Evaluating Modeling Approaches for State-Dependent Environmental Constraints in Medium-Term Hydropower Scheduling

Student: **Sofie Aandahl Børresen**
Supervisor: **Gro Klæboe**
Contact: **Linn Emelie Schäffer**
Collaboration with: **TrønderEnergi**

As concerns of climate change and environmental degradation are becoming ever more prevalent in society today, power producers have a great responsibility to operate in an environmentally sustainable way. Many of the large reservoirs in Norway also are used for recreational activities and there are strict regulations on some reservoirs to ensure high enough water levels and avoid drought in popular recreational areas. These regulations are state-dependent, making them challenging to implement in the modeling framework used in medium-term hydropower scheduling today.

This master's thesis addresses the inclusion of state-dependent environmental constraints in medium-term scheduling of hydropower plants with reservoirs. An exact restriction formulation is compared, through a case study, to linear approximations; one complete relaxation and one tighter relaxation with a lower auxiliary reservoir bound. The three approaches are benchmarked against a base case method.

Results from the case study showed similar improvement for the exact formulation and the tighter linear approximation of the state-dependent constraints. The financial results indicate an earning potential, but the overall reservoir level did not increase substantially. Still, the model is very price sensitive, and a different price profile could lead to a more significant impact. There was no significant difference between the complete relaxation and the base case method, indicating poor performance. The tighter linear approximation method can be used in today's industry approaches and is a good alternative for including state-dependent environmental constraints in medium-term hydropower scheduling.

Application of Stochastic Dual Dynamic Programming to evaluate long-term price signals in short-term optimisation of energy use in buildings

Student: **Christensen, Anne Marthe ter Woerds**
Supervisor: **Klæboe, Gro**

Summary

With a large potential to reduce energy consumption from the building sector as well as possibilities for cost reduction for consumers there is a demand for solutions promoting building energy efficiency. One such solution is an energy management system that can optimise how and when energy should be used and imported into the building while still covering the demands of the building residents. To perform a building energy use optimisation an accurate modelling of the energy costs is needed, and stochastic dual dynamic programming (SDDP) is a methodology that has potential to consider both short-term costs and the price signals of long-term costs.

This thesis therefore investigates the application of SDDP to optimise the building energy use in a system with an available battery energy storage system to provide flexibility. This is done to study the suitability of SDDP in scheduling the battery state of charge and the peak demand in relation to the long-term price signals. The thesis presents the SDDP model developed for application on the mentioned system, along with results from two types of simulations that have been performed. This is a set of in-sample scenario simulations and an out-of-sample scenario simulation performed based on data for the farm of Rye in the municipality of Trondheim from November 2020.

Results show that the SDDP-model does consider the long-term price signals in the scheduling of battery state of charge and peak demand. However, there is some inaccuracy in the estimation of future costs, shown in a dispersion of ± 6 % for the total costs of the in-sample scenario simulations, and a potential of 5 % reduction of the total costs in the out-of-sample scenario simulation. A main reason for the inaccuracy is the scenario generation and sampling that has been applied. A scenario generation method that is more advanced and can capture a more reasonable stochastic representation of the future should be investigated further to determine the potential for model improvement of the accuracy. Furthermore, a scenario sampling in the forward iteration of the SPPD algorithm that considers a larger number of scenarios may also improve the reliability of the convergence criterion, and the following accuracy of the SDDP model.

Discrete modelling of the dual active bridge converter

Student: **Csongovai, Norbert**
Supervisor: **Dimosthenis Peftitsis**

Summary

The importance of the bidirectional DC-to-DC power converters cannot be exaggerated in the context of today's power grids. As distributed energy resources become an integral part of electrical energy infrastructure, the ability to send power bidirectionally between source and load provides increased quality and flexibility to the power infrastructure as a whole, and the concept of smart grids in particular. The dual active bridge (DAB) DCto-DC converter has therefore been in the centre of attention due to its advantages over other devices of similar abilities, but it does not come without flaws and challenges. The purpose of this paper is to focus on one of these challenges, namely finding an optimal modelling technique for the converter.

This thesis recounts the main characteristics of the DAB converters, listing both its positive and negative attributes. By the means of literature review, state space modelling, and simulation, the nonlinear nature of the converter is explored, and a suitable modelling technique is presented. The main goal of the present work is to serve as extensive and sufficient support for future work, aimed at developing and implementing a modern, optimal control technique for the DAB converter.

The main contribution of this thesis is the detailed derivation of a discrete time model for the DAB converter, considering its operation both under single phase shift (SPS) and extended phase shift (EPS) modulation. With the purpose of developing the intuition of the reader, the relatively simple example of a Buck converter is covered as well. The nonlinear traits of the DAB converter are demonstrated by performing elementary stability analysis. The model is then tested and the relevant results are presented.

Magnetic Measurements of the Higher-Order Corrector Magnets for the High-Luminosity Upgrade of the Large Hadron Collider at CERN

Student:	**Eivind Dalane**
Supervisor:	**Prof. Arne Nysveen**
Co-supervisor:	**Dr. Ing. Carlo Petrone, CERN.**
Contact:	**eivind.dalane@gmail.com**
Collaboration with:	**European Laboratory for Particle Physics, CERN**

Problem description and task

The higher-order corrector package comprises a set of nine superferric correction magnets with the purpose of correcting for field imperfections and misalignments of new magnets for the High-Luminosity upgrade of the Large Hadron Collider.
The knowledge of the magnetic axis, roll angle, magnetic length and longitudinal center of the individual corrector magnet is of key importance to the assembly, installation, and operation of the accelerator complex. These qualities of the magnetic fields are to be determined through room temperature measurements. With the added complexity of low field values and gradients due to the low excitation currents in this state, already available measurement methods are ruled out. This calls for the development of measurement systems able to acquire these qualities within predefined limitations of the measurement uncertainty.
The development is concluded with the measurement of the first corrector package assembly.

The main objective of this thesis is therefore to develop measurement systems able to measure the required qualities of the magnetic flux density of the corrector magnets, while installed in the corrector package.
The work involved with the development can be divided into the following tasks:

- To design and develop one or more measurement systems for the measurements of the magnetic axis, roll angle, magnetic length, and longitudinal center. This can be achieved using already existing measurement techniques, or through the development of new systems.
- To establish measurement approaches, and through testing determine a set of optimal parameters for the measurement system. This includes the development of post-processing algorithms for the treatment of measurement data to acquire the required magnetic properties.
- Through a set of magnetic measurements validate and determine the precision, accuracy, and uncertainty of the measurement system. The outcome of this metrological characterization will be compared to the measurement requirements, to determine the systems' suitability to measure the required magnetic qualities.
- To measure the first corrector package assembly with the goal of providing initial results and feedback to the fabrication and assembly process of the corrector package.
- Present suggestions for the future steps of the measurement methods for further development and measurements at CERN.

Model/ measurements

Two measurement methods were developed in the work with this thesis.
The first system, the rotating single-stretched wire system, comprises a conductive wire, stretched through the aperture of the magnet, and moved by precision stages on a circular trajectory. It measures the magnetic flux density of the magnets and determines the magnetic axis and orientation through a study of the harmonic content of the B-field.

The second measurement system, the translating coil fluxmeter, consists of a set of twelve induction coils, mounted tangentially to a cylindrical measurement head. The head is moved manually along the axis of the magnets, measuring the field profile as a function of longitudinal position. From this, the magnetic length and longitudinal center is found.

The two systems were tested in several stages. First, a metrological characterization was conducted for each system, determining the uncertainty of the measurement methods. This was conducted on a decapole corrector magnet. Then, the present assembly of the corrector magnets within the corrector package was measured.

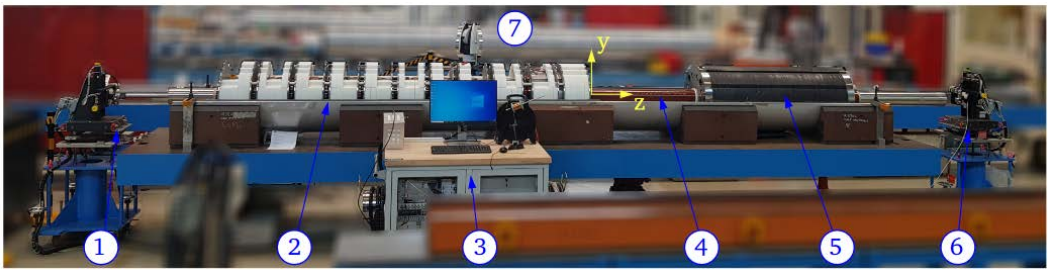


Figure 1: The setup for the rotating single-stretched wire measurements of the assembled corrector package. The picture shows wire stage A and B, (6) and (1), the set of higher-order corrector magnets, (2), the measurement bench with the electronics, (3), the cold bore, (4), the MCBXFB-magnet, (5) and LEICA absolute tracker AT930, (7). The reference system used for the measurements is shown in yellow, with the positive x-axis pointing into the paper.

Measurement results

The metrological characterization of the measurement systems showed that the system based on a taut conductive wire was able to measure the magnetic axis with a total uncertainty of less than 170 µm, where the largest portion of this is the laser tracker system, with a total uncertainty of 150 µm. It measured the roll angle with an uncertainty of less than 0.06 mrad.
The translated induction coils were able to measure the magnetic length and center with an uncertainty of approximately 1 mm.
The measured magnetic axis proved to be within the expected values, whilst the roll angles deviated too much. This was probably caused by a misalignment of the magnet assembly. The magnetic centers were measured to be within the deviations. This was also the case for the magnetic length for every magnet except for the skew quadrupole, which was slightly too short, caused by uneven movement of the measurement head.

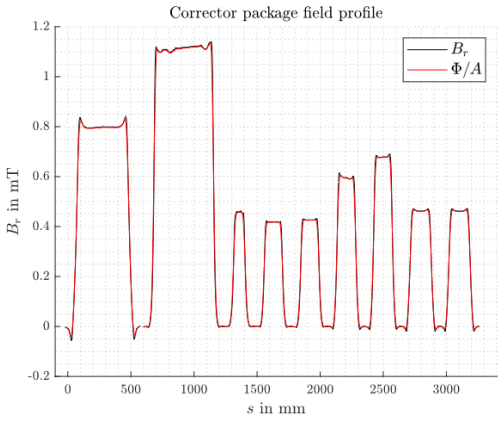


Figure 2: Radial field profiles acquired by the translating coil fluxmeter of the full set of magnets in the corrector package.

Conclusion

The developed measurement systems proved to be well suited for the room temperature magnetic measurements of the corrector magnets. The uncertainties of both systems were found to be well below the requirements to the systems. Therefore, the systems will be used for further measurements of these magnets. The second measurement system should be improved by adding motorized movement, which would reduce the added uncertainty added by mechanical instability of the movement of the measurement head.

Longitudinal Breakdown Strength of polymer Interfaces at VLF and 50 Hz AC voltages

Student: **Roger Dale**
Supervisor: **Erling Ildstad**
Co-supervisor: **Emre Kantar**

Problem description

The 50 Hz AC breakdown strength of dry interfaces is known to strongly depend upon the mechanical properties, contact pressure, roughness of the surfaces and the type of lubricant used at the interface. The purpose of the master thesis has been to experimentally examine how the longitudinal breakdown strength is affected by the frequency of the applied voltage and content of water, so-called wet interfaces. Such data are relevant for the design of subsea power equipment, expected to operate at very low frequency (VLF) or DC voltages.

The task

Conduct breakdown experiments with AC 50 Hz and DC (VLF) applied to solid|solid interfaces. The purpose of this is to determine the breakdown strength of the insulation materials when using different mechanical pressure, materials with different flexibility and varying the surface roughness with and without water applied to the interfaces during the breakdown tests.

Model/ measurements

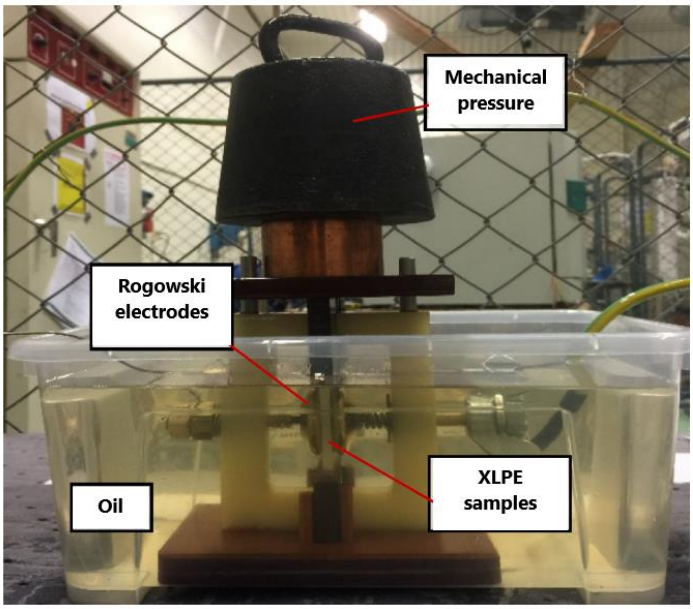


Figure 1: Image of the test setup during testing of XLPE|XLPE. The samples are mated and mechanical pressure is applied while the setup is immersed in transformer oil.

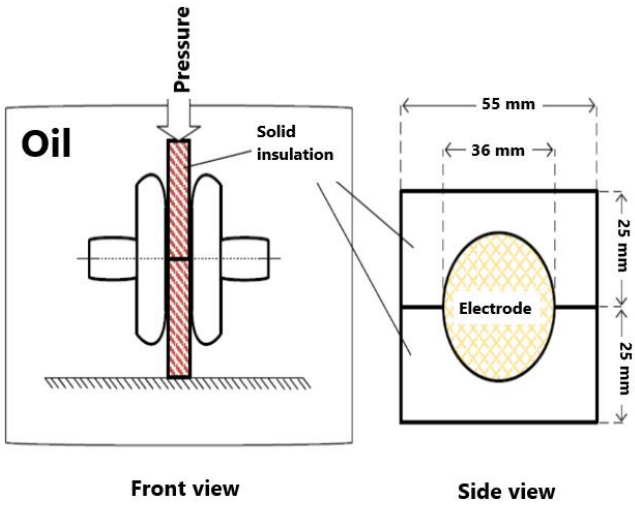


Figure 2: Simple illustration of the test setup.

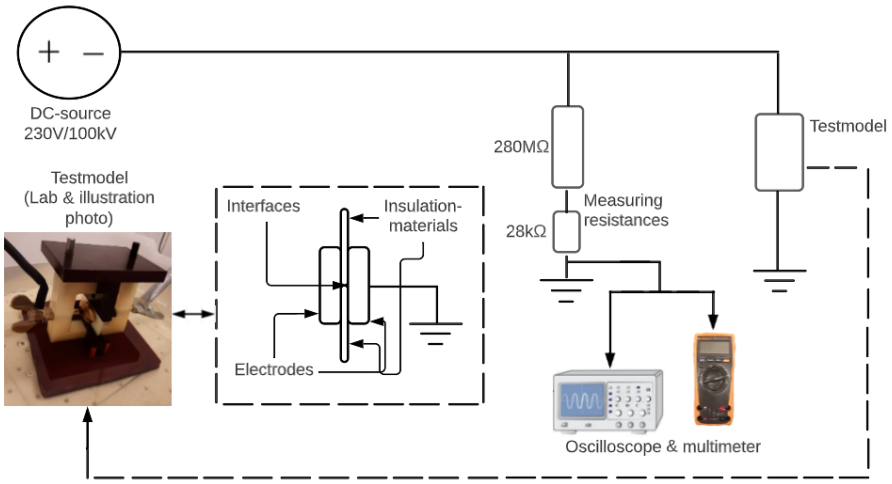


Figure 3: Experimental setup for the breakdown experiments with applied DC voltage (VLF) to the interfaces.

Results

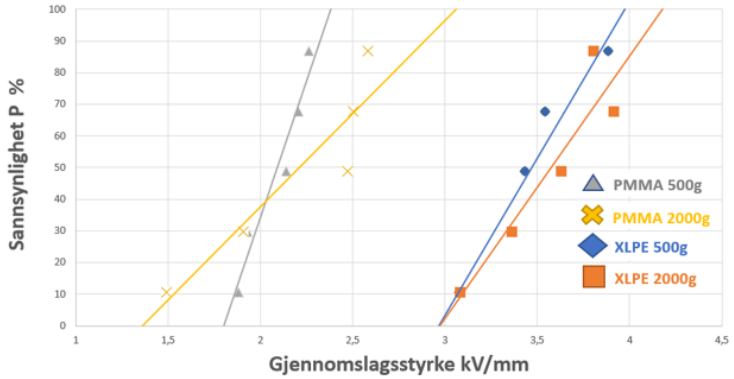


Figure 4: Measured longitudinal 50 Hz AC breakdown strength values of interfaces between wet XLPE and PMMA samples for the same high pressure (15,2 bar) but varying the surface roughness.

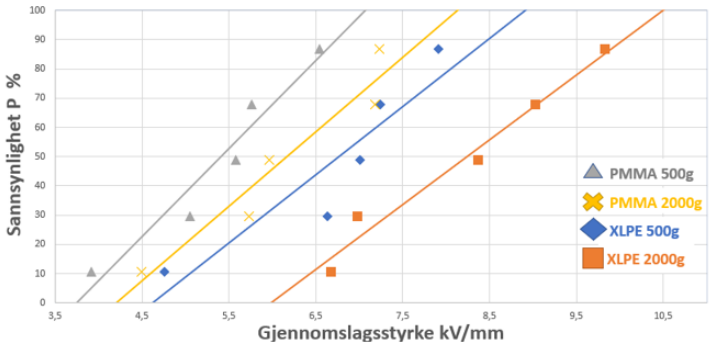


Figure 5: Measured values of longitudinal VLF (0.002 Hz) AC breakdown strength of interfaces between wet XLPE and PMMA samples with applied high interface pressure (15,2 bar) but varying the surface roughness.

Conclusion

The breakdown values with applied AC 50 Hz for wet XLPE samples were found to be approximately 80 % lower than for comparable types of dry samples for XLPE. This is in line with the assumptions about lower breakdown voltage in cases of contact areas connected in series with water-filled interface cavities, compared with dry samples which are assumed to contain only air in the interface cavities.

The 2-3 times higher breakdown strength has been demonstrated in all VLF tests compared to AC 50 Hz during the wet interface experiments. In VLF testing, higher breakdown strength is expected due to the slow rate of electrical tree formation at low voltage frequencies, since the degradation rate is lower than in tests at 50 Hz voltages.

Investigation of a Four Level Voltage Active Gate Driver for Loss and Slope Control of SiC MOSFETs

Student: **Halvor Bratvold Ekren**
Supervisor: **Dimosthenis Peftitsis**
Co-supervisors: **Daniel Alexander Philipps**
Gard Lyng Rødal

Problem description

As renewable energy resources become more prominent and the electrification of society continues, the presence of power semiconductor devices will increase in the future. Several renewable energy resources, such as solar energy and wind energy, has an intermittent power production. This leads to temperature fluctuations in the power semiconductor devices, which is an issue when it comes to lifetime and reliability for power semiconductor device.
By reducing these temperature swings, temperature induced stress in the power semiconductor devices can be mitigated. This will increase power semiconductor device lifetime and reliability.

One way to accomplish this is to manipulate losses in the power semiconductor device by utilizing the gate driver circuit of the device. In this Master's Thesis, a gate driver circuit capable of influencing losses as well as current and voltage slopes in a SiC MOSFET will be presented and investigated.

Four level voltage active gate driver

By introducing an intermediate voltage at the turn-on and turn-off switching transient of a SiC MOSFET, which is controllable in voltage amplitude and duration, the gate driver proposed in this Master's Thesis is able to influence switching losses, and the voltage and current slopes in a SiC MOSFET switching transient. Examples of the waveforms produced by the proposed gate driver can be seen in Figure 1 and 2.

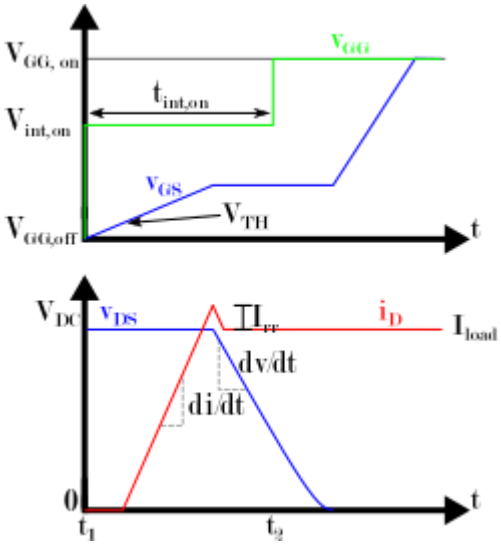


Figure 1: Proposed gate driver turn-on waveforms

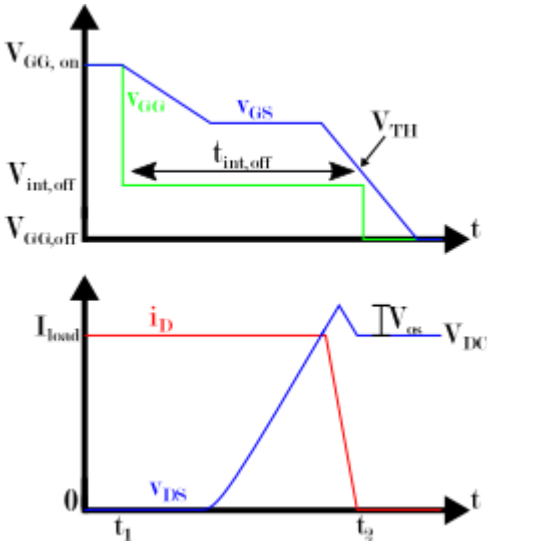


Figure 2: Proposed gate driver turn-on waveforms

Simulation study
To verify the performance of the proposed gate driver, a simulation study was performed. This simulation study was performed by creating a double pulse test in LTSpice. Evaluation of the simulation data was performed by utilizing Python functions created for this purpose. The voltage amplitude and duration were altered, and the switching loss, voltage overshoot, and current overshoot as well as voltage and current slopes were calculated. This was performed for both the turn-on and turn-off switching event.

Experimental double pulse tests
Experiments were also performed to verify the functionality of the proposed gate driver. In this regard, a PCB prototype was developed and tested. A test circuit capable of performing double pulse test was assembled. Software needed to perform the double pulse test and evaluate the experimental results was also developed. Due to production delays, only limited set of experiments for the turn-on switching event was performed.

Results
Exemplary results showing the drain-source voltage and drain current for the same values of voltage amplitude and duration for the experiments can be seen in Figure 4. It was from measurements like these, that switching losses and current and voltage slopes were calculated.

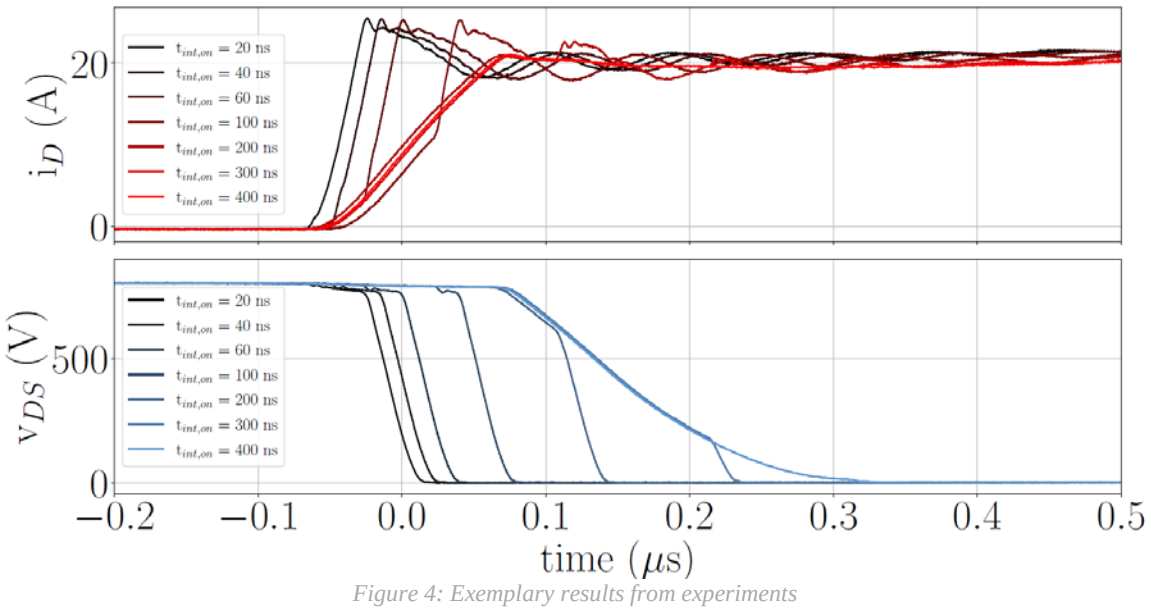


Figure 4: Exemplary results from experiments

Conclusion
Based on the simulation study and the experiments, the gate driver circuit proposed in this Master's Thesis is able to influence the switching transient of a discrete SiC MOSFET. More experiments are needed to obtain a complete characterization of the proposed gate driver.

Short-term hydropower scheduling in congested areas: A novel approach employing DC power flow and grid limitations

Student: **Eriksen, Marius - Trondal, Mathias Espeland**
Supervisor: **Klæboe, Gro**

Summary
This master thesis evaluates the impact of including power flow equations in the short-term hydropower scheduling algorithm. The research is conducted on a self-produced optimization model in a area with sparse transmission capacity in the power grid. A direct current approximation represents the power flow equations in the optimization model, where this entails that the properties of the power grid is included, and will affect the hydropower producers' decisions. The area of analysis, the northernmost price area in the Norwegian power market (NO4), is represented with a nodal approach due to the bottlenecks in the power grid.

The master's thesis has offered extensive and detailed work related to the development of the optimization model, as well as thorough data construction to make realistic analyzes. As information related to the hydropower plants is secret, efficient and satisfying methods had to be utilized to represent this data in a correct way. The various hydropower plants values the water in their reservoirs, which represent how they intend to produce now and in the future. This information is secret for that reason. With public water values, hydropower producers will reveal their market forecast.

A case study has been carried out on an existing, large-scale problem in the current power grid. Northern Norway experiences substantially lower area prices than the rest of Norway, due to surplus production and limited transmission in the power grid to the coupled price areas. By including the load flow equations in the short-term planning for hydropower, we will analyze whether the hydropower producers change their production pattern in our developed model. A base case, which can represent how the day-ahead market operates today, is compared to cases with limited transmission capacity to perform the analysis.

A result of the work and research done on this master's thesis is a paper submitted to The International Conference on European Energy Markets (EEM) 2022, which is one of the well established conferences in Europe. The paper is included in the Appendix. We are awaiting an answer on whether this will be approved and published at this time. The created datasets for this thesis, regarding production-discharge-curves, water values, inflow, demand and line data, has been passed on to the students who will do further research on this next year.

End-region losses in large hydropower generators

Student: **Børge Johannes Fagermyr**
Supervisor: **Arne Nysveen**

Summary

Large generators have reportedly experienced partial overheating in the generator end region under certain operating conditions. Leakage flux in the generator end region can contain a significant axial component that penetrates the end part of the stator, thus creating high eddy current losses. Under loaded operation, the armature flux varies for different generator operation points, and the total flux is consequently dependent on the generator loading. Calculating the combined end region flux is a complex three-dimensional problem that can be solved using finite element method (FEM) modeling. This thesis aims to obtain the end region magnetic flux distribution and the end region power loss at selected operating points corresponding to leading, unity, and lagging power factor. For this purpose, a 3D FEM model is created based on a 100kVA synchronous generator.

The proposed 3D FEM model is a virtual generator model with an increased number of slots, thus reducing the complexity of the overall modeling process. More importantly, the proposed model drastically reduces the required computational power for obtaining results within a reasonable time frame. Anisotropic permeability is included in the 3D model of the lamination stack. Additionally, an improved B-H curve is used in modeling the stator iron. Simulation results show that the eddy current losses in the end region pressing structure are up to three times higher when the generator is under-excited than when the generator is loaded at unity power factor or at over-excitation operation. Similar conclusions are drawn for losses in the stator iron end region. Simulation results show that the axial component of the magnetic flux density in the end region is considerably higher at leading power factor compared to unity and lagging power factor for the same output power.

A loss measurement apparatus is constructed for experimental investigation on the effect of end region leakage flux. An Epstein frame with excitation controlled by a power supply is initially magnetized. A C-shaped core is then magnetized separately. With the C-core placed normal to the main field in the Epstein frame core, an Artificial Leakage Flux test is conducted. Stainless steel plates of varying thickness are placed in the airgap, emulating the press fingers and clamping plate found in the end region of synchronous generators. Incremental losses are obtained at increasing phase shifts between the main flux and leakage flux. The results show that the incremental losses are sensitive to variations in the angle between leakage flux and main flux.

A study of the reliability of the RBTS distribution system with incorporation of Distributed Generation and Batteries

Student: **Finn, Alexander**
Supervisor: **Vadlamudi, Vijay Venu**

Summary

This thesis presents a foundation for understanding the reliability evaluation procedure of distribution systems, utilising both analytical and simulation methods to estimate the probability of the system's in-capability to supply the demand. This thesis introduces the power distribution system and its distribution facilities, where the overall objective is to install distributed generation (DG) and battery energy storage systems (BESS) to a RBTS distribution system. To perform the necessary actions in developing a reliability assessment of the RBTS distribution system with incorporated distributed energy sources, a software developed in MATLAB is used for validation purposes of the RBTS and simulating cases of passive and active distribution of buses in the RBTS.

The evaluation of incorporating distributed generation and energy storage to the reliability of distribution systems is accomplished by utilising Bus 6, Feeder 4, Bus 5, Feeder 4 and Bus 2, Feeder 1 of the RBTS. The microgrid, which consists of wind turbines and photovoltaic modules in the DG and battery, is installed in both sub-Feeder 2 and sub-Feeder 3 of Bus 6, and on the end of the single radial-line distribution system of Feeder 1 of Bus 2 and Feeder 4 of Bus 5. The two cases studied is a Feeder of a RBTS Bus with passive distribution, and then active distribution, which includes the intermittent behaviour of the renewable energy sources, and the facilitation of a battery energy storage system.

The overall objective of the thesis is to evaluate the contribution of the installed DG and BESS to the RBTS feeder, to the reliability of distribution systems.

The reliability assessment performed in this thesis reveals that the load points of the defined installation experienced a significant reliability improvement. with an overall system reduction on EENS of 28.2 % for Bus 2, Feeder F1, 28.2 % for Bus 2, Feeder F1, 16.6 % for Bus 5, Feeder F4 and 35.9 % for Bus 6, Feeder F4. The effect from the microgrid on a RBTS distribution system is substantial, with a greater reduction in load point failure rate and outage duration, improving the power quality and reliability for the consumer of the RBTS.

Investigation of PD behavior in ceramic substrates under fast repetitive square voltage pulses

Student: **Ingrid Gunheim Folkestad**
Supervisor: **Kaveh Niayesh**

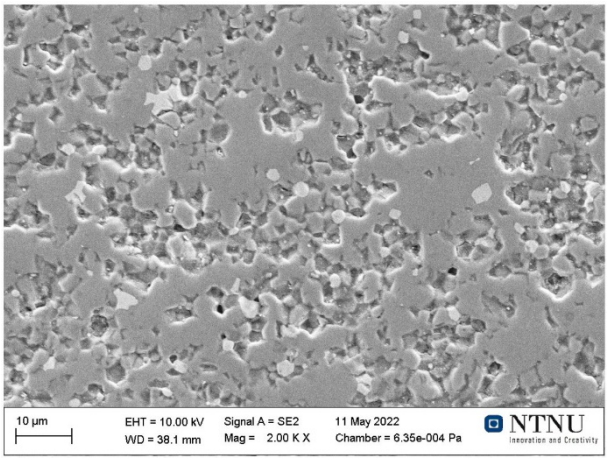
Problem description
To develop test methods that accommodate the real voltage stress caused by switching pulses, the effect of fast repetitive square voltage pulses must be understood. This applies to both the insulation systems in high voltage apparatus such as machines and transformers, and the insulation systems in the switching devices themselves. An investigation of the ceramic substrates used in IGBT power modules by partial discharge (PD) measurements was the focus of this master's thesis. IGBT power modules switch electric power on and off fast to ensure control of the power flow, and are typically stressed with switching frequencies in the range of kHz and rise times of tens nanoseconds.

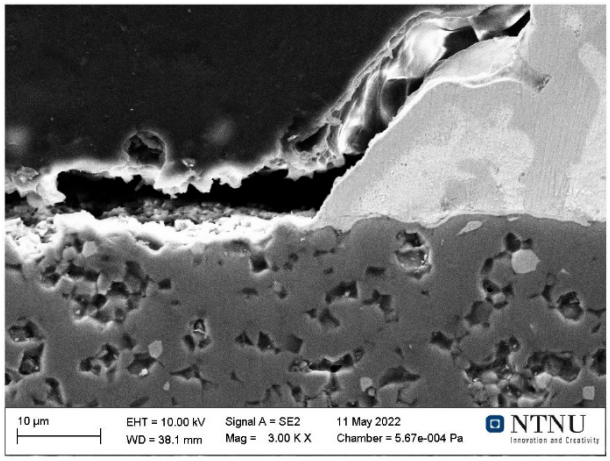
The task
The goal of this master's thesis was to investigate the PD behavior of AlN ceramic substrates under fast repetitive square voltage pulses, and observe the difference between AC sinusoidal voltages and fast repetitive square voltage pulses. To do so, several objectives had to be considered such as characterization of defects in substrates by using a scanning electron microscope (SEM), measurements of PD inception and extinction voltages (PDIV and PDEV, respectively) at sinusoidal voltage, measurements of PDIV at unipolar and bipolar square voltages under variation of rise time and repetition frequency, and establish a basis for comparison between the results. The results under square voltages indicated the role of space charges, and the thesis aimed to discuss the space charge effect under the applied voltages.

Model/measurements
Two experimental setups were used to perform the PD measurements. Under AC sinusoidal conditions, electrical measurements using the OMICRON measuring system and optical measurements using a single PMT were performed. In the square voltage setup, the exact same PMT was used for optical measurements to ensure the same sensitivity. Example of a measurement in in the square voltage setup is shown in the figure below. Due to the frequency spectra of a square voltage pulse, electrical measurements were complicated. Therefore, the measurements depended on a reliable optical measurement system. Because of the limitation of the measurement setup only external PDs were recorded. During the measurements, the ceramic substrate was placed in a sample holder and filled with transparent silicone oil so that the external defects were visible for the PMT.

Results

In the ceramic substrates, two defects were considered the main PD sources, pores in the ceramic material (image to the left) and sharp metal edges in the triple junction (image to the right). In the square voltage setup, only external PDs from the sharp metal edges were observed.





The experimental results showed that the PD inception voltage was about twice as low under square voltage conditions than under sinusoidal voltage conditions. Under square voltages, no difference was observed between bipolar and positive unipolar voltages. However, the effect of polarity was observed by comparing the PD behavior under negative and positive unipolar voltages. Almost no difference was observed by changing the repetition rate and rise time.

Conclusion

The standard testing condition using AC sinusoidal voltage does not match the real voltage stress. When ceramic substrates are used in IGBT power modules in various applications, PD activity may occur earlier than indicated during the testing, and an early breakdown can be a danger. The PDIV value indicates at which voltage level the degradation mechanisms occur and is often used to characterize the PD behavior. However, to thoroughly understand the level of degradation, the PD magnitudes and how often PDs occur must also be considered. This is a step for future work.

Development Of A Cloud-Based Wireless Communication System For Home Automation And residential Demand Response Applications

Student: **Fossmo, Kristoffer**
Supervisor: **Cali, Ümit**

Summary

Internet of Things, home automation, and energy management systems have gotten an increasing prevalence the last decade. To facilitate communication between homeowner's energy management systems and other market actors, it is necessary to use long range communication technologies. With wider reach, it is possible for more actors to participate in demand response and similar actions, making the overall market more efficient.

In this thesis we look at two low power wide area network technologies, and investigate a cloud deployment using both technologies for the purposes of metering, demand response, and home automation. This thesis aims to determine which technology is better suited for what use case.

Design and Control of a Local Offshore Network for a Multi-Use Offshore Platform

Student: **Frøhaug, Einar Ingmar Skirdal**
Supervisor: **Anaya-Lara, Olimpo**

Summary

Multi-purpose offshore platforms (MPPs) are a part of the sustainable and renewable energy strategy to The European Union, active through the projects "The Ocean of Tomorrow" and "Horizon 2020". The concept includes offshore industries within transportation, energy, aquaculture and leisure (TEAL), and is proposed to have offer a broad set of services. Despite that the projects has been going on for over ten years, very lite research has been performed regarding the electrical aspects of the MPP. Therefore, this thesis is set to design a local offshore network (LON) for a MPP dedicated to fish farming activities of aqua-culturing, powered by a totally renewable energy system, and assessing its feasibility through the dynamic system performance when exposed to contingencies.

The motivation behind this choice is to emphasis how the huge offshore wind resources can be used to produce seafood and meet the increasingly high demand of seafood on a global scale. In addition, the thesis will attempt to address how excessive energy can be used to power auxiliary equipment on the farm to enhance the life quality of the fish or support the LON on the MPP. In the first phase of the thesis an overview of conventional offshore fish farms and available wind resources are presented. Together with a presentation of the fundamental theory of necessary system components, this creates a the required basis and tools to develop a suitable system model in MATLAB/Simulink. The LON comprises of a Permanent Magnet Synchronous Generator (PMSG) wind turbine, a main fixed inductive load of variable-speed Induction Motors (IMs), a dump load of a variable inductive load and a directly connected IM and a Lithium-ion battery. All components are connected to the 400V AC LON using different types of converters.

The proposed local offshore network model has been validated, and the controller developed for the system is found to perform sufficiently. Following the validation, the system dynamics are investigated under a set of cases representing the some of the most severe and frequent situations that the system has to withstand on a daily basis. The results shows that the system is technical feasible, under the assumptions and simplifications made in this thesis.

Start and stop of the main load applied little stress on the system, even at low wind speeds. The battery kept the voltage and frequency stable and mostly within the grid code limits and regulated the operation to damp transients. However, the system is vulnerable to directly connected IMs, due to the high initial reactive power requirement. Large abrupt changes in the reactive power load causes a permanent voltage collapse. The discussed solution to add system stability is a shunt capacitor and hydrogen based fuel cell. The fuel cell would be preferable, despite the increasing system and control complexity, as it brings benefits to the whole system in terms of stability, redundancy and security.

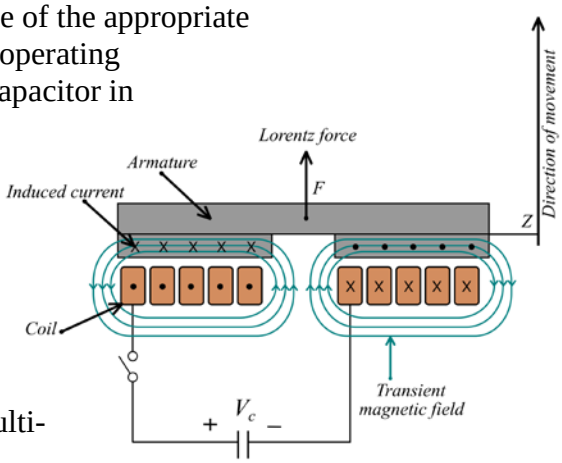
Overall, the control of the VSCs operates satisfactory and shows great potential in terms of dynamic stability, and the finding from this thesis indicates that a LON for a MPP solely based on renewable energy is possible.

Simulation and design of an electrodynamic Thomson coil actuator for fast mechanical switches

Student: **Håkon Risbøl Hansen**
Supervisor: **Kaveh Niayesh, Ivan Semenov**
Contact: **risboel@gmail.com**

Problem description

The electrodynamic (Thomson) drive mechanism is one of the appropriate solutions used in fast opening switches. In this type of operating mechanism, a pulse current, created by discharging a capacitor in a flat coil,
is used to induce large eddy currents in a metallic part. The currents
flow through the coil and induced current in the metallic part and produce an opposite magnetic field resulting in the exertion of a large force giving fast acceleration of the metallic body.

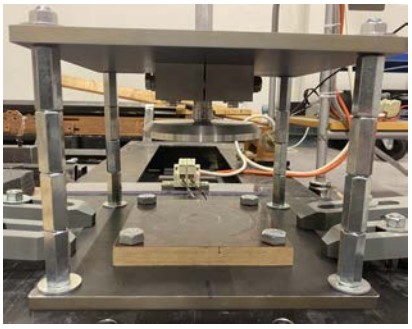


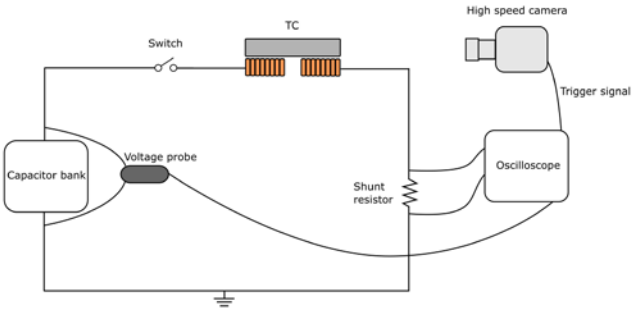
The task

The goal of the work is to create a working coupled multi-physics simulation model of the Thomson coil drive mechanism based on the FEM-software COMSOL Multiphysics. Further validating the model through experimental validation lab work by creating a prototype of the mechanism. This model can later be used for optimization studies of such a mechanism. Further, the model will be used for deriving design and dimensioning rules for a Thomson drive actuator. The work is targeted at the development of alternative driving mechanisms for ultra-fast disconnectors for use in HVDC circuit breakers.

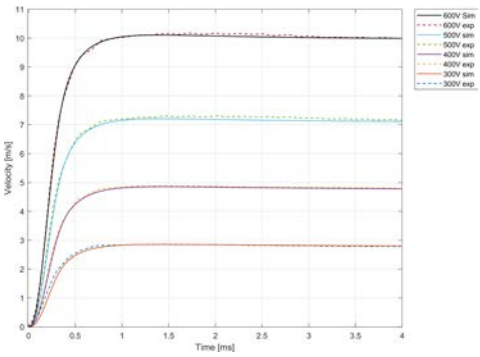
Model/ measurements

The figure shows how the lab-experiment was setup:

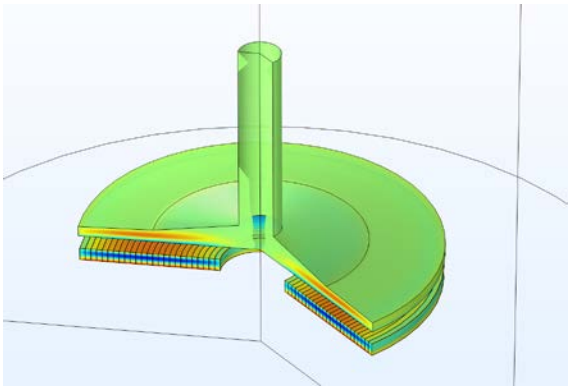




The results from the experimental verification:



The model used for the parametric study:



Conclusion

The experimental verification of the general concepts behind the simulation model was confirmed within the limitation of the model.
The model was verified at all voltage levels with good accuracy, indicating that the model design is adaptable and robust. However, the assumption that the armature is infinitely stiff may not be valid for less robust armatures. The armature in the prototype was over-dimensioned, making it very stiff, making the model valid for this case.

The parametric study shows some clear tendencies when it comes to optimization of efficiency and opening time for the different components allowing for some conclusions about the factors that affect the driving characteristics of the Thomson coil actuator: For any given TC, there would be an optimal energy source with regard to opening time and energy input. This means that if the energy input is limited to a maximum constant energy and the voltage and capacitance are varied with respect to each other, for that given energy and TC, an optimal voltage to capacitance ratio can be found, making the capacitor the easiest component to adapt to the system. For the coil, a relatively high number of turns (35-45) allows for a larger magnetic field, thus increasing the eddy currents in the armature. However, the increased inductance reduces the currents rise rate, reducing the initial acceleration. Consequently, an optimization of the coil is required to find the fastest OT for the specific case. The armature radius should be equal to or slightly smaller than the coil radius. Increasing the armature thickness did not affect the armature current significantly, making it likely that the limiting factor of the armature thickness and design will be the force stress.

Making generalized dimensioning rules for a Thomson coil actuator is challenging due to the many factor and parameters that affect the driving characteristics of the device. The design and optimization of electromagnetic devices have historically shown to be a complex and time-consuming task, and still is. The implementation of FEM-simulation models allows for faster and more cost-effective exploration of the design parameters. The iterative design process suggested in the thesis requires the implementation of stress calculations in the model before it can be tested. Even with the limitations set for the design process, the flow charts for the iterative design process become complex and intricate, highlighting the difficulty of making general dimensioning rules for such devices. Standardizing the mechanism for different voltage levels and power ratings might be possible but require specific design and optimization within the limits of the requirements for the specific system.

Development of an XAI-Based Residential Load Forecasting Model

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Collaboration with: **-**

Problem description
The ever-increasing complexity in the power system has introduced a higher demand for forecasting to keep the grid stable. Load forecasting has been an integral part of planning and maintenance by power system operators for both short and long horizons. Due to lacking technology, load forecasting has mainly been applied at the regional level. However, the revolution in sensor technology and data processing for machine learning has also enabled the investigation of residential load forecasting. The current practice within machine learning consists of black box models, which are highly complicated, giving little insight and reliability. Explainable artificial intelligence has seen a rise in prosperity, allowing domain experts and others to understand the choices of the model.

The task
This thesis sets out to explore the possibilities of XAI within energy forecasting and will try to answer, how can application of XAI-tools improve and gain insights towards the inner workings of black box models as a step towards trustworthy AI? This master's thesis is structured into three main parts. The first part consists researching the current environment of relevant topics. Additionally, during this segment, data is collected and investigated to gain insight ahead of the modelling stage. The second part involves developing an hour-ahead load forecasting model for a residential house using different measures. Two different approaches are used. The first type is an LSTM model, and the second is a hybrid approach consisting of a Convolutional Neural Network (CNN) hybridized with an LSTM model. The third part of the thesis concentrate on implementing SHAP to the different models in hopes of unlocking a deeper understanding of the models.

Model/ measurements
The approach can be divided into five steps and is visualized in Figure 3.1. **(1)** Collect raw data, consisting of electrical load data and weather prediction data. **(2)** pre-processing of said data. Here, outliers and irregularities are removed, and categorical data is added. In addition to the aforementioned, the data is visualized to get insight into patterns. **(3)** Training data is used for model development. During model development, different input variables and hyperparameters are tuned and experimented with to find the best model. **(4)** The different models are investigated using XAI methods, such as Shapley Additive exPlanations (SHAP). **(5)** The different models from step three are compared using traditional performance reviews such as RMSE, MAPE, and MAE.

Calculation
Three generations of models were presented. The first generation of models consisted of just historical load data and variations of Numerical Weather Predictions (NWP). The second generation added categorical features such as day and month. Finally, the last generation added regional load forecasts to the aforementioned features. SHAP was applied to the second generation of models to get insights into feature importance to make further improvements. From Figure 1 a summary plot is seen which give an indication of which features the model

emphasizes on. Using this and other tools from SHAP the third generation of models were created.

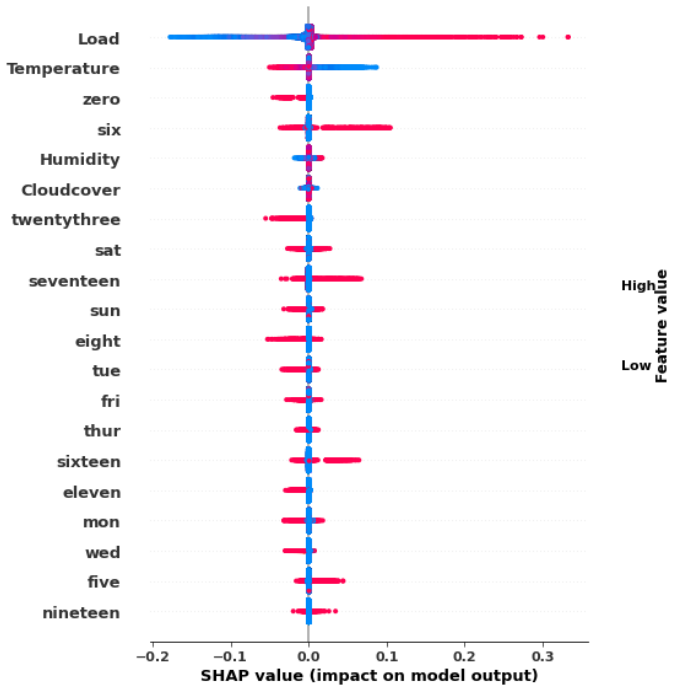

Figure 1 Summary plot for a model from the second generation.

Overall, the models improved throughout the development period with the final model achieving a MAPE of 24.66%. An excerpt of the predictions can be seen in Figure 2.

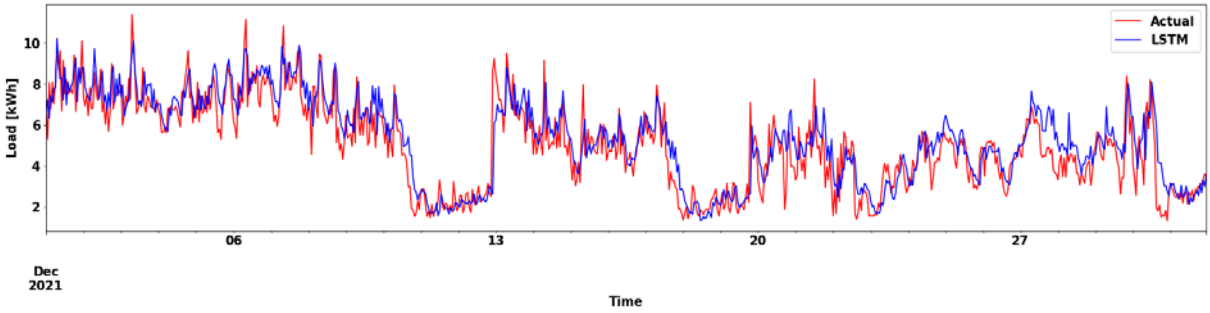

Figure 2: The month of december for the final model. LSTM signifies predictions

Conclusion

The improvements and increased insights provided by explainable artificial intelligence found in this thesis suggest that there is a potential for explainable artificial intelligence to be a fundamental path toward trustworthy artificial intelligence. However, to reach its potential, more research is needed.

A co-simulation framework to coordinate battery optimization and load flow
Improving voltage quality in the distribution grid

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Problem description
The most crucial question that the thesis addresses is as follows: How can a co-simulation framework coordinate a battery optimization model and a load flow simulation to improve voltage quality in the distribution grid?

Model/ measurements
A house connected to the LV network with battery and PV was modelled. Co-simulation was used to combine two models: an optimization model in Python of the battery and a load flow simulation in Simulink of the lines connecting the house to the LV network. The co-simulation was used by having an optimization model and a Simulink model simulate the voltage when the house was charging and discharging the battery

The task
There are three cases: a base case, a power peak case and a battery case. All three cases were simulated for one day in all four seasons of the year. The optimization decides first how the spot price of electricity, load and PV impact the charging/discharging of the battery and grid exchange. The output from the optimization is used in the Simulink simulation, where the voltage is the output. The co-simulation platform analyses the simulated voltage. If there is a voltage violation the maximum power allowed at PCC is reduced. After the maximum power allowed at PCC is reduced, there is a new iteration of optimization and Simulink simulation. The co-simulation iterates until there is a solution without voltage violation, or the optimization is unable to find a solution.

Calculation
Because of the grid tariff on import, the battery is used to store the excess power when residual load is negative. When the PV generation is low, the battery was used to buy electricity when it was cheap, and use it later in the day when the prices were higher. The results show that co-simulation can be used to improve the quality of power supply. With a larger battery, there is a greater chance of the optimization to find a feasible solution and voltage within the given range. Although a larger battery makes a feasible solution more likely, a larger battery cost much more. With higher power peak factors, the co-simulation had to do more iterations to find a valid solution, and it was not able to find a solution during the days with low PV generation.

Conclusion
Co-simulation can be used to coordinate a battery optimization model and a load flow simulation to improve voltage quality in the distribution grid by the two models exchanging data on a co-simulation platform. By implementing a stepwise decrease of maximum power at PCC when the voltage quality is violated, the two models adapt and change charging and discharging patterns for the battery.

Autonomous Optimization of Agrivoltaic Systems in Norway

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Problem description

Humanity must increase the efficiency at which it utilizes land area. About 70% of the land surface of Earth is currently being used for either agricultural activity or can be classified as desert areas. As agricultural land is being repurposed to other human activities or lost to desertification, it must expand into natural habitats to meet the increasing food demands of humans. Additionally, a rapid expansion of the area devoted to renewable energy sources such as utility-scale solar parks is posed to happen in the next few decades. By combining agricultural activity and energy production from solar panels on the same land area it is possible to greatly increase land-use efficiency, while at the same time exploiting beneficial synergy effects such as reduced water consumption and increased resistance to extreme weather conditions.

The task

This project is the first modelling study of agrivoltaics in Norway and will focus on the design of vertical bifacial PV systems combined with the grass crop timothy, which covers almost 70% of Norwegian agricultural land. In what may be a first, an autonomous system will be developed to optimize the agrivoltaic system with respect to energy and crop yields, while also being able to accommodate for any limitations or objectives such as, e.g., maximum power peaks or minimum allowable crop yield within the system.

Modelling

There are essentially three things that needs to be assessed when modelling an agrivoltaic system: The energy yield from the PV system, the changes in the environmental conditions caused by the PV system such as reduced ground surface irradiation, and the crop yield in those modified conditions. These are traditionally separate subjects, and therefore needs to be modelled in separate software. This project utilized a wide range of software that can be observed in figure 1. Figure 2 shows what the annual ground surface radiation distribution within an East/West-facing vertical bifacial system might look like, where red is unshaded areas and yellow indicates about 25% reduced irradiation.

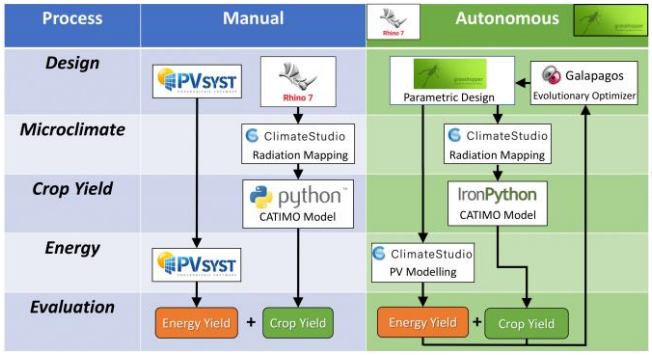

Figure 1: Software Overview of Agrivoltaic System Assessment

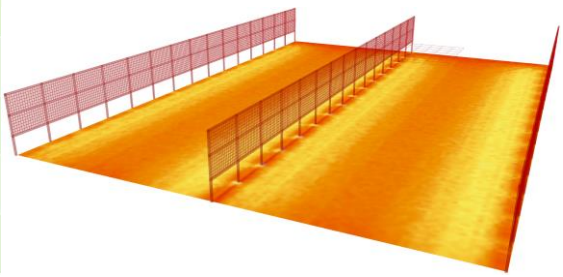

Figure 2: Ground Surface Shadow Assessment

Calculation

In addition to presenting a thorough analysis on the effects of system design parameters such as panel row distances and orientation on energy and grass crop yields, the project also included several autonomous system optimizations. These were done using increasingly more complex objectives that started off by simply orienting a system with 12m panel row distance to get the most energy or crop yield. Eventually the system was optimized by changing both orientation and row distances to find the highest combined energy and crop yield per unit of land area, while also implementing several limitations such as minimum annual energy generation and grass crop yield. Some of the results from the final optimization are shown in Table 1, where 100% crop yield would be that of regular farming activity. The design that produces this output has 8m distance between the panel rows and was oriented such that the front side of the panels faced South-West, or more specifically, 22° rotated in a counterclockwise direction from due West.

Table 1: Example of Minimum Requirements and Corresponding Results from an Autonomous Optimization

	Lower Limit	**Result**
Crop: Absolute Minimum Yield	70%	70.2%
Crop: Average Minimum Yield	80%	84.2%
Energy: Minimum Annual Yield	1000 kWh/kWp	1015.4 kWh/kWp

By increasing the pitch to about 12m it is expected that about 90% of normal grass harvests can be gained from these agrivoltaic systems, while still yielding higher specific energy yields than regular rooftop PV systems.

While this study did not account for the economic costs and capital gains of the system, it can easily implement in the optimization procedure once such figures are quantified.

Conclusion

This project has resulted in the first agrivoltaic model in Norway and is currently capable of assessing the energy output of vertical bifacial PV panels in combination with the agricultural output of the grass crop timothy. To the author’s knowledge, this is also the first time an autonomous system has been developed to optimize agrivoltaic system designs.

The model estimates that the assessed agrivoltaic system can increase the land use efficiency by 40-100% in Trøndelag, depending on the system design.

With relatively minor modifications the system should also be able to optimize other kinds of PV systems and crops than those that have been the subject of this study. Even though not currently implemented, the model is also inherently able to optimize with respect to, e.g., economic profitability if the metrics are inserted into the model during the optimization procedure.

On-line Condition Assessment of 420 kV Terminations – design and development of PD sensors

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Collaboration with: **SINTEF, Nexans Norway, Statnett**

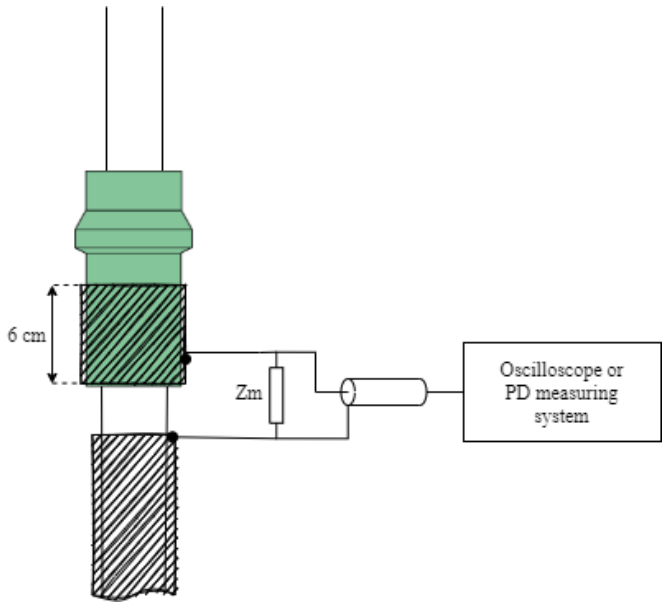
Problem description

Terminations are considered a weak point in the transmission grid, and utilities experience that poor termination is a major cause of cable system failures. Partial discharges caused by void formation at the intersection between the field regulating stress cone of the termination and the cable are one of the significant causes of breakdown. The SmartACT project aims to develop a novel hardware based on sensors placed inside 420 kV oil-filled terminations for on-line condition assessment to increase the security of supply. This hardware shall, among other factors, measure partial discharge activity. A PD measurement is a well-established criterion for condition assessment and often follows the conventional measuring technique as established by IEC. However, PD detection has also been investigated by employing non-conventional electrical coupling methods.

The task

The project examines if a capacitive coupler can be constructed by screen copper mesh to measure PD activity in a HV termination. Five preliminary sensor proposals have been analysed in terms of frequency response analysis (FRA). Further, it was chosen to focus on one of the sensor proposals. This sensing method has been examined in terms of sensitivity analysis and analysis in LtSpice. The thesis also addresses how a micro-glass sphere can be utilised to create an artificial void defect with reproducible PD characteristics to test the sensitivity of the sensor proposal relevant to a defect. PDIV calculations, testing, and field simulations in Comsol have been conducted to examine the breakdown field of one micro-glass sphere cast into the cable insulation.

Model



Figur 1 Copper mesh sensor proposal

Figur 2 Micro-glass sphere implementation in cable insulation with the use of epoxy

Calculation

The results indicate that the frequency response gain of the five sensor proposals, except case 5, increases with increasing frequency. The highest gain is achieved at frequencies ranging from 10 MHZ to 100 MHz. Simulations in LtSpice indicate that C_s should be as low as possible and R_s as high as possible. The sensitivity analysis illustrate that the copper mesh sensor can measure charges down to 5 pC. The PDIV tests of the micro-glass spheres resulted in a breakdown field of the spheres equal to 5.64 kV/mm, which corresponds well to the simulated field in Comsol. During the PD sensor test of the implemented void defect, the copper mesh sensor captured 2.84% more apparent charge values than the conventional measuring technique. Meanwhile, the PDIV of the implemented micro-glass sphere was measured lower than expected, and the measured signals were not reproducible.

Conclusion

The copper mesh sensor has proven adequate sensitivity based on the sensitivity analysis and the PD sensor test. Nevertheless, the measured void discharges do not stem from the implemented micro-glass sphere. The measured discharges are probably due to an unsymmetrical void in the silicone grease. Consequently, the generation of an artificial void defect is not successful. The experiments in this thesis can be used as a proof of concept of the copper mesh sensor. Several tests and experiments are necessary to obtain a full-functioning PD sensor.

Impact of CO_2 compensation methods on the sizing of PV panels in Zero Emission Neighbourhoods

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Problem description
Buildings account for 32% of total final energy use and 19% of energy related greenhouse gas (GHG) emissions. Hence, a reduction in this sector would have a significant impact in order to reach our climate goals. Zero emission neighbourhoods (ZENs) have been enabled as a possible abatement measure. The main objective of a ZEN is to achieve net zero emissions over the neighbourhood's lifetime. From local renewable power production, most often solar PVs, the neighbourhood covers for its own compensation, in addition to the embodied emissions from construction, materials, and maintenance through power export to the grid. Quantification of total emissions is therefore needed in order to understand the environmental impact of the neighbourhood. Quantification of emissions from materials is fairly established, while quantifying the emissions related to the energy demand has proven to be rather challenging. As of today there exist several calculation methods for emission factors, while there exist no consensus regarding when to use which.

The task
The task of this thesis was to expand the knowledge around calculation of emission factors for electricity. Further, to investigate the required dimensions of a PV system as local renewable energy source (RES) in a ZEN, using different calculation methods for emission factors for electricity; namely the annual average, the hourly average, the short-run marginal and the long-run marginal emission factor.

Model/ measurements
A case study was performed building a simplified north-Europeanm power system, by parameterizing and configuring the GenX modeling framework. GenX is minimum cost-optimizing model developed in Julia and JuMP and allows for co-optimization of several power system decision layers. Further different simulations were run, to calculate the different emission factors.

- Simulation based on installed capacities, fuel- and CO_2 prices for 2019/2030,
- Simulation for 2019/2030 where load profile for the investigated ZEN is added to the Scandinavian demand,
- Simulation for 2019/2030 where load profile and local solar PV capacity for the investigated ZEN is added to the Scandinavian demand without allowing for investments in the power system,
- Simulation for 2019/2030 where the load profile and solar PV capacity for the investigated ZEN is added to the Scandinavian demand allowing for investments in the power system

The simulations was done with cost data for 2019 and 2030, to see how an eventual decarbonization of the power system would affect the resulting PV area. Further, as solar power production is quite dependent on hour-of-the-day and seasonal variation, the

simulations were rerun but now using onshore wind power as the local RES, to see how this would affect the required area.

Calculation
Based on this it was found that the chosen calculation method resulted in quite different areas for the RES.

Table 42: Resulting area in 2019 and 2030 based on calculation method, when solar PV is used as the local RES.

	2019 [m^2]	**2030** [m^2]
Scandinavian annual AEF	143 640.21	-
European annual AEF	43 637.50	496 868.57
Scandinavian hourly AEF	267 811.93	-
European hourly AEF	49 783.33	-
SRMEF	36 117.86	-
LRMEF	-	-

Table 43: Resulting area based on linear emission factors when solar PV is used as the local RES.

	Scandinavia [m^2]	**Europe**[m^2]
Linear annual AEF	-	535 091.13
Linear hourly AEF	-	-

Table 44: Resulting area in 2019 based on calculation method, when onshore wind is used as the local RES.

	2019 [m^2]
Scandinavian annual AEF	34 389.11
European annual AEF	14 242.11
Scandinavian hourly AEF	37 057.78
European hourly AEF	14 780.70
SRMEF	12 392.59
LRMEF	11 820.19

For more information the reader is referred to the master's thesis.

Conclusion
The above results show that the choice of calculation method gives quite differing results. Using the short-run marginal emission factor for 2019 for dimensioning would require a quite small area of solar PV, making it possible to reach ZEN-COM at a lower cost compared to when using the linear annual average emission factor for Europe. Dimensioning using the short-run marginal emission factor would result in expected compensation as long as the existing power system remains static. However, as the power system emissions would decrease due to more commissioning of renewable energy sources, this would result in an under-compensation, eventually resulting in the ZEN not being zero emission. The thesis found that choice of calculation has a clear impact on dimensioning of local RES, as well as project feasibility. Due to this it is necessary with a standard that communicates the actual consequences of developing ZENs. As this thesis is meant as a knowledge foundation no conclusion is taken regarding “best practice”. However, the thesis has contributed in expanding the level of knowledge around the calculation of emission factors. Additionally, it has shown possible consequences of using the different methods when calculating the required area of a PV system in a ZEN.

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Electrification of Fish Farms with Hydrogen
Retrofitting vs Building a New Feed Barge

Student: **Jesper Wimann Ingebretsen**
Supervisor: **Steve Völler**
Contact: **Thomas Bjørdal**

Problem description

This thesis is written in cooperation with Renewable Energy Cluster, NTE, Midt-Norsk Havbruk AS, and H2 Marine. The aim is to find the most suitable way to electrify an offshore fish farm, where it is too expensive to connect to the power grid. Two scenarios have therefore been introduced where the first is a retrofit of an existing feed barge with fuel cells and batteries. The second is building a new feed barge with the newest technologies and efficiency measures. Waterborne feeding is a prominent new technology that can drastically decrease load demand and fuel usage.

The task

The load data for three fish farms are analysed. They are Eiterfjorden, Skrosen and Årsetfjorden. The fuel cell and battery size were calculated by analysing the average load profile of the month with the highest load for a locality. This was performed for all three fish farms and both scenarios. The new build scenario used the same data set for the retrofit scenario but adjusted for the efficiency measures.

Model/ measurements

From the given dataset, cycles were created. This was to simulate an economic analysis. The cycles were four years for Eiterfjorden, two years for Skrosen, and four years for Årsetfjorden. In these cycles, the fuel consumption for periods with fish and without were included. The yearly expenses were used for the net present value analysis.

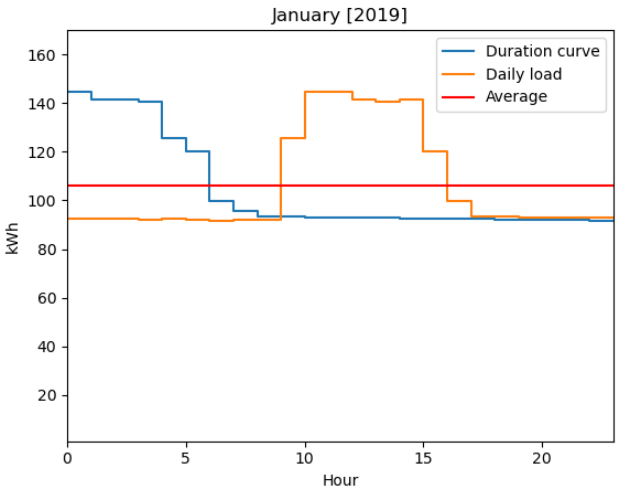

Figure 1: Analysed load profile

Eiterfjorden got a fuel cell size of 140 kW and a battery size of 360 kWh for the retrofit scenario. For the new build scenario, were the fuel cell size 60 kW and the battery size 230 kWh at Eiterfjorden. In analysing the given feed barge schematic, it was decided that two containers were the best for storage, but this can be further optimised. A basecase was also created to weigh against the two scenarios. This case shows how much fuel expenses can be saved by changing to hydrogen.

Calculation

The total CAPEX was calculated to be around 16 million kr for the retrofit scenarios and 32 million kr for the new build scenarios. The significant difference in initial investment can be attributed to the cost of building a new feed barge, which was found to be 25 million kr. From the resulting yearly expenses, which are hydrogen and maintenance, the difference is about 700 thousand to one million kr, in favour of the new build scenario. From the net present value analysis, the retrofit scenario for Eiterfjorden broke even after about 17 years and did not break even for the new build scenario. This was with a fixed diesel and hydrogen price. If the diesel price increases and the hydrogen price decreases, the retrofit breaks even after 11 years and the new build after 16 years. The other fish farms showed the same tendencies. Furthermore, the Eiterfjorden had a payback time of 13 years and 14.1 years for the retrofit and new build scenario, respectively. The other fish farms have a higher payback time.

Conclusion

From this, it can be concluded that the bigger the fish farm, with higher energy usage, the more yearly expenses can be saved by performing one of the scenarios. From this thesis, it can be concluded that a retrofit is the most cost-beneficial choice for fish farms with a life expectancy left of over ten years. If the fish farm has under five years, it can be concluded that it is better to live out its lifetime and then build a new feed barge with all the newest technologies and efficiency measures implemented because there is much to save from the yearly expenses.

Economical Optimisation of Wind Powered Pump Hydro Storage Systems in Norway

Student: **Jamessen, Eivind**
Supervisor: **Cali, Ümit**

Summary

In this thesis, it is investigated how the capacity at the Sørfjord wind farm can be increased although it will exceed the grid capacity. This is feasible because of the new Regulation on grid regulation and the energy market (NEM) rule that allows grid connection with terms of limitation of production. Two main approaches are tested at the Sørfjord wind farm: a standard model where the wind farm only uses the remaining capacity after the hydro production, and the other method is to adopt a multi-objective framework (MOF) as an optimisation tool that uses a pump of 20 MW to create a wind-pumped hydro storage (PHS) system. The latter aims to find a trade-off between the wind and hydro plant. Different trade-offs are created by assigning weight numbers to the objectives and expanding the wind farm by scales between 1 and 3. Both approaches are created in Python with the package Pyomo as the optimisation tool.

The obtained framework in this thesis treats wind and hydro production as two competitive objectives with the same target: to achieve the best possible income by energy export through a 140 MW line. Both weights and wind farm scales affect the way the MOF is considering the importance of each objective relative to each other. With the current size of the hydro and wind plant, an equal weight ratio leads to a power production dominated by hydropower as the decision maker in the MOF finds it more valuable. As the wind farm scale increases, the decision maker prioritises wind power export more.

The simulations of the ideal production pattern of both plants show that the major production occurs in the period December-March. Therefore, it is necessary to move hydropower outside this period when more wind power penetration is desired. With the spot price data from 2019, it turns out that about 8 % of the annual wind power can be curtailed without causing any significant decrease in the wind farm income. Considering this, the wind farm can be expanded by a factor of 2 with the standard simulation approach. Further, setting 8 % as a curtailment limit in the wind-PHS model, makes it possible to increase the wind farm capacity by a factor of 3.

Considering that a positive relative income for both producers is a fair trade-off, the simulations have shown that this requires a weight ratio more than 3/1 and a wind farm up-scale limited to 2.25. In addition to higher wind power penetration, adapting the wind-PHS is beneficial for grid utilisation and the system operator. It turns out that both a wind farm expansion and more transfer priority for the wind power producer increase the grid utilisation. A wind farm upscale of 3 will increase the grid utilisation from 25 % to more than 50 %.

Analysis of Power System Scenarios for Norway 2030 using the Fundamental Market Model FanSi

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Mathilde Klungland Ljøkjel

Supervisor: **Magnus Korpås**
Contact: **Arild Helseth**
Collaboration with: **SINTEF Energy Research**

Problem description
There have been discussions about Norway's role in the European power market in the last decade. Norwegian area prices have skyrocketed in the last year due to an interconnected power system and low inflow to the reservoirs. The future is uncertain. There is expected to be an increase in energy demand in all sectors, while the aim is to be net-zero by 2050. The introduction of more variable renewable energy to the electricity mix creates the need for better optimization tools that can handle more uncertainty.

The task
This thesis assesses two different aspects of FanSi. A feature investigated is the technical model and how to optimize datasets through parameters used when running FanSi. An assessment of two parameters, respectively, the number of scenarios and the number of weeks in the scenario fan, is done. The second aspect investigated is using FanSi as an analysis tool to understand the consequences of different changes to the North-European power system. The analyzed cases are high fuel prices, a high rationing price, removing the subsea cables from Norway, and increasing the capacity from Norway to Great Britain. In addition, this thesis utilizes FanSi to elaborate on future energy situations in Norway, running the scenarios presented above on Norway in scarcity and Norway in surplus situations. SINTEF Energy Research has provided the dataset used for the analysis, representing a possible power situation in 2030.

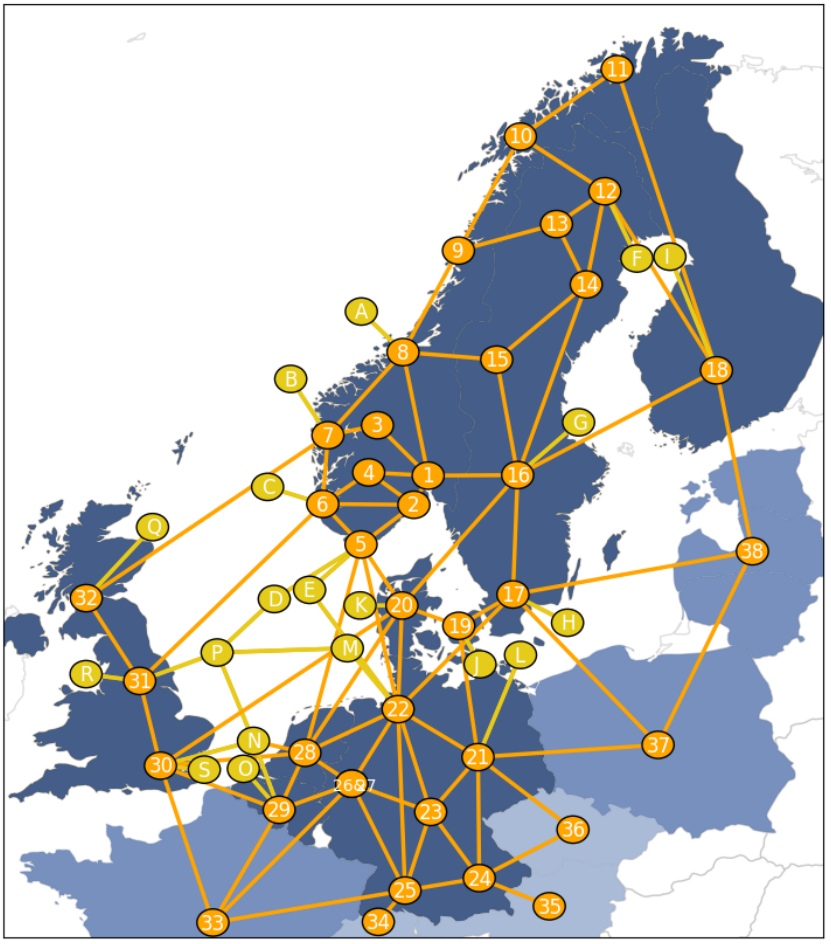
Model/ measurements
FanSi is a long-term hydro-thermal scheduling model developed by SINTEF Energy Research. It is built on a concept that uses historical records for inflow represented as scenarios to model possible future weather year scenarios. A widely used scheduling model, EMPS, uses an aggregated reservoir representation. FanSi does not aggregate reservoirs, which increases the computational time drastically. On the other hand, it better models short-term flexibility and is a model better equipped to handle uncertainty.

The figure to the right shows all the areas of the system used in this thesis. The dataset contains detailed modelling of Norway, Sweden, Denmark, Finland, Belgium, the Netherlands, Germany, France, Poland, the Baltic region and Great Britain in terms of demand and supply of electricity.

The different datasets and scenarios run in the thesis were:

Dataset A/F: Base
Dataset G: Norway in scarcity
Dataset H: Norway in large surplus of variable energy sources

Scenario B: High fuel prices
Scenario C: Removing subsea cables out of Norway
Scenario D: Increasing capacity on subsea cables to Great Britain
Scenario E: High rationing price



Conclusion

From the analysis of the different parametrizations, increasing the number of scenarios proved to be superior for all datasets. Augmenting fuel prices has the highest significance for the North-European power market, leading to extremely high prices. Scaling up the capacity from Norway to Britain benefits Northern Europe due to relieving the system of bottlenecks, resulting in higher social welfare. When Norway is in scarcity, the area prices experience an increase. In this situation, removing the subsea cables will be detrimental, which is the opposite of the observations for Norway in surplus. It is clear from the results that the subsea cables have a fundamental role in the European system, lowering area prices and working as a security of supply for the Norwegian power system in critical times.

Influence of voltage frequency and rate of change on internal partial discharges

Student: **Magnus Normann Johannessen**
Supervisor: **Pål Keim Olsen**
Co-supervisor: **Espen Eberg**
Collaboration with: **SINTEF Energy Research**

Problem description

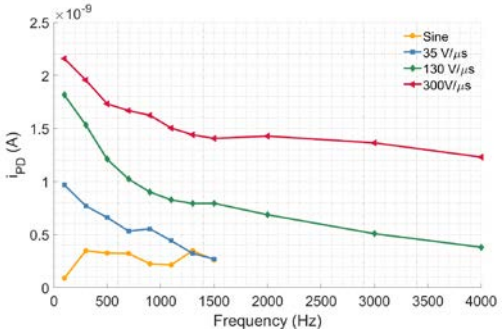
Internal partial discharges in electric machine insulation represents a significant source of degradation, ultimately leading to breakdown. High voltage machines are, to an increasingly degree, exposed to fast repetitive voltage pulses caused by transistor-switching in power electronic converters. An understanding of how such high-voltage pulses affects the behaviour of partial discharges is therefore necessary. The objective of this thesis is to investigate and explain how the behaviour of partial discharges are affected by high-voltage pulses with short rise times, compared with sinusoidal voltage.

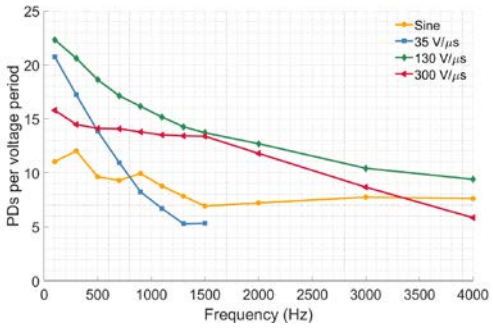
Model/ measurements

A partial discharge prediction model is developed that expands on the well-known capacitance model, in addition to experimental measurements performed on test objects with various void gap distances. Experiments are performed on mica-epoxy groundwall insulation with cylindrical cavities at voltages slightly above the inception voltage levels, and a high-frequency transformer connected to an oscilloscope is used to measure the discharges. The partial discharge characteristics of interest are the repetition rate and magnitude, as well as the phase-distribution of the discharges.

Calculation

As voltage frequency is increased, both the PD repetition rate and magnitude decreases when square wave voltage with various voltage rate of change is applied, while the results with sinusoidal voltage is observed to increase at certain frequencies. The PD magnitude, represented by the discharge current, is observed to be larger at a higher voltage rate of change, while the PD repetition rate is less dependent on the voltage rate of change in its numerical values. However, the rate at which the PD repetition rate decreases is observed to be lower at a larger voltage rate of change.





Conclusion

The experimental PD results show a clear dependency on voltage frequency and rate of change, and an implementation of frequency-dependent statistical time lag and remanent voltage is necessary to obtain similar results with the model simulations. With the values selected in the model, qualitatively similar results are achieved in the model and experimental results. However, a significant numerical difference is observed, which is mainly thought to stem from the simplifications made in regards to discharge types and changing void surface characteristics.

Image processing and machine learning application for fault diagnosis in synchronous motors

Student: **Markus Fredrik Johansen**
Supervisor: **Arne Nysveen**

Summary

Synchronous motor fault diagnosis provides insight into motor health and operational reliability. Diagnostic analysis is typically performed by examining changes in frequency components. This thesis presents an image processing and machine learning approach to detect faults in the motor automatically. The image processing method would use continuous wavelet transformation plots as input, generated on experimental and simulation data. The machine learning method, gradient boosting on decision trees, would use spatial and statistical image region descriptors as input. The effectiveness of the developed method produced a classification accuracy of 92%. The method is dependent on healthy data, but it is argued that with a more extensive sampling size, the method could become independent of healthy data and could potentially become applicable as a diagnostic tool in practical applications.

Estimating the dynamic current rating of power cables using the principle of superposition and transient temperature responses

Student: **Sondre Aslaksen Kaldheim**
Supervisor: **Erling Ildstad**

Problem description
As electric power consumption increases steadily and more renewable sources are being used to generate power, the available power grid needs to increase its capability and flexibility. Current rating of existing equipment is today determined by static ratings for worst case scenarios, leaving components such as power cables not fully utilized.

The task
This thesis proposes an estimation method that facilitates advancing the current rating of power cables from static to dynamic rating. The method uses two different procedures as basis, that has established transient and steady-state conductor temperature for given load and laying conditions. By using an applied scaling principle that corresponds to the change in load current, thus considering the thermal changes in the cable. As well as applying the principle of superposition. The total transient temperature response of the cable conductor during dynamic loading can be estimated. The estimate can then be utilized to enhance the current rating of the power cable.

Model/ measurements
By using an applied scaling principle that corresponds to the change in load current, thus considering the thermal changes in the cable. As well as applying the principle of superposition. The total transient temperature response of the cable conductor during dynamic loading can be estimated. The estimate can then be utilized to enhance the current rating of the power cable.

The first basis used in the estimation method is calculated conductor temperature according to international standards. The second basis uses a long-term established temperature measurement of the cable conductor with known conditions. The estimates are compared to a dynamic loading case, experimentally executed in a practical laboratory setup. The setup uses a Nexans TSLF 24kV 1x50 A power cable, that has an aluminium conductor with a cross-sectional area of 50 mm^2, and cross-linked polyethylene (XLPE) insulation.

Results
Results show that the estimates are able to give a realistic imitation of the experimentally measured conductor temperature response. The estimate based on measured temperature has the least average temperature deviation compared to measurement, which is 5.2°C. This estimate also has an additional scaling for the temperature dependency of the conductor resistance. Estimation based on analytical calculations only gives an adequate estimate when the change in conductor resistance is included, with an average temperature deviation of 8.3°C.

Conclusion
The simplicity and precision level of the developed method suggest that the applicability has potential to facilitate the current rating of power cables from static calculations to more dynamic considerations. Improving the utilization of the potential grid reserve not fully exploited in power cables.

Evaluation of available capacity in distribution grids

Student: **Robert Grindborg Karlsen**
Supervisor: **Olav Bjarte Fosso**
Contact: **Iver Bakken Sperstad & Susanne Sandell**
Collaboration with: **SINTEF Energy Research**

Problem description
The electricity grid, which enables the electricity transport of renewable energy from producers to consumers, has a central role in the green shift. However, an aging grid combined with the accelerating rate of electrification of the energy system is challenging the Norwegian distribution system operators (DSOs), and the increase in load demand is driving the need for grid upgrades and development. In addition to faster grid development, higher utilization of existing components and infrastructure will be crucial to meet the increased demand and the transition towards a green energy system.

The installation of Advanced metering system (AMS) infrastructure for all Norwegian electricity consumers has given the grid operators large amounts of new available data. This can potentially be used to improve the utilization of the existing grid, in order to reduce the costs of developing the grid, both for the DSOs and the electricity customers.

The task
The main objective of this master project has been to investigate how the smart meter load data can be used to provide better insight into the available capacity and potential for load increase in distribution grids.

In order to achieve this, three sub-objectives of the project are set as following:

- Propose a methodology for evaluation of available capacity in distribution grids.
- Evaluate the available capacity in the two radials of the industrial grid of Øra under normal operation and in outage situations, based on the proposed methodology.
- Evaluate the potential for connection of new end-users and increased load demand in the two radials of the industrial grid of Øra.

Model/ measurements
The work of this project thesis was based on smart meter data from two radials in the industrial distribution grid of Øra in Fredrikstad. The radials (Radial A and Radial B) are shown in Figure 1.

The analysis of load data presented in this thesis is based on a Python code developed by SINTEF Energy Research. The software performs loading, anonymization, preprocessing, modification and analysis of mass load and grid data. As a part of this master project, more functions regarding modification of the grid and analysis and presentation of the load data are implemented to the code.

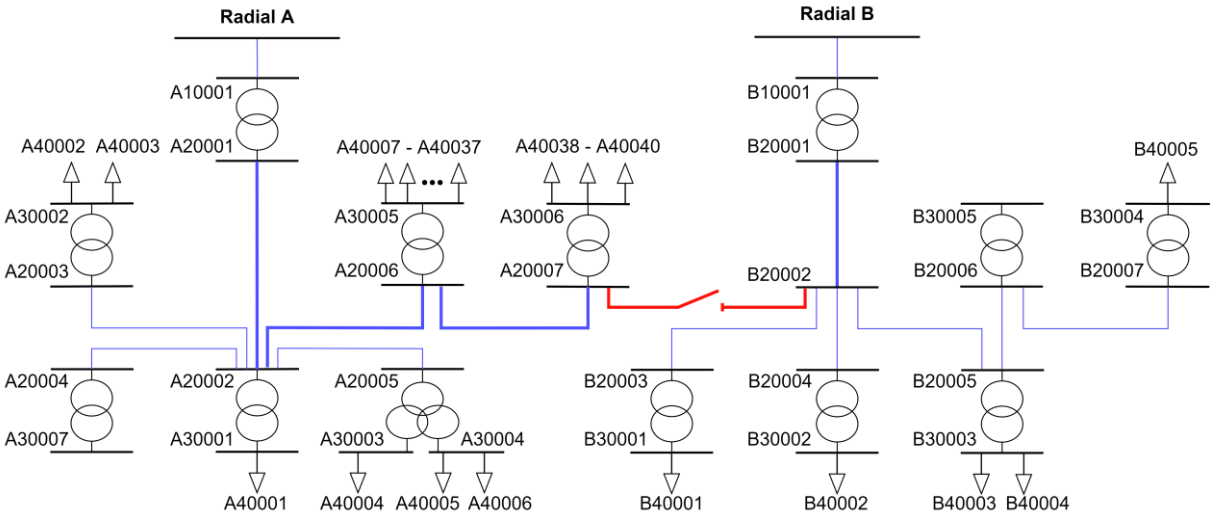


Figure 1: A simplified model of the two radials in the distribution grid of Øra.

Calculation

A methodology for evaluation of available capacity in distribution grids was proposed. The methodological approach can be used to provide better insight into the room for connection of new end users and increased load demand. The main focus of the approach is on the remaining capacity of the grid components during normal operation and during outage situations.

The methodological approach was utilized on the industrial distribution grid of Øra. The available capacity of the grid was evaluated for normal operation and for outage situations. In the coming years, electrification of industrial processes and connection of new power-intensive industries will possibly put pressure on the existing grid and challenge the DSO. Therefore, a scenario with increased load demand in the industrial grid was investigated, both for normal operation and for the most critical outage scenarios.

Conclusion

The results from the evaluation of the two radials in the industrial distribution grid of Øra can be summarized as following:

- Under normal operation, the ratings of the power lines and transformers in the two radials were, in general, sufficient to cover today's load demand, based on the historical load data from the last three years.
- Four relevant branches in the high-voltage part of the distribution grid, where the reserve branch can take over the supply in case of an outage, were identified. Further, an outage of one of the main branches, i.e., the branches connecting the distribution grids to the secondary transformer substations, was identified as the most critical outage scenario for this network. However, the contingency analysis showed that the system could handle an outage of any of the relevant branches without violating the power transfer capacities.
- For the future scenario, the historical aggregated load demand supplied by each distribution transformer in the grid was increased. The results showed that, under normal operation, the ratings of the power lines in the two radials were still sufficient to cover the new demand after the load modifications. However, during outage of the main branch of Radial A or the main branch Radial B, the line rating of the remaining main branch was exceeded. An outage of the main branch of Radial B was most critical in terms of the size and number of overload events.

Hybrid Slotless Permanent Magnet Machines as a Disruptive Solution for Electric Vehicles

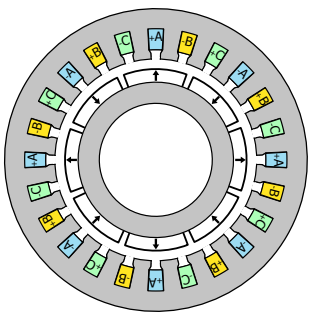
Student: **Andreas Edvardsen Killingberg**
Supervisor: **Jonas Kristiansen Nøland**
Contact: **Alexey Matveev**
Collaboration with: **Alva Industries AS**

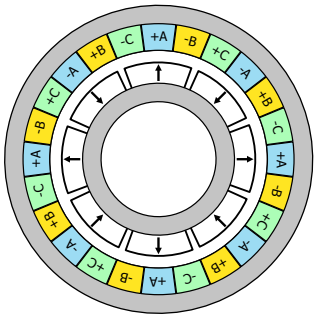
Problem description

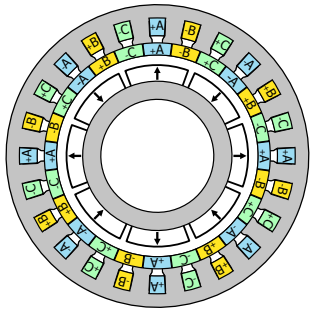
Slotted permanent magnet synchronous motors (PMSMs) have led to significant performance improvements in electric vehicles (EVs). However, the problems associated with the range of battery-powered EVs compared to conventional combustion engine vehicles are still a significant barrier hindering a large-scale adoption of EVs. As the world transitions from fossil fuel transportation to electric propulsion, the need for EVs with increased range becomes more evident. The key requirements for EV motors include 1) a high torque and power density, 2) a high starting torque, 3) a wide speed range, 4) a high efficiency, 5) low acoustic noise and 6) a low or reasonable cost. Investigation of a novel hybrid PMSM, which combines the stator design of a slotted and slotless PMSM, has indicated improvements in the torque density compared to slotless PMSMs, which can contribute to an extended range for EVs. However, the torque density should also be compared to slotted PMSMs, which have a higher torque density than slotless PMSMs. In addition, the remaining requirements for EV motors must also be considered.

The task

The objective of the master's thesis is to investigate the applicability of the hybrid PMSM for EV applications. The performance of the hybrid PMSM is compared to both slotted and slotless PMSMs, using the key requirements for EV motors as a basis for the comparison. The slotted, slotless and hybrid PMSM designs investigated are shown in the figure below.

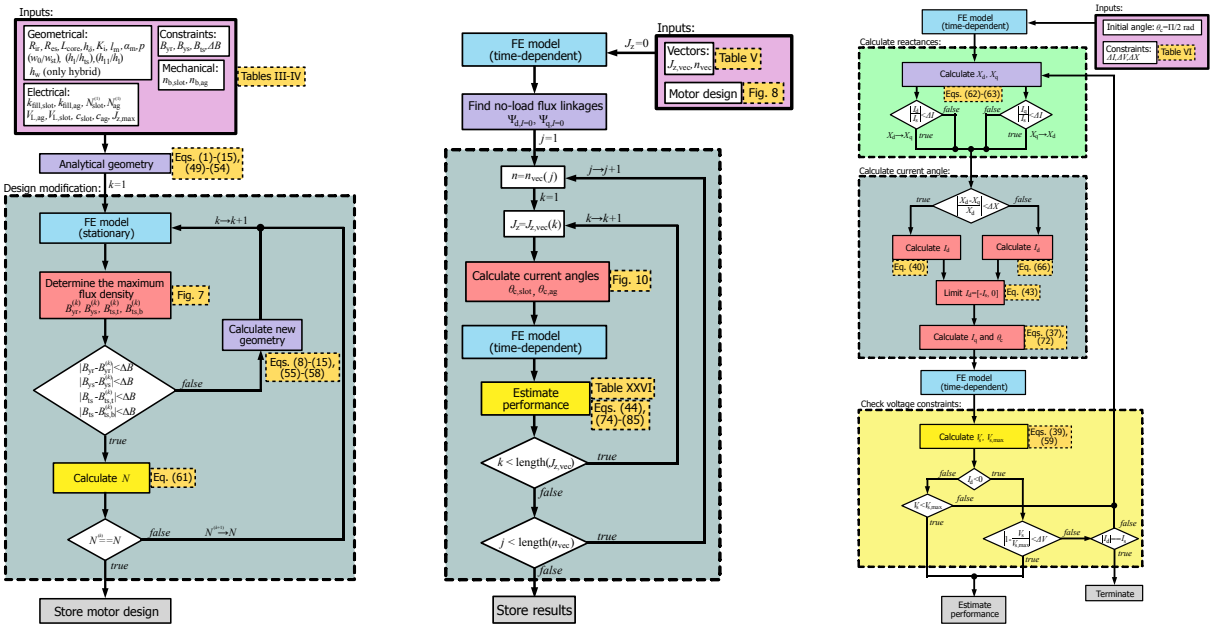

Slotted


Slotless


Hybrid

Model/ measurements

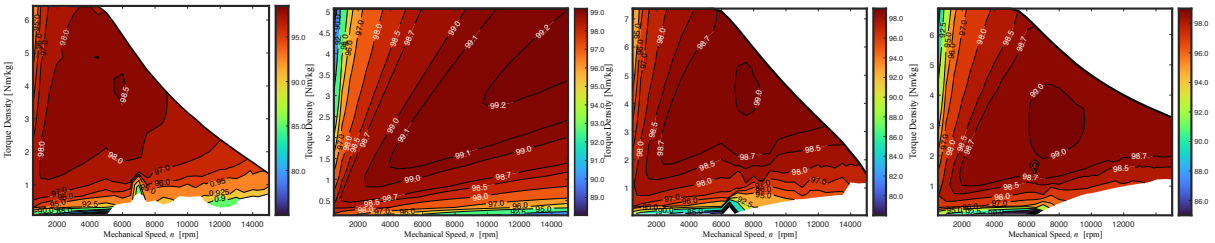
The design and performance estimation of the motors are obtained using a combination of the finite element software COMSOL Multiphysics v. 5.6 and MATLAB, communicating through Livelink. A finite element (FE) model for each of the PMSM variants is created. The designs are obtained by satisfying a fixed volume and specified flux densities in the steel core. The hybrid PMSM is investigated by varying the air gap winding thickness (AGWT). Two values are tested, 2 mm and 5 mm. The performance is found for mechanical speeds (n) and current densities (J) between 500-15000 rpm and 0.5-10 A/mm^2, respectively, using a base speed of 5000 rpm as the point where field weakening initiates. The methods used in this thesis can be summarised by the figures below.



Design Performance estimation Field weakening

Calculation

The results show that hybrid PMSMs can achieve a higher peak torque density than both slotted and slotless PMSMs. However, the field weakening capability of the hybrid PMSMs is limited, similar to slotless PMSMs. Moreover, a reduction of the steel loss, magnet loss and torque ripple are identified, while the resistive loss for hybrid PMSMs is higher compared to slotted PMSMs. The efficiency maps indicate that hybrid PMSMs can improve the range of EV applications operating at lower and higher speeds. Finally, the results indicate a higher cost for hybrid PMSMs. The efficiency maps for some of the designs investigated in this thesis are shown below.



Slotted Slotless Hybrid (2 mm AGWT) Hybrid (5 mm AGWT)

Conclusion

The results suggest that employing hybrid PMSMs can result in multiple improvements compared to slotted PMSMs, indicating a high applicability of hybrid PMSMs for EV applications. However, fewer improvements are expected when the entire EV drive is considered. In addition, the expected increase in cost can hinder the adoption of hybrid PMSMs in favour of slotted PMSMs. Further work comparing the performance of the complete EV drive is required to determine the applicability of hybrid PMSMs for EV applications completely.

Forces and vibrations in a\Modular HVDC Generator

Student: **Klop, Casper Leonard**
Supervisors: **Keim Olsen, Pål and Dong, Jianning**

Summary

Offshore wind energy is expected to play a major role in the upcoming energy transition. For long distances to shore, it is preferable to connect the wind farms to land by means of High-Voltage DC (HVDC) cables to reduce losses and costs. This currently poses challenges, as wind turbine generators produce variable low-voltage AC power, which needs to be converted to HVDC with heavy transformers in the wind turbine nacelle and large offshore substations. One proposed solution is to develop integrated drives which produce HVDC directly inside the nacelle, by segmenting the stator of a direct-drive generator. Each segment has its own dedicated Power Electronic (PE) converter, of which the DC output is connected in series.
This thesis studies one of the challenges of this Modular HVDC generator concept: the segmented stator generates additional vibrations in the structure, and will respond differently to the occurring forces than a stator without segmentation. The goal is to design a concept for the structure that holds the segments in place, while still allow individual modules to be replaced after failure.
As a first step, the machine design updated taking into account saturation and design limits which were neglected in previous studies. For a 10 MW Direct-Drive generator with an output DC-link voltage of 100 kV, a 10 m diameter inner-rotor Permanent Magnet Synchronous Machine with Fractional-Slot Concentrated Windings (FSCW) is designed. It has 384 slots and 320 poles, and the stator is split in 16 segments. The design is verified with Finite-Element simulations in COMSOL.

Secondly, the electromagnetic effects of the flux barriers created by the insulated gaps between the segments are analyzed analytically and numerically. The analytical model of the magnetic fields and forces agrees well with the numerical simulations in COMSOL. The FSCW result in a broad spectrum of vibrations, including the slot harmonic caused by the open slots. Segmentation of the stator has two important consequences: the addition of low spatial order radial harmonics at multiples of the number of segments, called the segment harmonics, and an increase in the cogging torque. These effects are more pronounced in the numerical simulations than in the analytical model, due to the change of the magnetic flux distribution in the segmented stator, which is neglected in the analytical calculations. Furthermore, time harmonics in the current due to the PE converters are found to significantly increase the breathing mode and torque ripple.

Thirdly, the mechanical response of two different design concepts has been analyzed by performing a modal analysis. The first design uses an interference fit, where the segments are pressed into the frame and held in position by friction. This design behaves similarly to a ring-shaped frame, and has the same eigenmodes at similar eigenfrequencies. The second design uses beams between the frame and stator to support the segments. In this case, the stiffness and structural integrity of the design is significantly reduced, leading to larger deflections and lower eigenfrequencies.

Combining the obtained forces and eigenmodes, the breathing mode, the segment harmonics and the slot harmonics are concluded to cause the strongest vibrations. The amplitude of the forces causing the first two is low, but the mechanical stiffness of these modes is low and the excitation frequency is close to the eigenfrequency. The slot harmonic is mainly important due to the low spatial order and large amplitude of the force, caused by the combination of concentrated windings and open slots. The PE converter harmonics will not lead to a stronger breathing mode vibration due to the high switching frequency of the converters, but could create resonance of the slot harmonic.

Based on these results, both designs were found to be feasible from an electromechanical perspective, as long as care is taken to mitigate the vibrations caused by the segment harmonics, and resonance of the PE converter harmonics is prevented. Due to the uncertainty of the mechanical model, experimental validation of the eigenfrequencies and the vibration levels is recommended, which can be done by using modal analysis.

25 MW Permanent Magnet Synchronous Generator for Two-way Working Tidal Turbines

Student: **Sageeban Krishnasothy**
Supervisor: **Robert Nilssen**
Contact: **Arne Kollansrud**
Collaboration with: **Tidetec AS**

Problem description

Tidetec is currently working on a rotating turret used at a tidal range power plant. The turret is a two-way working turbine that improves the efficiency of the most cost-effective tidal turbine technology by securing optimal efficiency both ways. The turning mechanism is patented and has received international recognition. This thesis will provide an overview of properties and challenges regarding scaling up a machine worked in the specialisation project. This machine will be scaled up to produce 25 MW of power at a rated speed of 53 rpm.

The task

there will be various slot options for the scaled up machine where output values, and losses will be compared. Two of the machines has a distributed winding configuration with a double layer layout, and three of the machine has a concentrated winding configuration, while one of them has a single layer layout.

Model/ measurements

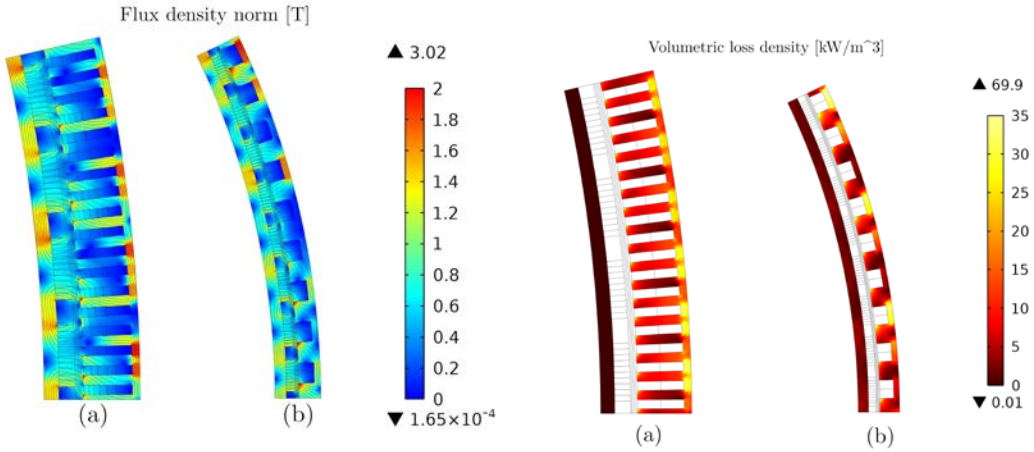
The analysis was managed through the 2D finite element method (FEM) in COMSOL multiphysics. The machine is scaled after a generator delivered from Indar that will be used on a rotating turret provided by Tidetec. The machine has a rated speed of 53 rpm, and that gives an electrical frequency of 49.467 Hz. From the frequency value, the number of poles will be 112. In this thesis, there will be several machine designs with different slot numbers. The slot options are given in the table below.

Table 1: Amount of slots in the stator

Slots	Winding configuration	q	Layers	numbering
504	Distributed	1.5	Double	machine nr. 1
336	Distributed	1.0	Double	machine nr. 2
126	Concentrated	0.375	Double	machine nr. 3
120	Concentrated	0.357	Double	machine nr. 4
126	Concentrated	0.375	Single	machine nr. 5

The steel used in the rotor and stator is a non-gran-oriented (NGO) M400-50A is chosen because of the low loss. The magnets where a NdFeB magnets of grade N45. Each coil consists of copper windings, and conductivity was assumed to be constant and not change with temperature.

Calculation



From the flux density norm figure, the flux density was highest at the tip of the stator, which is about 3.02 T. The flux density value around the teeth for machine 1 was around 1.14 T and 1.05 T for machine 3. Around the yoke, the highest flux density was around 1.75 T for machine nr. 1 and 3. Rotor area, the value was around 1.4 T for machine nr. 1 and 3.

Table 2: Torque

Machine	Maximum Torque [kNm]	Minimum Torque[kNm]	Average Torque [kNm]	Torque ripple [%]
1	4872.6	4450.1	4677.5	9.032
2	5210.0	4186.7	4677.5	21.88
3	4755.9	4559.6	4677.5	4.20
4	4744.3	4605.4	4677.5	2.97
5	4722.7	4634.8	4677.5	1.88

machine nr. 5 has the lowest torque ripple at 1.88%, and machine nr. 2 has the highest torque ripple at 21.88%. It is clear to see that the machines with concentrated winding have lower torque ripple than the machines with distributed. Since every single machine has an average torque of 4677.5 kNm, the average mechanical output power will be at 25961 kW.

From the Volumetric loss density figure, most of the losses occur at the tip of the machine's teeth and around the stator yoke. The total loss calculation and efficiency can be seen in table below.

Table 3: Total loss at full load

Machine	Mechanical Power[kW]	Iron losses [kW]	Copper losses [kW]	Magnet losses [kW]	Output power[kW]	Efficiency [%]
1	25961	27.312	257.74	13.102	25579.84	98.85
2	25961	18.402	212.8	38.24	25645.92	98.96
3	25961	23.794	165.68	120.44	25569.49	98.81
4	25961	20.295	163.97	128.18	25584.33	98.80
5	25961	86.255	165.68	118.98	25216.76	98.57

Conclusion

Since machine nr. 2 had a high torque ripple, and machine nr. 5 had the highest losses, machine nr. 1, with q equal to 1.5, and machine nr. 3, with q equal to 0.375, are the options that should be considered.

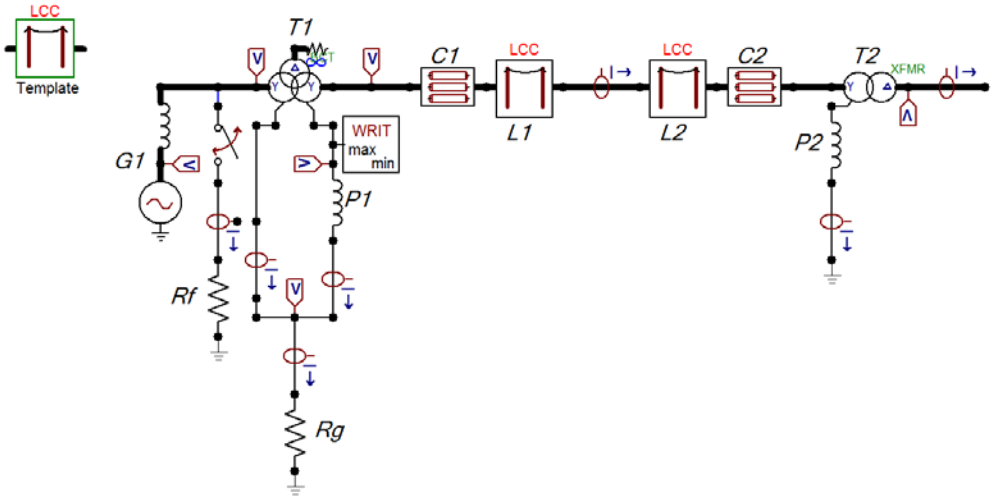
Temporære overspenninger i spolejordede nett på grunn av overført spenning gjennom transformator

Student: **Maren Malm Landsem**
Veileder: **Bjørn Gustavsen**
Medveileder: **Hans K. Høidalen**

Problemstilling
Spolejording er en jordingsmetode som er mye brukt i norske regionalnett. Spolen monteres mellom nøytralpunktet og jord for stjernekoblede transformatorer. Ved enfase jordfeil vil spolen kompensere for den kapasitive feilstrømmen og sørger dermed for en sikker selvslukking av lysbuen. Dette gir betydelige fordeler som lave feilstrømmer og nettet kan driftes videre uten frakoblinger. På den annen side er spolejordede nett utsatt for temporære overspenninger. I resonanspunktet, hvor spolen er perfekt justert mot nettets kapasitans, vil nøytralpunktspenningen øke betraktelig. Disse overspenningene er et resultat av ulike forhold, deriblant fasebrudd og jordfeil. Dette er et kjent problem og NVE har erfart at det er flere utfordringer knyttet til spolejording. Med en økende elektrifisering av samfunnet er spoler og innstillingene av disse et sentralt tema for å sikre at nettet kan håndtere feilsituasjoner.

Oppgaven
Hensikten med denne masteroppgaven er å betrakte ulike overspenninger som kan inntreffe i et spolejordet nett ved enfase jordfeil i overliggende direktejordet nett. Oppgaven er avgrenset til å studere temporære overspenninger på grunn av overført spenning gjennom transformator og tilhørende jording. Det finnes mye litteratur rundt oppbygging og virkemåten til en transformator, derimot er det færre studier som undersøker transformerte overspenninger som følge av jordfeil i overliggende nett. Denne masteroppgaven tar for seg flere spørsmål som til sammen skal gi en bedre forståelse av overført spenning gjennom transformator.

Modell/målinger
For å undersøke jordfeilstrømmer, spenninger og resonanskurver har ulike modeller blitt etablert i simuleringsverktøyet ATP, deriblant figur 1. Det ble brukt en funksjon kalt "WRITE MAX/MIN" til å finne resonanskurven. Dette er en viktig funksjon som punktvis kan plotte spenningen slik at man får den karakteristiske resonanskurven. Kretsene i ATP er designet for å avklare hvilke forhold som påvirker overført spenning gjennom transformator. Modellene fungerer til sitt formål og det ble prioritert å bruke mye tid på å verifisere modellene slik at resultatene er pålitelige. Det ble valgt å studere enkle kretser for å oppnå god innsikt i virkemåten til spoler og transformatorer. Komponentene i kretsene er valgt med hensyn på funksjonalitet. Spolene er dimensjonert ved bruk av variabler og man kan selv endre på spoleinnstillingene etter eget ønske. Transformatoren er basert på faktiske verdier, hvor benyttet data er hentet fra en anonymisert testrapport. Den etablerte transformatoren i ATP (BCTRAN-modell) er kvalitetssjekket med testrapporten for å sørge for korrekt implementering av nullsekvensimpedansen. I tillegg til programvaren ATP har MATLAB blitt benyttet som beregningsverktøy slik at man enkelt kan justere variabler og studere nullpunktspenningen som funksjon av kompenseringsfaktor og fordeling av spolestrøm.



Figur 1: Utarbeidet nettmodell i ATP for undersøkelse av overspenninger i forbindelse med enfase jordfeil.

Beregninger

Resultatene viste at for å oppnå en lav nullpunktspenning kan man inkludere en konduktiv avledning. Dersom man doblet wattstrømmen ble resonanstoppen halvert som følge av dempingen til konduktansen. Det ble også observert at resonanspunktet ikke forflyttet seg selv om man endret den konduktive avledningen. Konduktansen vil kun bidra til å dempe nullpunktspenningen.

Modellen som er laget i ATP inkluderer to spoler for å undersøke hvordan fordelingen av spolestrøm påvirker nullpunktspenningen. Resultatet illustrerte at jo lavere spolestrøm spolen nærmest feilstedet kompenserte for, desto lavere ble nullpunktspenninger. Det er altså fordelaktig med en lav spolestørrelse dersom det oppstår jordfeil i overliggende nett. I en kobling fra 300 kV til 134 kV-nett kan man få magnetisk og galvanisk overført spenning i forbindelse med enfase jordfeil på 300 kV-siden. Uavhengig av verdien på motstanden mot jord ble det konkludert med at spenningsoppsvinget hovedsakelig skyldtes den magnetiske koblingen gjennom transformatoren. Manglende potensialheving av stasjonens jordingssystem i forhold til fjern jord gjorde at man ikke fikk galvanisk overført spenning til 134 kV-siden.

Konklusjon

Resultatene i denne masteroppgaven kan brukes til å danne en generell anbefaling for planlegging og drift av spolejordede nett. Undersøkelsene viser at det er flere forhold en bør ta hensyn til for å sikre at nettet håndterer feilsituasjoner. Plassering av spoler og innstillingene av disse er et sentralt tema.

Investigation of series connected SiC MOSFETs in a low inductive layout

Student: **Kjetil Langelid**
Supervisor: **Dimosthenis Peftitsis, NTNU**
Co-supervisor: **Tobias Nieckula Ubostad**, **NTNU**

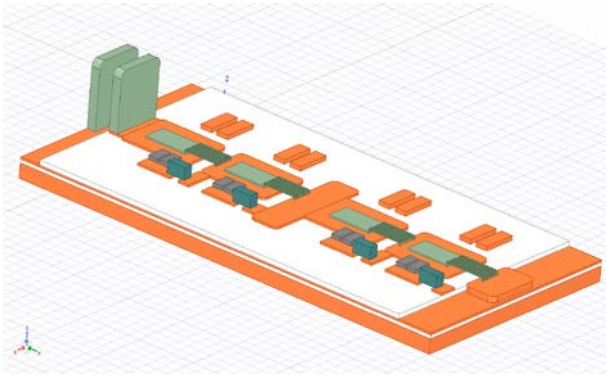
Problem description
Silicon(Si) devices have dominated the world of power electronics in the last decades but are unable to deliver sufficient performance for high power, high frequency, and high temperature applications. Wide bandgap power semiconductor devices, such as the Silicon Carbide (SiC) MOSFET have started to gain significant importance in the applications where such performance is required. However, the maximum voltage ratings of commercially available SiC MOSFETs is still only 1.7 kV.

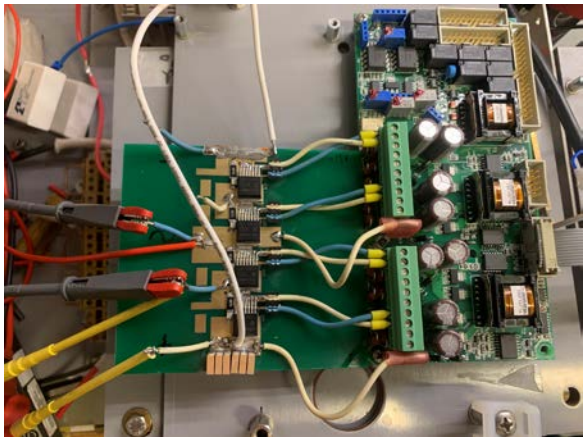
Series-connection of several SiC MOSFETs is an efficient way to increase the system voltage by using low voltage devices. It is cost effective and shown to increase the efficiency. However, there are two main problems related to the series connection: unequal voltage distribution among the serialized devices due to device parameter mismatch and Common Mode (CM) current caused by the fast switching of the devices which can circulate in the control part through isolation barrier. Another problem is excessive stray inductance in the power path which leads to overvoltage and oscillations.

The task
The objectives of this thesis is briefly summarized in the following statements:

1. Develop and investigate new power semiconductor packaging designs through simulations in finite element method (FEM) software.
2. Find critical design points in the packaging and examine their effect on the performance, as well implementing new solutions to overcome existing challenges.
3. Look into efficient solutions for driving series-connected devices

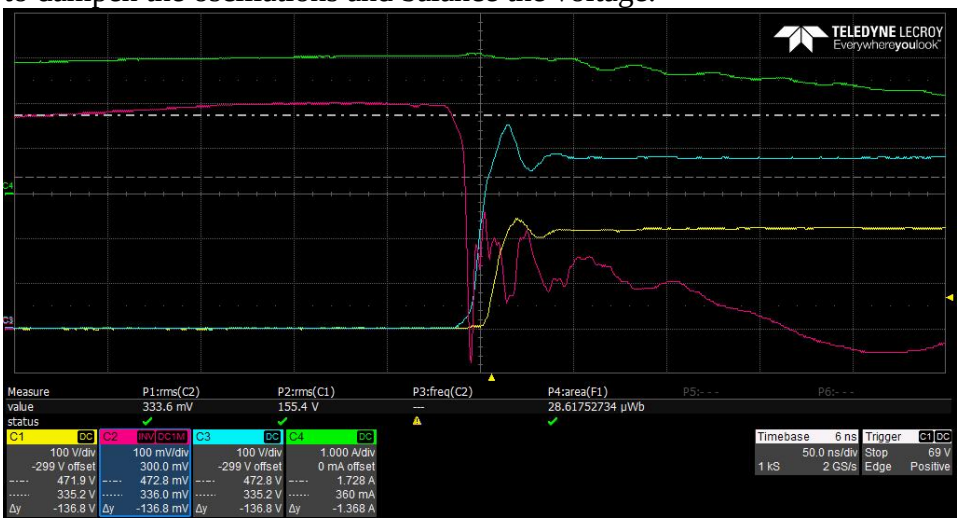
Model/ measurements
The 3D model of one of the designed power modules are shown in the picture below on the left. The same power module was designed in a circuit design program and fabricated to test at a lab and the setup is depicted in the picture below on the right.





Simulations and measurements

In the picture presented below, the voltage distribution over the series connected transistors are shown. The voltage distribution is unbalanced even though large RC snubbers are utilized to dampen the oscillations and balance the voltage.



In the table below, the inductance of the positive path(top layer of the DBC) and the return path(copper layer under the substrate) are shown together with the total loop inductance of the power module. The total inductance is significantly reduced due to the mutual impedance caused by the magnetic field cancellation between the positive and negative path.

Electrical path	Inductance(nH)
Positive path	40.029
Return path	25.739
Total loop inductance	9.489

Conclusion

The stray inductance of the power path was significantly reduced, due to the magnetic field cancellation effect, as the overlapping current paths were moved close to each other. Utilizing the magnetic field cancellation phenomenon resulted in the effective power loop inductance being reduced by 85% for the power module design presented.

The electrical field strength simulations, together with the thermal simulations, showed that an even more compact layout could be made to even further lower the inductance. Results showed there would be no voltage breakdowns between the different voltage potentials, and the thermal resistance was found to only increase by 2.3% when the copper islands of the DBC were moved closer to each other. Rounding the edges of the DBC should always be done in power modules, as the electrical field strength was reduced by 82% when the sharp edges were rounded.

In the lab experiments, the inductance of the layout was found to be 10.2nH, which is pretty accurate compared to the layout inductance, which was found to be approximately 9.8nH at higher frequencies. Achieving an even voltage balance over the series connected transistors proved to be very difficult due to the high accuracy required. Only a time delay between the gate drivers of 2-3ns resulted in an uneven voltage balance. Manually tuning of the gate circuit could be performed to gain an even voltage balance. However, manually tuning is not realistic if the power modules are mass manufactured.

Use of FEM in design program for hydropower generators

Student: **Leite, Asgeir**
Supervisor: **Nysveen, Arne**

Summary

Design of hydropower generators is a difficult optimization problem. Generators are normally designed using a calculation program. The designer gives all geometrical and physical parameters of the machine, and then the program calculates the performance and machine parameters. For the most part, the dimensions have to be guessed and adjusted until an analysis gives the desired result. Companies that have a lot of experience with generator design often develop a so called in-house manufactures "secret" formulas used to ease the design procedure.

At our department, we are developing a program of this kind based on open and free sources called GenProg. The core script first developed almost 10 years ago is based on a design procedure of a typical salient pole generator ranging from 10 to 50 MVA. GenProg uses several key parameters obtained from the customer needs to return every parameter describing a complete generator.

This project will expand the accuracy and quality of the program. The main goal is to include COMSOL for more accurate calculations of parameters and increased understanding of the design process. A considerable effort has been made to understand the core script in order to adapt and create the COMSOL models incorporated with the program. The program is planned to be used in various courses in electric machines and also to be made public as part of the results from the research center Hydrogen.

The newest version of GenProg numerically solves for to conditions, Dynamic and Static. The Dynamic condition is time dependent and simulates a rotating machine that results in a study of flux density and voltages. The Static condition simulates for two time instances, maximised MMF in d-axis and q-axis. This results in a study of flux density and synchronous reactances for both d-axis and q-axis current.

GenProg creates a user friendly learning environment with visual interactions required for this trial and error analysis that is needed in order to achieve desired results. The numeric solutions calculated from COMSOL are more detailed and accurate than the analytical part of GenProg. Flux density values are quite similar, but the visual map of flux density from COMSOL offers far more information for the user. Simplifications in the GenProg script creates a big differences in reactance values, thus indicating more accurate value from COMSOL. There are still several analytical parameters to numerically calculate with COMSOL, however with the COMSOL models as groundwork simply time is needed before more are implemented.

Techno-Economic Analysis of Rural Microgrid at Eco Moyo Education Centre in Kenya

Student: **Kari Thorset Lervik and Anja Myhre Waitz**
Supervisor: **Steve Völler**
Contact: **steve.voller@ntnu.no**
Collaboration with: **Engineers Without Borders**

This master thesis is a Master with Meaning (MmM) written on behalf of Engineers Without Borders (EWB) Norway in the Spring 2022. The thesis addresses the electricity supply at the primary school Eco Moyo Education Centre in Kenya. The school needs reliable electricity supply, and it is desirable to use renewable energy sources for the electricity production. The purpose of the master thesis is therefore to propose a system design for a microgrid supplying electricity to the school from renewable energy sources. Off-grid solutions supplied by PV panels and batteries are the main focuses.

As a part of the master thesis, fieldwork at the school was conducted in March 2022. The main purpose of the fieldwork was data collection about the electricity demand and buildings at the property. The fieldwork was important for understanding the possibilities and limitations for future systems for electricity supply at the school, and thus to set the project boundaries for the master thesis.

The bottom-up stochastic model «Remote-Areas Multi-Energy Systems Load Profiles (RAMP)» is used to establish minute based annual load profiles for the school. This modelling tool is chosen based on its high performance, as well as due to the inaccuracy related to data collected from user surveys and interviews. RAMP model input are constructed for each building at the property, and both seasonal and weekly variations are accounted for. The load profiles should account for future developments at the property, and hence the buildings that are expected to be built in the next few years are also included in the model input.

The buildings at the school is currently organized in clusters. Based on preferences defined by Eco Moyo, as well as experiences from the fieldwork, system solutions with separate systems for each cluster is evaluated, referred to as a clustered solution. This clustered solution is compared with a system solution where the whole property is supplied by one system, referred to as a non-clustered solution. Load profiles are therefore constructed in RAMP for each individual cluster, as well as for the non-clustered solution.

To obtain the proposed system solutions simulations are conducted in PVsyst. The proposed system topology is an off-grid AC coupled microgrid supplied by PV panels and lithium-ion batteries. Load profiles are used as input to the off-grid PVsyst simulations for each cluster and the non-clustered solution. System solutions are decided based on the simulation results in PVsyst. Investment costs, autonomy, and load coverage are considered important parameters when determining these system solutions. Other project specific considerations are also used for the decision making of the final system solution proposal. For comparative purposes back-up solution evaluations with diesel generators and grid-connection are also performed.

It is concluded that both system solutions for clustered and non-clustered solutions offer high performances, and acceptable investment costs. However, a clustered solution allows for gradual expansions in accordance with available funding, when building projects are realized, and when more electricity supply is needed at the school. Due to this main advantage, as well as other advantages, the clustered solution is found to provide the optimized system solution for electricity supply at Eco Moyo Education Centre.

Grey-box modelling of a domestic hot water tank to be used for flexibility services

Student: **Erlend Magnus Løvstakken**
Supervisor: **Karen Byskov Lindberg**
Contact: **Karen Byskov Lindberg**
Collaboration with: **Sintef**

Problem description

Make a model of an EWH and estimate unknown parameters by using gray box modelling.

The task

The task presents relevant theoretical background on electric water heaters, power consumption habits in a Norwegian scenario, grid tariff structure, flexibility and data communication systems. It also presents a literature review of gray box modelling, previous work on parameter fitting and previous work on flexibility of EWHs. The experimental part of the task is to perform experiments on the water heater at the NTNU Smart House Lab to obtain temperature and power profiles. These measurements are performed to be able to fit unknown parameters by using gray box modelling. The fitted parameters are compared with equivalent parameters of previous and others work on the topic.

Model/ measurements

The measurements are performed on the water heater located in the NTNU Smart house laboratory. 6 temperature sensors, water flow meter and a power meter are fitted to the water tank. Three temperature sensors are located "inside" the tank. These are referred to as upper, middle and lower temperature sensor. Figure 1 shows the electric water heater with the installed equipment. By using LogicMachine and ELOG 15 interfaces, temperatures and powers are collected and gathered in an CSV-file. Three different Experiments are performed to test different scenarios. Case 1 checked the water heater in steady state without water draining. Case 2 and 3 are experiments where water is drained from the tank. By modelling the water heater as three different RC-circuit and using CTSM-R unknown parameters are estimated. The best model was decided by looking at one-step-ahead plots, simulated-value plots, RMSE and LogLikelihood value. Figure 2 shows the 3R3C-model of a water heater.

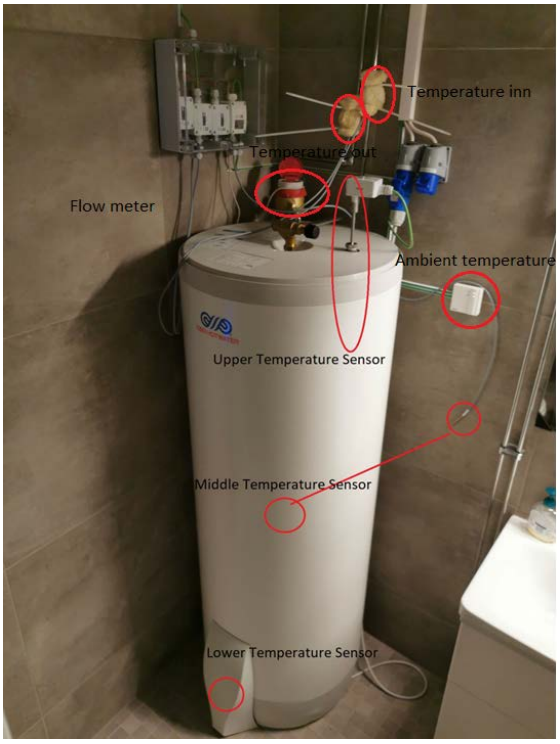


Figure 1: Water heater and installed equipment

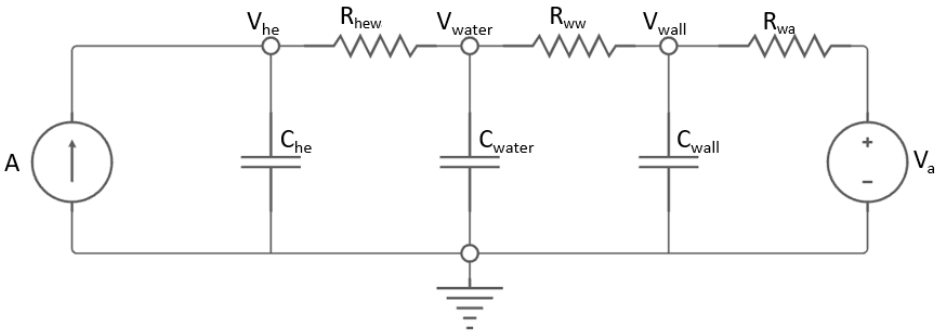


Figure 2: RC-equivalent of an EWH

Calculation

There are differences in the measurements and parameter fittings. The lower temperature sensor gives poor measurements. The upper and middle temperature sensor gives better results. The middle sensor was chosen as main sensor as it gives the best results. For steady state the resistance is estimated to be 355.17 °C/kW and the capacitance is estimated to be 0.3173 kWh/°C For the dynamic case the estimated resistance is 170 °C/kW and the estimated capacitance is 0.3 kWh/°C.

Conclusion

By looking at one-step-ahead plots, simulated-value plots, RMSE and LogLikelihood value the 3R3C-model as shown in Figure 2 is decided to be the best model. Figure 3 shows the simulated-value plot pf Case 3. By comparing the estimated parameters with other research papers, it is observable that the measurements are a lot better during this thesis compared to the project thesis. New equipment and improved lab-setup gives better results and the model is improved.

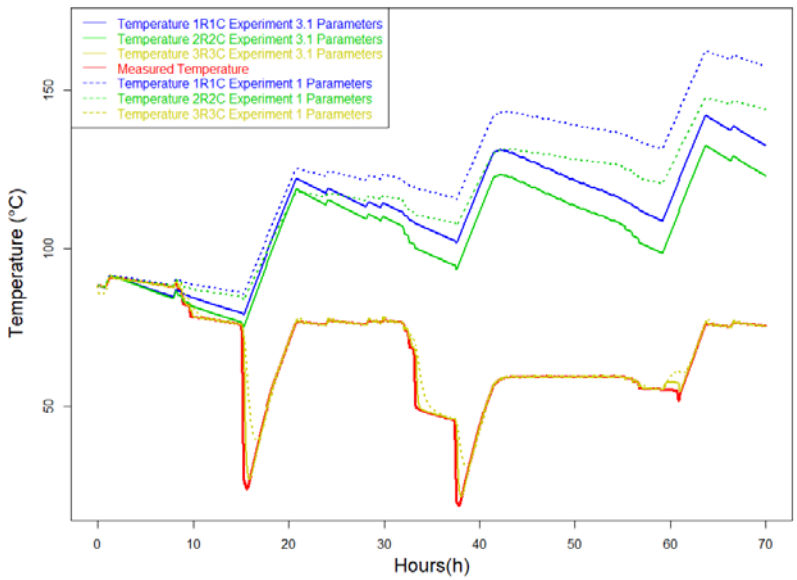


Figure 3: simulated-value plot of Case 3.1

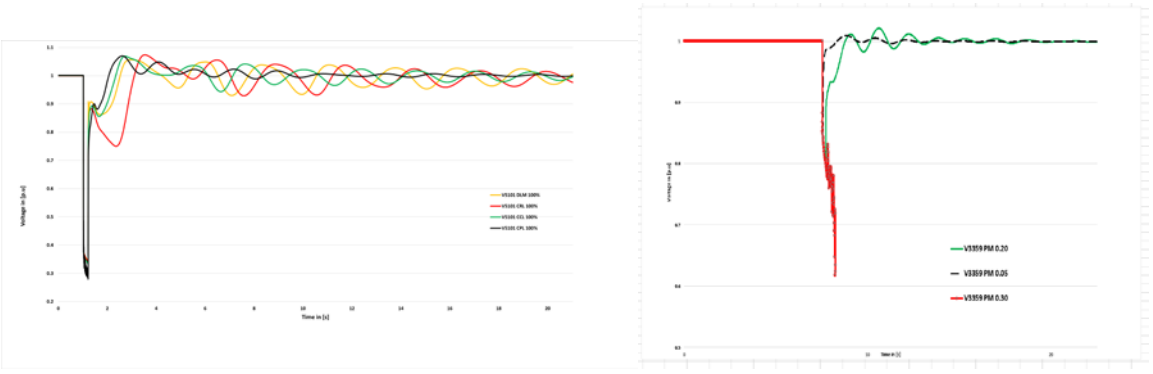
Future Operation and Control of Power Systems- Laboratory Models and Real-Time Simulation

Student: **DANIEL WELDAI, MESGENA**
Supervisor: **KJETIL UHLEN**
Contact: kjetile.uhlen@ntnu.no

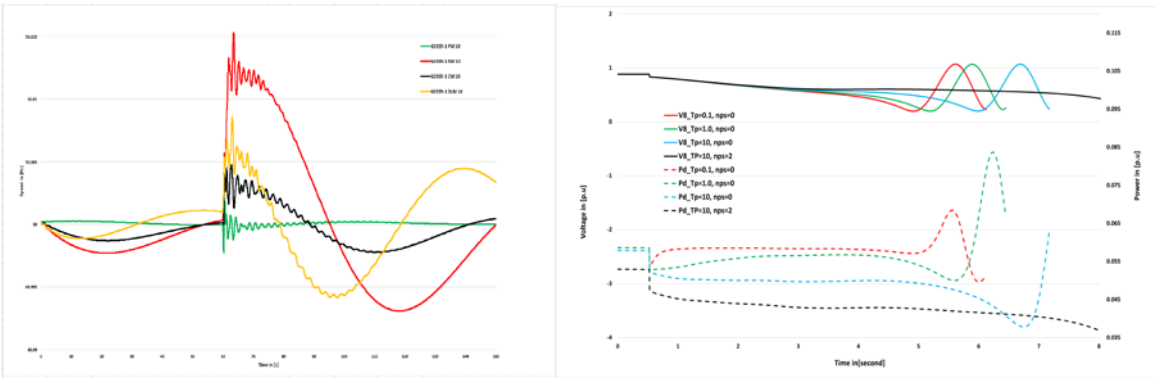
Recently, growing electrical energy demand and increasing integration of renewable energy sources in power system have led to new challenges for the transmission system operators and the network planning step. Besides, flexible load and increasing energy consumption also have problem in the stability of the power network. Thus, power systems are becoming heavily stressed, operating more and more often close to their stability limits. This situation makes the system vulnerable to any disturbances that might occur. One way of controlling those sudden changes in the network is by real-time digital simulation and accurate dynamic load model. This is to provide a response at exact time to return the system stability.

The aim is to study the effects of the load models on the voltage stability and power oscillation. Power systems are expected to become more heavily loaded in the next decade as the demand for electric power rises. Consequently, power systems are closer to their stability limits and voltage collapse, blackouts will occur if suitable monitoring and control measures are not taken. Therefore, it is very important to understand the mechanisms of voltage collapse so that voltage collapse blackouts may be effectively prevented. The goal of this thesis is to produce accurate dynamic load model in real-time simulation.

A realistic dynamic load model is developed and implemented in the Python Dynamic Power System Simulation (DynPSSimpy), developed by PhD student Hallvar Hauglad at the Norwegian University of Science and Technology. By trial-and-error method, it can be checking the critical clearing time of different load models, while the damping ration and natural frequency was utilized by participation factor.



In the short circuit scenario, different load models provide various simulation results on the power system as shown in the following figure. It indicates that the system was leading to voltage collapse at different recovery time and load exponents on small network, whereas on the large network has shown different damping ration and power oscillation regarding to load models.



The impact of load model parameters on system dynamics is qualitatively investigated based on the voltage stability and transient stability limits. During the transient periods, one key driving force for instability is the tendency of dynamic loads to restore their consumed power within a very short time frame. Thus, different load models can result in contrary stability statues. From the simulation result observed that constant power load was the severe situation, and it has the negative incremental resistance and can lead to instability or unacceptable oscillation response. Moreover, load recovery was influenced by the steady-state, transient and by recovery time constant. Therefore, without an appropriate representation of dynamic load models, the voltage stability or transient stability margin may not be able to maintain the system stability if the contingency really occur.

Analyzing the impact of increased electric vehicle penetration on cost and grid burden with bidirectional charging and solar energy production

Student: **Morsund, Balder Bryn**
Supervisor: **Lindberg, Karen Byskov**

Summary

The Norwegian government has set a target for all new personal vehicles sold in Norway to be zero-emission from 2025. This will lead to a significant increase in the number of electric vehicles. When the electrical car fleet expands, the energy demand of the transport sector and energy demand overall increases. This thesis answers how different grid tariff models, bidirectional charging with V2G, solar energy production, and energy meter locations impact the total cost and grid burden for an apartment block in Risvollan with 117 apartments and 70% EV penetration. The increase in EVs leads to smart and controlled charging rapidly emerging as a relevant topic. The question then arises about incentivizing controlled charging to avoid costly grid reinforcements. In the thesis, the Pyomo-based modeling tool BUTLER is adjusted to optimize the operational stage of the apartment block with bidirectional charging. The model has complete information on the future, optimizing for 2018, with measurement data for the apartment electricity load from Risvollan and EV charging session information for 82 EVs across Norway. A peak per monthly penalty tariff model leads to a decrease in maximum peak load 39% lower than uncontrolled charging. The peak load burden is negligible compared to having no EVs, thereby removing the need for grid capacity reinforcements due to higher EV penetration. On the other hand, solely having energy pricing tariffs leads to an increase in the maximum peak of up to 44% compared to uncontrolled charging. The amount of energy discharged by the EVs was generally low, but it occurred at the morning and afternoon peaks, thereby cutting costs and grid burden. The maximum income per kWh discharged from the EV achieved in a case is 0.69 NOK, reducing the total costs by 0.45%. The amount discharged on average per EV was far below what is considered to cause more than negligible capacity reduction on the EV batteries. Using the EVs as energy storage with bidirectional charging further increases the effectiveness of the solar panels, increasing the yearly self-consumption to 82%, from 72% without bidirectional charging. Having a separated energy meter for the apartments and the garage with peak per month tariffs leads to a flat charging profile over the day due to the flexibility of the EV charging, but when aggregated with the apartment electricity load, it leads to an overall increase in grid burden. This suggests that looking at EV charging load and apartment electricity load together can decrease the grid burden.

Voltage distribution in medium voltage machines for aerospace applications fed by power converters

Student: **Per Henning Hammerstad Møllevold**
Supervisor: **Pål Keim Olsen**
Contact: **Njål Rotevatn and Viljar Fjellanger**
Collaboration with: **Rolls-Royce Electrical Norway AS**

Problem description

An important factor for the development of all-electric aircraft (AEA) is the design of electrical machines. Today's trends suggest medium voltage DC power systems are advantageous compared to medium AC power systems in AEAs. The standard is 540V DC (±270V), however, voltage levels in the kV range are now being suggested. The emerging wide-bandgap (WBG) semiconductors such as Silicone Carbide (SiC) and Gallium Nitride (GaN) introduces the possibility to increase the efficiency and the power density. These semiconductors have low switching losses and enable higher switching frequencies, creating high dV /dts in operation.

Electrical machines in aerospace applications experience low pressure, where the breakdown voltage is substantially lower than at ground level, putting insulation systems in an extra challenging situation. Therefore, it is crucial to have accurate predictions of the voltage distribution in the machine's windings. In this way, voltages higher than the Partial Discharge Inception Voltage (PDIV) where degrading of the insulation occurs can be avoided.

The task

This thesis aims to investigate and predict the voltage distribution in medium voltage machines for aerospace applications based on a developed Lumped parameter equivalent model consisting of RLC parameters.

Model/ Measurements/Results

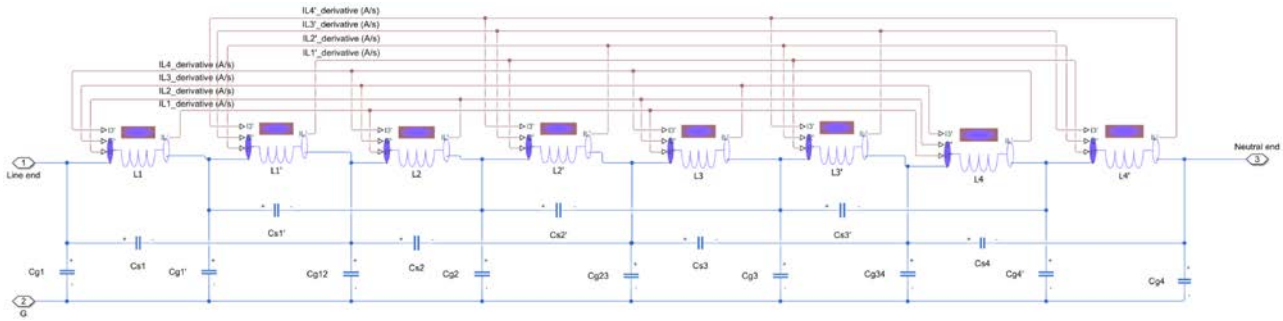
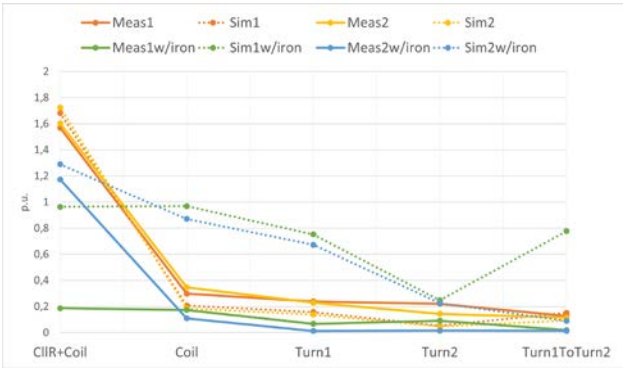
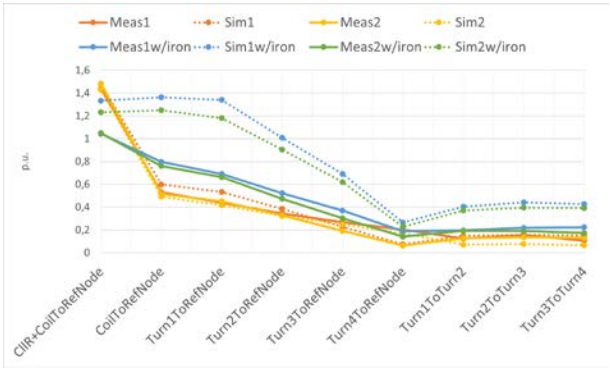


Figure 1: Proposed equivalent model for simulation of the four turn winding configuration in Simulink.





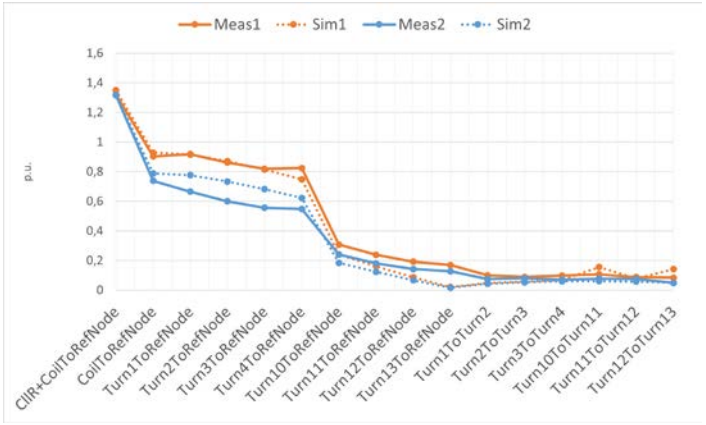


Figure 2: Measured and simulated peak voltages for all three winding configurations.

Resonance	1st [MHz]	1st' [MHz]	2nd [MHz]
Two turn winding (Air)			
Measured	19.82	33.98	-
Simulated	33.97	150.61	215.28
Two turn winding (Iron)			
Measured	19.82	26.98	-
Simulated	10.61	47.03	67.24
Four turn winding (Air)			
Measured	16.96	19.82	31.49
Simulated	19.22	85.55	94.91
Four turn winding (Iron)			
Measured	10.69	19.82	36.73
Simulated	3.98	17.70	19.63
Thirteen turn winding			
Measured	7.86	14.56	16.99
Simulated	42.11	101.04	106.02

Figure 3: Observed resonance points for measurements and simulations in Simulink.

Abstract

The thesis describes a detailed MATLAB & Simulink based model for predictions of the voltage distribution of windings exposed to repeatedly steep fronted surge voltages generated by a PWM inverter. The proposed model is a Lumped parameter equivalent consisting of RLC parameters. The frequency dependency of the parameters was calculated both analytically and with the help of the Finite element method in the simulation software COMSOL Multiphysics®. Finally, the model was validated through two experiments conducted on three different winding configurations. The first validation measured the frequency impedance response of the winding, and a second validation compared the simulated and measured voltage distribution of inverter fed windings. The model showed the best performance for both validations utilising stationary parameter values for air coils. Although the simulated results gave a reasonable degree of confidence in the proposed model, further testing and investigations are required for the model to be valid in more complex contexts.

Study on the Variable Frequency Transformer's Operation and Frequency Range

Student: **Nasrollahi, Kooshiar**
Supervisor: **Anaya-Lara, Olimpo**

Summary

Inherently variable power generation from renewable energy sources (RES), such as wind turbines and solar panels, is challenging for energy shifting. Merging separated power grids into a super grid with various RES besides the different peak times and seasons in distinct regions help to overcome the RES fluctuations. The variable frequency transformer (VFT) asynchronous grids interconnection offers flexible power flow between different areas, developing power grids' reliability and balancing mismatches in supply and demand in an area.

The recent shift from conventional synchronous power generation plants to wind power and PVs reduces power systems' frequency stability. Increasing full-converter wind turbines, which isolate the generator rotational speed from the grid frequency, decreases the power system's physical inertia. PV power plants also miss any physical inertia. Physical inertia is vital in the early stage of the frequency disturbances for power systems' stability. General power systems' frequency droop characteristic suggests that employing a VFT, which has significantly high inertia constant, improves the power system's frequency stability. Also, the VFT fundamental structure offers frequency ancillary service in frequency transient of rotor swing, stage I, inertial frequency drop, stage II, primary control, stage III, and secondary control, stage IV. Utilising the VFT interconnection with energy storage banks (ESB) show similar dynamics to a synchronous generator. The VFT bidirectional power transfer capability contributes to both over and under power mismatch.

This study reviewed the VFT operating and power systems' frequency transient response to analysing the VFT behaviour during the frequency shifting operation and possible involvement in inertial, primary, and secondary frequency control. The VFT behaviour is analysed and tested in the MATLAB\Simulink. This study focuses on the maximum possible active power transmission during frequency shifting and the VFT's frequency drop characteristic during a frequency disturbance.

Sensorless Control of a PM motor Drive for Drones based on STMicroelectronics STM32 microprocessor series

Student: **Pål Nerbøberg**
Supervisor: **Roy Nilsen**
Contact: **paalnerb@stud.ntnu.no**
Collaboration with: **Alva Industries**

Problem description

The topic of this master-project is proposed by Alva. Alva wants to develop its own series of motor controllers. One of the key tasks is development of motor control strategy and the software. The design requirements include high switching frequencies and high-dynamic operation - fast changes in speed and load.

The task

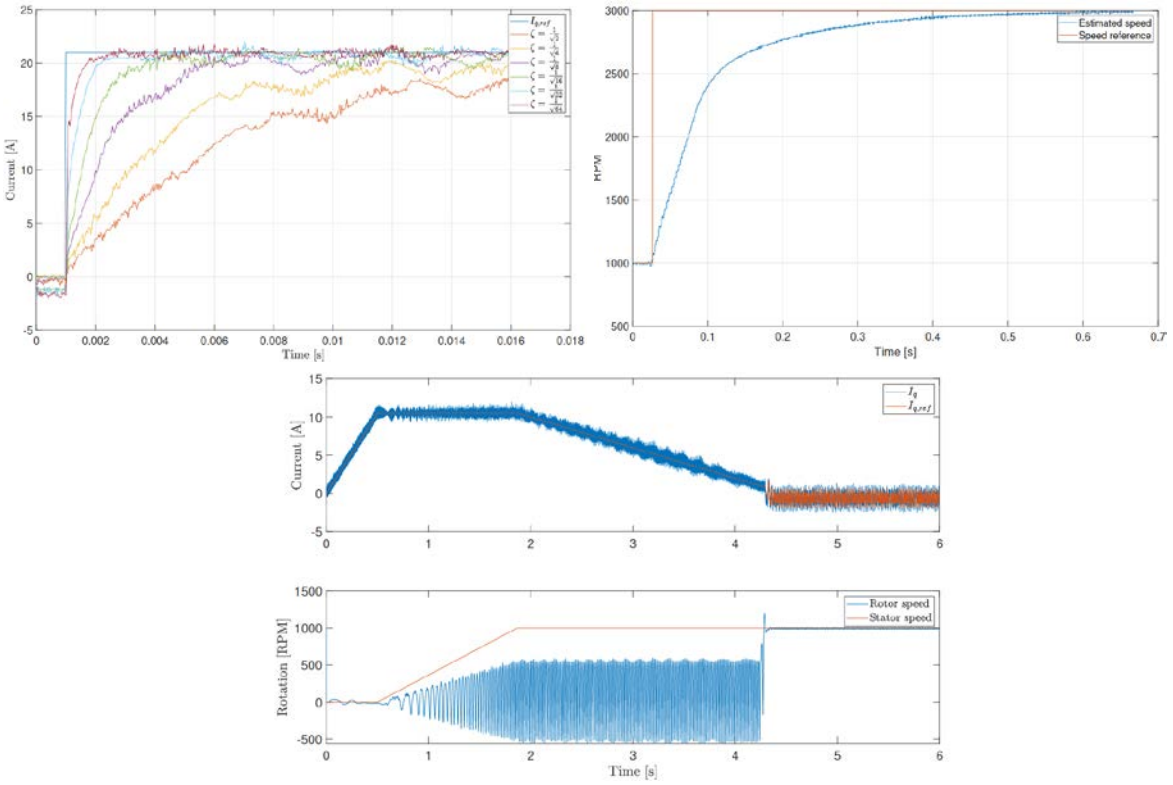
The Main Target is to demonstrate the capability and customability of sensorless motor control software for slotless permanent magnet synchronous machines (sl-PMSM) by using a commercial control platform and converter layout. The platform will be explored and documented in addition to implementing tuning techniques.

Model/ measurements

The testing is done on a thingap TG2341 BLDC motor with no load attached, STMicroelectronics Nucleo STM32G431RB control board, X-Nucleo IHM08M1 powerboard. The testing is done with the tuning methods Modulus Optimum for the current controller, Symmetrical optimum for the speed controller and an I/f startup routine.

Calculation

The current controller, speed controller and startuproutine is shown in the figures below respectively.



Conclusion
The STM32 environment provides useful tools through its Motor Control Software Development Kit (MCSDK) with the Motor Control Workbench for fast set up of the motor control and Motor Pilot as an interface for steering and logging. The STMCubeMX generates initializationcode for the system clock, timers, pins, etc. At the same time, it offers high flexibility for low-level configuration. These tools generate source code for the STM32 IDE, which can be customized. The STM32-series is a flexible system and provides the tools which simplify further development and customization on this platform.

Implementing modulus optimum for the current regulator and symmetrical optimum for the speed regulator is done successfully. The results suggest a dampening factor of $\zeta= \frac{1}{\sqrt{64}}$, which results in a rise time of $0.47 ms$. The lack of a filter in the speed estimation caused large speed estimation ripples resulting in a current reference output of the speed regulator reacting to the ripple. To avoid the reaction, the symmetrical optimum β-value was increased to 10, and the calculated proportional gain was reduced by a factor of 10. This led to an over-damped speed regulator, which is not optimal. A filter for the speed estimation should be implemented.

I/f startup routine was implemented. The alignment stage of the startup routine resulted in oscillations around the magnetic axes causing the startup to be unreliable. The startup was successful and reliable by adding an external friction force in this stage.

New Environmentally-friendly Insulation Gases: Pre-breakdown and Breakdown Mechanisms near Insulating Surfaces under Fast Voltage Impulses

Student: **Stian Nessa**
Supervisor: **Frank Mauseth**
Co-supervisor: **Hans Kristian Hygen Meyer**
Contact: **stian.nessa@gmail.com**

Problem description

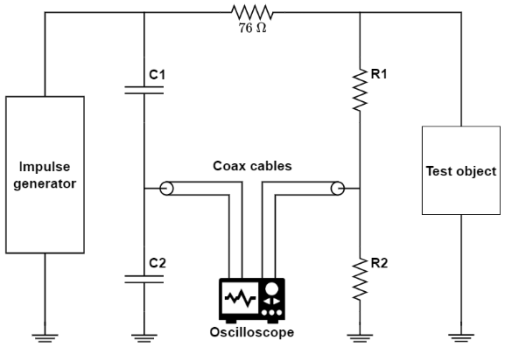
With the current push for phasing out SF_6, new designs for high voltage equipment are needed to minimize the impact of the shift to more environmentally friendly insulating gases. To achieve this, a deeper understanding of electric discharges in alternative gases is required.

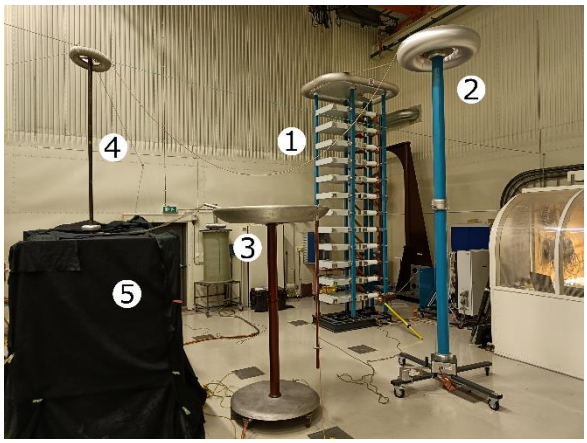
The task

This thesis is a continuation of a previous project where a sudden increase in breakdown voltage was observed under particular conditions. The phenomenon occurs when a fast positive voltage impulse is applied across a rod-plane gap with a dielectric surface placed a small distance away from and parallel to the electrode. The work performed for this thesis investigates other aspects of this phenomenon, including how it is affected by the distance between the surface and electrode, and negative impulses.

Setup

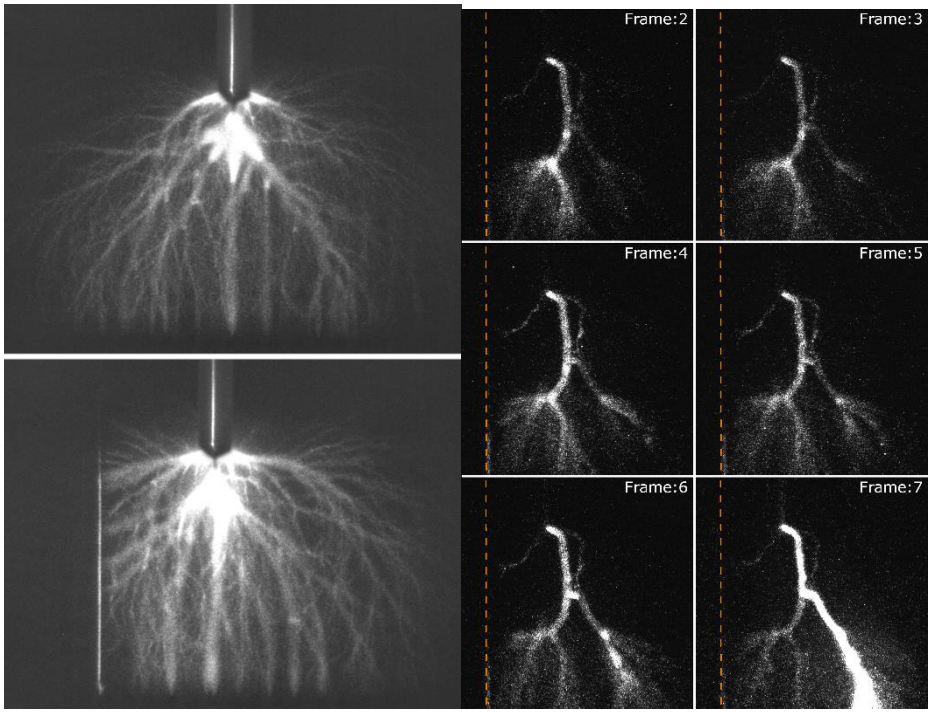
The setup for voltage impulse testing consisted of a marx impulse generator (1), front capacitor (2), resistive voltage divider (3), a current limiting resistor (4), and a dark tent containing the test object, cameras, and a photomultiplier tube.





Results

Some of the images captured of streamer discharges (left) and leader discharges (right).



Conclusion

The up-and-down tests show that the breakdown voltage under fast positive voltage impulses is highly sensitive to the distance between the surface and the electrode. There is a significant increase in breakdown voltage at a distance of 20 mm, but with a much smaller increase when placed both closer and farther away. The tests also showed that the breakdown voltage increase is not present for negative voltage impulses. Additionally, the images captured using high-speed cameras showed that certain discharges are affected by the parallel surface. The breakdown tests and the thermal camera showed no significant negative effects caused by the evaporated carbon layer during AC application.

Towards Plug-and-Play Control of Wind Power Systems: Scalable stability certificate guaranteeing large signal stability for entire wind parks

Student: **Trond Markus Tutturen and Jørgen Nyhus-Solli**
Supervisor: **Gilbert Bergna-Diaz**

Problem description

To reduce global warming, power generation must transition from fossil sources to renewable energy sources with a lower carbon footprint. The traditional power grid structure is comprised of large fossil-fuelled power plants often located in the vicinity of the power consumption, such as big cities. The transition to distributed renewable energy sources introduces new challenges. The renewables will be intermittently integrated into the power grid, potentially far away from where most of the power is consumed, causing less predictable power generation and more challenging transmission. Where traditional power generation is dominated by large synchronous generators with large inertia, most renewable energy sources are connected to the power grid through power electronic converters where the inertia cannot contribute to the stability of the power grid. The increasing penetration of renewables, therefore, has the potential to jeopardize the stability and the performance of the entire power system. Therefore, a new strategy for controlling power electronic converters is needed that allows for the continuous growth of distributed renewable energy sources without compromising the stability of the power system.

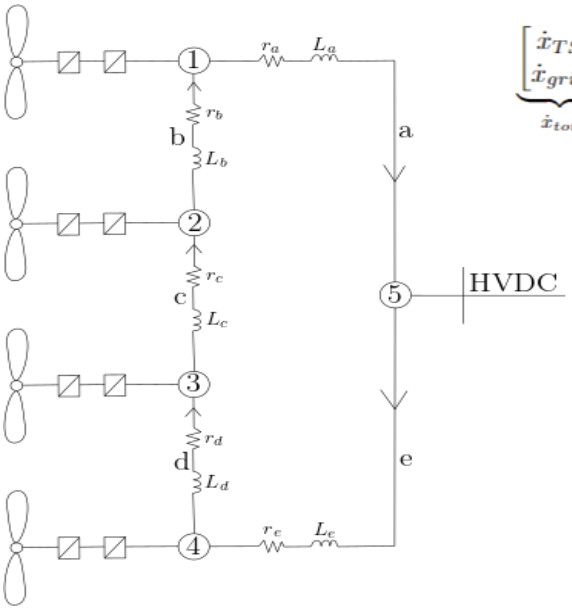
The task

The main objective of the thesis is to develop a stability certificate for a wind energy conversion system including the nonlinear dynamics of the PMSG, the wind and back-to-back 2L-VSCs and generalizing the result to include any (multi-machine/converter) wind-park configuration. The stability certificate is developed using passivity in combination with port-Hamiltonian modeling and Lyapunov stability analysis.

More precisely, we aim to:

- Derive the port-Hamiltonian model of a wind energy conversion system consisting of a wind turbine with a permanent magnet synchronous generator and full scale back-to-back converters.
- In combination with industry standard proportional integral (PI) controllers, use the shifted Hamiltonian as a Lyapunov candidate function to investigate the stability properties of the system and check if the conditions for stability are satisfied.
- Simulate the wind energy conversion system with the full back-to-back converters and validate the stability criteria. By use of simulation different control strategies are investigated such as comparison with traditional PI-current control, cascaded control structure and practical solutions to challenges introduced by cascaded control structure.
- Expand the stability analysis to apply for a wind park with the help of graph theory.

Model/ measurements



$$\underbrace{\begin{bmatrix}\dot{x}_{TS}\\ \dot{x}_{grid}\end{bmatrix}}_{\dot{x}_{tot}} = \underbrace{\begin{bmatrix}F_{TS}(\omega_m,u) & -G_{p,TS}\mathcal{B}_{TS}\\ \mathcal{B}_{TS}^{\mathsf{T}}G_{p,TS}^{\mathsf{T}} & F_{grid}\end{bmatrix}}_{F_{tot}(x_{TS},u)} \underbrace{\begin{bmatrix}\nabla\mathcal{H}(x_{TS})\\ \nabla\mathcal{H}(x_{grid})\end{bmatrix}}_{\nabla\mathcal{H}(x_{tot})} + \underbrace{\begin{bmatrix}E_{TS}\\ E_{grid}\end{bmatrix}}_{E_{tot}}$$

Power preserving interconnection between the grid and wind turbines

$$2d_i - 2\frac{\partial T_{m,i}(\omega_{m,i})}{\partial \omega_m, i} - \frac{\left(\bar{i}_{q,i}\frac{P_i}{2}L_i\right)^2}{2(r+\gamma V_{c,i}^2)} \geq 0$$

$$2\left(G_i + \gamma \bar{i}_{q,i}^2\right) - \frac{(2\gamma \bar{i}_{q,i}\bar{V}_{c,i})}{2(r_i+\gamma V_{c,i}^2)} \geq 0$$

Local stability criteria at each wind turbine

Figure 1: Grid model under study

Conclusion

- The major result of this master thesis is a scalable certificate for a wind park that guarantees large signal stability. To ensure the stability of the entire wind park, it is sufficient to satisfy the local stability criteria at each turbine string. Such decentralized control is beneficial in multiple ways. It does not require an exchange of information between turbine strings and the grid, nor the need for communication between the turbine strings. The control structure for the wind park is, therefore, simple, as each turbine can be controlled independently from the others. From a commercial viewpoint, it is beneficial for the companies delivering the different components in the wind park to avoid sharing their company secrets as it is unnecessary to ensure stability. Another great advantage of decentralized control is that it allows for unlimited expansion as long the stability is satisfied at each turbine string. Such a scalable stability certificate with a plug-and- play feature can allow for needed continuous expansion of distributed renewable resources without risking jeopardizing the stability of the power grid
- The industry standard PI current controllers are compared with the PI-PBCs designed in this thesis. The performance is very similar when the two controller types are tuned identically. Unlike the PI-PBCs, which can guarantee large signal stability, the current controllers do not have that feature. Therefore, the PI-PBCs are the preferred controller type of the two when they are tuned identically and subjected to the disturbances simulated in this thesis.
- From the stability criteria, one can see how the PI controller only affects the last term. As a consequence, the damping d must be designed such that it counteracts the second term to fulfil the stability criterion. The damper windings in the rotor are a part of the design process of the machine; hence, the stability certificate should therefore ideally be a part of the design process as well to guarantee large signal stability. Including the certificate in the design process also minimizes the risk of sacrificing too much performance by having over-dimensioned damper windings.

Towards zero-emission power systems – A generation expansion study of the North Sea region 2040

Student: Mikkel Nærby
Supervisor: Magnus Korpås
Co-Supervisor: Martin Kristiansen

Problem

Recently the UN published the Climate Change report 2021, concluding that the world is off-track to fight climate change. Data shows that greenhouse gas concentrations in the atmosphere continue to rise to record levels.\cite{IPCC} The European Union is targeting climate neutrality by 2050, meaning an economy with net-zero greenhouse gas emissions. Significant investment within a variety of sectors is needed to reach this goal. The transition to renewable energy generation is one of the critical factors in reaching a sustainable future.\cite{EU}

Model and objective

This master thesis utilizes a deterministic optimization model, PowerGIM, for power system simulations in the North Sea. The model simulates a year of operation with the objective of minimizing investment and operational costs. The main objective of the master thesis is to analyse the optimal generation expansion of the North Sea power system in 2040 in scenarios with flexible demand effects and zero-emissions requirements. Generation expansion planning showcases the optimal location, capacity, and generation technology to benefit the whole power system. Transmission expansion planning is included to give a realistic power system development. Power systems with a high share of renewable power sources(RES) have a considerable flexibility problem because the generation output from RES varies and is not controllable. The effects of flexible demand in a zero-emission power system are analysed in different power system configurations. The TYNDP 2020 scenario report for 2040 is the primary source of assumptions and input data in this master thesis.

Conclusion

The initial basis results show that batteries and expanded transmission will partly balance the power grid and efficiently exploit the power output, such that no generation expansion is needed. Investments in the transmission are more beneficial when added renewable generation leads to more flexibility issues than the power system can handle. The case studies show that an integrated international power system and a mix of variable power generation sources contribute to the balancing of the power system. However, less transmission is needed when flexible demand is included, and the results show that onshore wind generation expansion in Norway is the most cost-beneficial expansion. A share of 26 percent flexible demand results in a 94 percent reduction in emissions compared with the initial scenario. Nevertheless, reaching a zero-emission power system is increasingly more difficult. The variability of renewable power generation is the main obstacle to reaching a sustainable power system. With zero-emission requirements, the power system is experiencing more significant flexibility problems and periods of power shortages. In order to reach a functioning, fully renewable power system, additional energy storage and flexible demand are needed than what is investigated in this thesis.

Active Front End Converter with Virtual Damping and Inertia

Student: **Kazi Shoffiuddin Roni**
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Supervisor: **Roy Nilsen**
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Collaboration with: **HydroCen Project**

Problem description

For some high-power applications, for instance, in Adjustable Speed Hydro (ASH), Active Front End Converters are used as grid-connected converters. This project is a part of the HydroCen project. The drive should operate both in generation mode and in pump mode (pump storage plant). This project is a continuation of a Master-project about an AFE. The same converter topology is used in Marine Drives and Off-shore Wind Turbine applications. The synchronous generator is controlled by an inverter and is feeding power into the DC-link. The AFE is a similar converter with an LCL filter connected to the AC grid, feeding the AC grid from the DC-link. The control of the AFE should include AC voltage and frequency droop, as well as virtual damping and inertia effects. This means that the AFE should behave as a generator in the AC grid.

The task

The trend of high proliferation of renewable energy sources (RESs) like solar PV and wind in conventional generation systems is reducing the presence of inertia. Despite the numerous benefits of these non-depleting energy sources, the inverter-based generation has no mechanical inertia response feature, and thus jeopardizes frequency stability. Figure 1 shows how the displacement of synchronous generators in power systems by RESs, diminishes the inertia response. This results to an increased rate-of-change-of-frequency (ROCOF), and a low frequency nadir (lowest frequency point) in a very short time as highlighted in section AB.

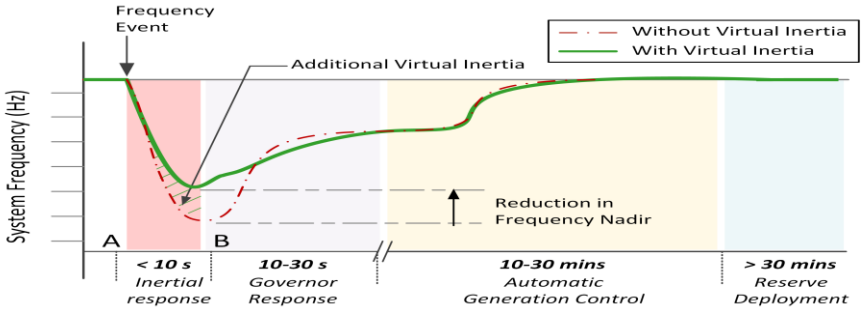


Figure 1:Multiple time-frame frequency response in a power system following a frequency event.

Model/ measurements

The filter capacitor frequency converter was modelled to behave like a synchronous generator to achive virtual inertia control.

$$\frac{du_c}{dt} = \omega_N \,.x_c\,.(\,i_{1d} - i_{2d}) \qquad (1)$$

$$\frac{du_c}{dt} = \omega_N \,.x_c\,.(i_{cd}) \qquad (2)$$

From Figure 2, the filter capacitor is modelled in u_c oriented coordinates system (stationary DC quantities) to generate the i_{cd} and i_{cq} current reference signals deployed for the switching operations of the frequency converter (VSI). The q-axis component which is orthogonal to the d-axis component is used in generating the reactive current i_{cq}. The q-axis can be oriented to align with the d-axis component. The reactive current can be expressed in relation with the frequency as:

$$\frac{du_c}{dt} = 0 = \omega_N \,.x_c\,.(i_{cq}) - \omega_N \,.f_k\,.u_c \qquad (3)$$

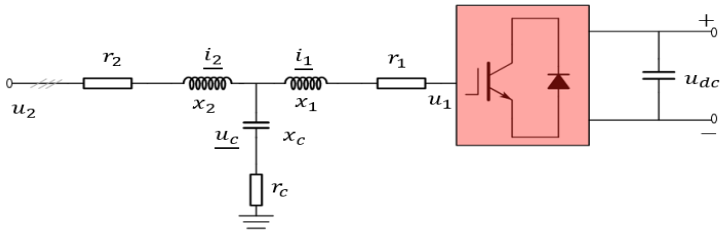


Figure 2: Schematic Diagram of the Control of Capacitor voltage.

When comparison is made between the synchronous machine and the capacitor voltage control the following observations can be drawn:

- The amplitude of the voltage vector e_{af} of the synchronous generator is cotrolled by field current i_f
- The speed ω of the synchronous generator is controlled by the turbine torque $\tau_{turbine}$
- The amplitude of the capacitor voltage vector u_c^s is controlled by the active current i_{1d}
- The frequency of the capacitor voltage vector f_k is controlled by the reactive current i_{cq}

The concept of virtual inertia is based on the swing equation and droop control:

$$T_m \frac{dn}{dt} + d_{DQ}(n - f_{\_ref}) = T_{turbine} - T_{g,syn} \qquad (4)$$

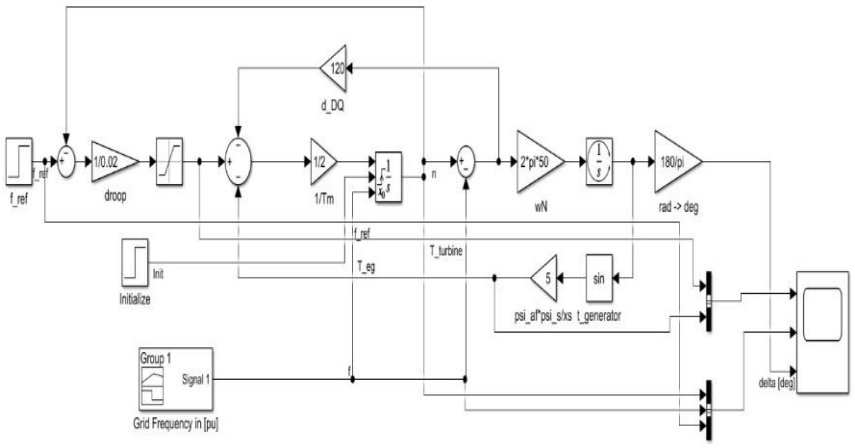


Figure 3: Virtual Inertial Control Model from Simulink.

Calculation

At 1 second, the frequency reference $f_{\_ref}$ increases beyond the nominal value of the grid frequency f (1.0 p.u. or 60Hz). This step-change creates a disturbance in the speed n, at that instant of time but quickly re-aligns with the grid frequency because of the restrictions of the

damper winding. A step-change $f_{\_ref}$ increases the turbine torque from 0-0.5 p.u. but the speed n, of the turbine remains the same in steady-state. This constant speed is decided by the characteristics of the grid frequency. However, a sudden variation in speed n, will result to a corresponding trip in the system.

From 5 to 7 seconds, the grid frequency drops by 6% and the frequency or the speed of the VISMA follows the grid frequency. Currently, the difference between $f_{\_ref}$ and speed n, increases, which increases the magnitude of the turbine and generator torque. A slight increase in $T_{e,g}$ decelerates the system and later tracks the torque of the turbine. At this point, the machine is braking. After that, the system maintains a constant speed and frequency values for an additional 3 seconds.

For 10-12 seconds, the grid frequency increases again and the difference between $f_{\_ref}$ and speed n reduces, which subsequently reduces the magnitude of the generator torque. At this point, the machine accelerates (generation mode). The generator torque $T_{e,g}$ becomes less than the turbine torque and more active power is supplied to the grid. After 12 seconds, the grid frequency is restored to 1.0 p.u., and the speed perfectly tracks the grid frequency. In addition, the grid frequency stabilizes for 2 seconds and beyond.

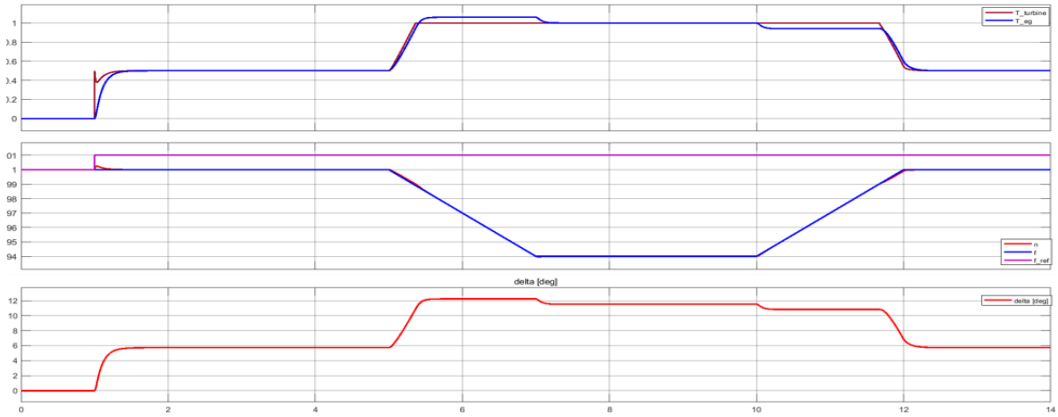


Figure 3: Simulink Results of the Virtual Inertia Control.

Conclusion

- The engagement of the classical control theory and symmetrical optimum has been deployed in developing a strategy to tune PI controllers to achieve filter capacitor battery control in stator-orient coordinates (AC stationary quantities) and polar-orient coordinates (DC stationary quantities).
- The PI controllers in alpha-beta and d-q coordinates are efficient for good current reference tracking.
- The voltage amplitude and the angle of the filter capacitor are highly essential for maintaining active power balance between the converter and the grid.
- With the absence of synchronous machines, the proposed virtual inertial emulation in the AFE is essential for maintaining inertia with rapid changes in grid frequency.

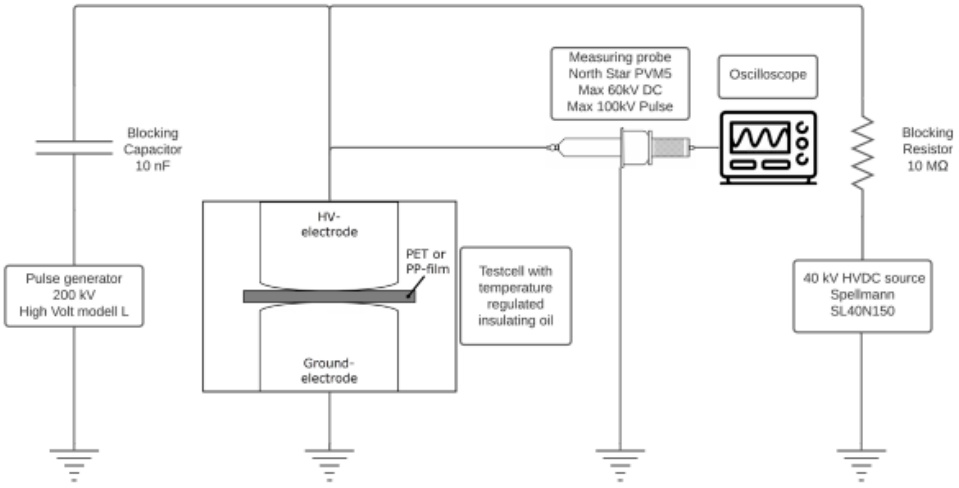
Impuls holdfasthet til polymerfolier ved påkjenning av DC-spenning med overlagret lynimpuls

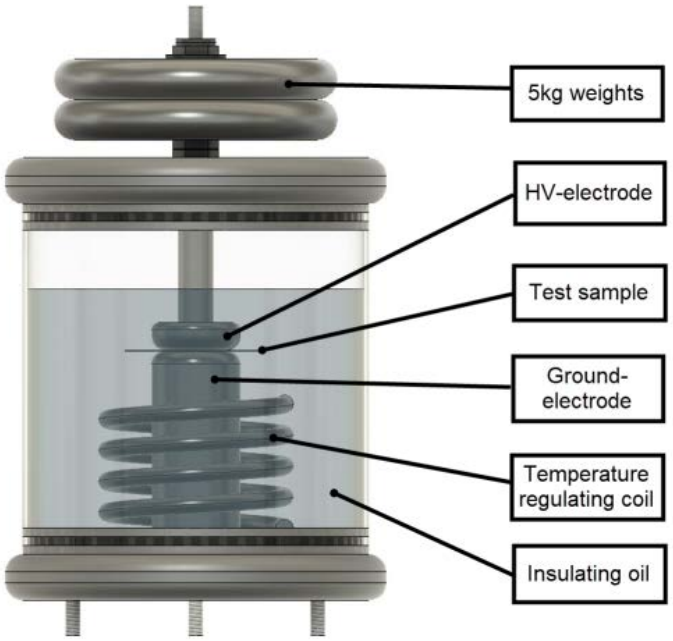
Student: **Espen Torlei Olsen**
Veileder: **Erling Ildstad**
Medveileder: **Frank Mauseth**

Problemstilling
Polymerkabler har i lang tid vært brukt ved HVAC-energidistribusjon. Særlig XLPE har vært et foretrukket valg av isolasjonsmateriale siden det har gode elektriske og mekaniske kvaliteter, er pålitelig og har lave produksjonskostnader. For HVDC-overføring er det i hovedsak papirisolerte (MIND) kabler som har vært brukt. I nyere tid har polymerisolerte HVDC-kabler fått en økende andel av markedet, og tilbyr flere fordeler sammenlignet med den tradisjonelle papirisolerte oljekabelen, som redusert miljøpåvirkning, samt at den tillater høyere ledertemperatur og er enklere å reparere. En utfordring er derimot tilstedeværelsen av romladninger som er spesielt risikabelt ved polaritetendring og blir sett på som den dominerende årsaken til feil i polymerisolerte HVDC-kabler.

Oppgaven
Dannelse av romladninger gjør det vanskelig å forutsi hvordan det elektriske feltet distribueres i HVDC-kabelisolasjon. Romladninger fører til forsterkning av det elektriske feltet og reduserer holdfastheten, spesielt ved rask polaritetendring av spenningen. Formålet med denne oppgaven har vært å studere hvordan impulsholdfastheten i polymerfolier påvirkes av DC-spenning, polaritet og temperatur. Forsøk er utført på tynne filmer av polypropylen (PP) og polyetylenteraftalat (PET) med parallelle plateelektroder. Testobjektene ble først tilført en DC-spenning i 60 sekunder før det ble påtvunget lynimpuls som førte til gjennomslag. Det ble også utført forsøk med DC-spenningsnivå mellom 2 og 12 kV for å studere effekten av det forspente feltet.

Modell/målinger
Det er benyttet en testkrets som består av DC-kilde, impulsgenerator og en oljefylt testcelle med testobjektene. For å kunne måle og dokumentere spenning over testcellen brukes en måleprobe med forhold 1:1000 som gjør det mulig å lese av verdier i oscilloskopet. Det ble utført målinger ved temperaturer fra 20 - 100 °C. Testcellen består av to parallelle plateelektroder i messing innkapslet i pleksiglass. Elektrodene er Rogowski-formet med en diameter på 50 mm og en krumming på 4 mm.





Konklusjon

Holdfastheten økte betydelig ved DC-prestress med lik polaritet som lynimpuls. Økningen var 40-60% i PET-film og 20% i PP-film sammenlignet med impulsholdfasthet. Økningen i holdfasthet skyldes homoladninger som akkumuleres under DC-prestress. I PET-film økte den akkumulerte ladningen ved høyere temperaturer. Ved lynimpulser med motsatt polaritet som DC-prestress sank holdfastheten i begge materialer med 20-30 % sammenlignet med impulsholdfasthet. Svekkelsen i holdfasthet skyldes heteroladninger som øker feltpåkjenningen i polymerfilmene nær elektrodene og fører til tidligere havari.

Design and construction of a miniature smart house

Student: **Tor Erlend Brækkan Olsen**
Supervisor: **Steve Völler**
Contact:
Collaboration with:

Problem description
The goal is to build a miniature smart home that could be used on exhibitions and for teaching to visualise a more practical example.

The idea is to use a dollhouse which could be transformed to a miniature smart home by building in elements that is found in normal smart homes. The elements could be a combination of consumer electrics (lighting, heating, electrical vehicle charging), energy sources (grid power, photovoltaic panels, wind power generator), energy storage (batteries, hydrogen) and a control system. The setup will visualise the energy flow (generation and consumption). The control system is to be visualised and controlled on a touchscreen by the teacher and students.

The task
In this master thesis it is built a miniature smart house for use for teaching purposes or used on exhibitions to visualise a practical example. The smart house contains photovoltaic panel on the roof top that could be changed from parallel to series connection by using the touch screen. This change is done by relays.

The smart house is based on a ordinary dollhouse which is provided by the Department of Electrical Power Engineering, NTNU.

This project uses four types of sensors, all from Adafruit which is a manufacturer for development products. A power monitor sensor is used to measure voltage and current on photovoltaic panel and a precision power monitor sensor used on one set of photovoltaic panel to compare the difference when one panel is cooled down by using a peltier element. The peltier element is a semiconductor that is cooling by applying DC current.

The next sensor used is a air quality sensor that is primary used to measure the temperature on the roof top when a halogen light is used to simulate the sun. This sensor does also measure humidity and atmospheric pressure. This values is visible on the touch screen.

The last sensor is used to measure light. This is reporting the value in lux, but this is converted to show W/m^2

A microcontroller, Arduino, is used to collect the data from the sensor and make them visible on the touch screen.

Model/ measurements

The goal for the master thesis is to connect all the components, sensors and photovoltaic panels so most of this could be viewed and controlled on the touch screen. In the beginning of the master thesis the Arduino was upgraded from UNO to Mega. This is because the UNO only has one serial port and is shared with USB to computer. This made some problems to communicate with the touch screen and serial monitor on the computer for troubleshooting and transferring the code since they both used to same port. The Arduino Mega has four serial ports including the USB serial.

Calculation

Conclusion

The peltier element worked better than expected. It has much more cooling if the current is increased. But the limit here is 12V and therefore the current is limited. But if the peltier element has cooled even more, the heat sink will be to small. At this setup this is an excellent combination.

Adafruit INA219 and INA260 does only have four I^{2}C-addresses, and also the same combination. This means it can be used up to four totally (e.g. two INA219 and two INA260). The chip itself, from Texas Instruments has 16 I^{2}C addresses, but then it is needed to do some soldering modifications with jumper wires.

Due to long Arduino code, the response when using buttons on the touch screen could happen that the user need to push more times. This is because when the Arduino runs the receiving of sensor data the code is busy. When push buttons it pressed in this sequence there will be no response. The sensor data part of the code is running every 2.5 seconds. This could be fixed by modifying the to have a priority on push button and after the sensor data.

Visualizing Electromechanical Oscillations for Control Room Purposes

Student: **Maiken Borud Omtveit**
Supervisor: **Kjetil Obstfelder Uhlen**
Collaboration with: **Statnett**

Problem description

With more intermittent energy sources in the power system, electromechanical oscillations occur more frequently. Generators oscillating against each may affect the operating capacity of transmission lines. Uncontrolled oscillations may in worst case cause islanding of the grid and blackout.

The task

In order to counteract the oscillations, they must firstly be measured and visualized. This is possible with the novel phasor measurement unit (PMU) technology, which is not widely implemented in the Nordic grid. The first step towards controlling electromechanical oscillations is to visualize the parameters in the national control centre. Therefore, this master thesis focuses on developing an algorithm that processes the data from the PMUs and visualizes the information about present oscillations in a clear manner.

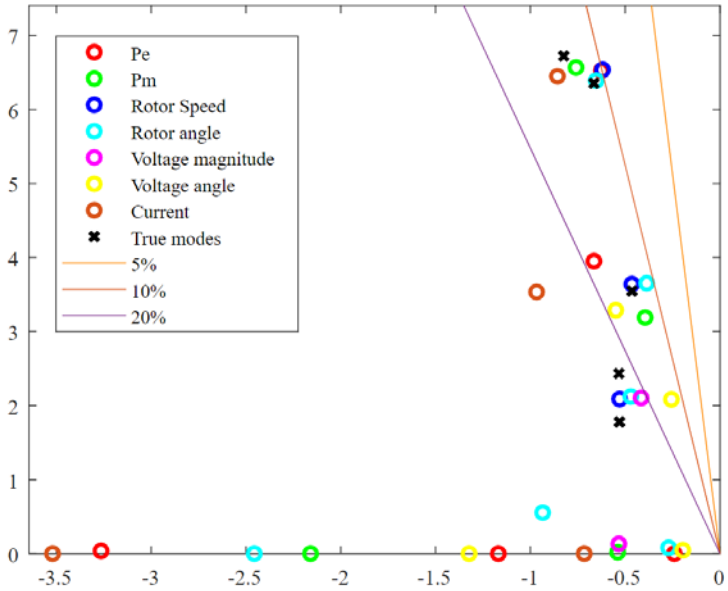


Fig. 1 Average cluster values based on various outputs from the power system.

Procedure

The master thesis begins with a literature review of existing visualization tools for oscillations, and a study of existing algorithms to extract information about the oscillations from PMU data. A novel algorithm is developed to detect the oscillations. The algorithm is tested on simulated and real data, and compared with the linearized system and previous studies respectively. It is investigated which power system parameters yield the best outcome of the algorithm, as well as its capability to detect new modes quick.

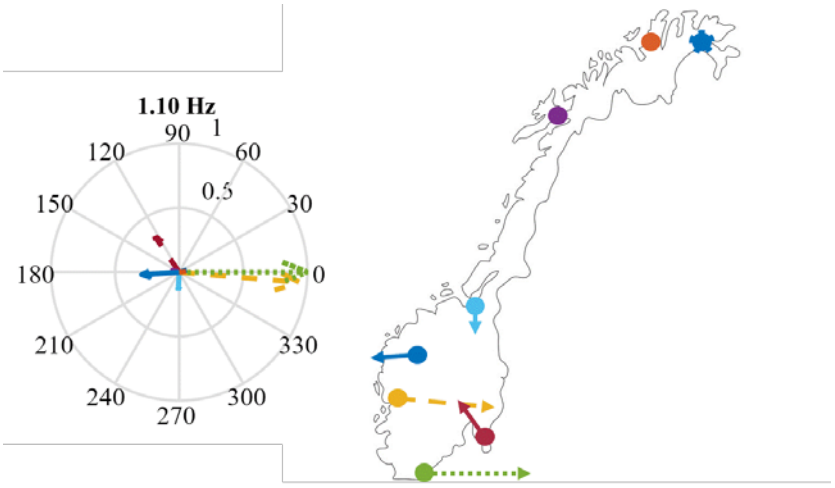


Fig. 2 Mode shapes of a 1.10 Hz mode estimated with N4SID+DBSCAN, and illustration of visualization on GIS.

Results

A novel algorithm based on subspace system identification (N4SID) and clustering (DBSCAN) is developed. The weakness of N4SID is that the choice of model order must be set manually, and is impossible to optimize without full knowledge of the system. Using DBSCAN post-identification turns this into an advantage by running N4SID on an interval of model orders and clustering the results. The averaged cluster values are closer to the actual modes of the system. The results are visualized with mode shapes, eigenvalue plots and numerically.

Conclusion

The tests show that the new algorithm is promising as it shows mode parameters coherent with the linearized model and previous studies. It seems to be fit to use on real PMU data, and it quickly detects new modes. The biggest drawback is the computation time of the algorithm. It works relatively well with most inputs from the power system data, but slightly better with rotor speed and angle. More testing is needed to obtain statistically significant results, but the initial study is promising.

Artificial Neural Network Based Power Management in Microgrid

Student: **Onsrud, Martin Wirak**
Supervisor: **Mohammad Amin**

Summary

Climate change, and the resulting focus on the green transition is rapidly changing the structure and characteristics of the power systems around the world. The implementation of microgrids are facilitating renewable power production in the power system, by allowing for smaller components of local production and storage such as solar panels and batteries. These microgrids need intelligent control schemes in order to regulate the power, frequency, voltage and currents within the system. Artificial neural networks (ANNs) are proposed as one option for microgrid control with the use of machine learning.

The objective of this thesis is to develop and test a simulation model of a hybrid microgrid with an artificial neural network based centralised controller, and compare the performance to a more traditional power management based power flow algorithm. This was to be done with the overarching goal being the assessment and identification of future possibilities as well as challenges around the use of ANNs in microgrid controls.

The research started with the development of a Simulink model of a microgrid system consisting of solar panels, a battery, an electric vehicle, constant and variable loads. The power flow algorithm was produced, and the microgrid was simulated with a base case consisting of standardised solar and load curves. In parallel, an ANN was developed with the results from the simulation of the base case being used for the training. The two control systems were simulated for three cases each: a base case, a case with irregular irradiance and a case with irregular load.

The results indicated that when provided the same previously unseen input, the ANN based control system managed to adjust the output values towards a more optimal solution compared to the power flow algorithm. The complex structure of the ANN creates and identifies its own patterns that is able to provide expected output values even if the situation is different from the training data. However, as this project only tested a few cases, the ultimate usability of ANN as a centralised controller cannot be concluded. Nevertheless, the result indicate that this may be a viable option for a more secure and effective control system for power management in the future.

Design of a Hybrid Winding PM Machine for Electric Aviation

Student: **Fredrik Opdal**
Supervisor: **Robert Nilssen**
Contact: **Fredrikopdal@gmail.com**
Collaboration with: **Alva Industries**

Problem description
While society moves towards electrification and renewable energy, new technology and solutions are necessary to enable the transmission to a greener aviation sector. Unfortunately, aviation relies heavily on fossil fuels, as the electric solutions available today do not fulfill the performance requirements. This thesis examines if a new permanent magnet(PM) hybrid winding machine topology that combines airgap- and slot windings can be a viable solution for small aircraft applications.

The task
The thesis will discuss whether a motor topology that combines airgap- and slot windings in the same magnetic structure can outperform conventional slotted PM machines in terms of power density and efficiency. A hybrid winding PM machine with an outer stator core diameter of 28cm and a core length of 8cm is to be designed, analyzed, and optimized using the commercial software COMSOL Multiphysics. To determine the performance of the machine, the peak output power, produced torque, losses, efficiency, and weight must be calculated. These results are to be compared with results obtained in the specialization project, where a slotted PM machine of the same dimensions was designed and analyzed.

Model/measurements
No general sizing procedure for hybrid winding machines exists, so a new procedure had to be made. An existing sizing procedure for slotted PM machines was altered to obtain a slotted PM machine design of the correct dimensions, which was then transformed into a hybrid winding machine by implementing a set of airgap windings. Implementation of airgap windings was based on a copper distribution ratio, describing the ratio between the amount of copper in airgap windings compared to slot windings, based on weight.

A model of the hybrid winding machine with 24 poles and 72 slots was made in COMSOL Multiphysics. Due to symmetries in the geometry, only a single-pole had to be modeled to analyze the entire machine. A parameter study was conducted to decide on Halbach array or radial magnets as excitation source, magnet segments thickness, and fill factor of airgap windings. Through Bertotti's method in the frequency domain in COMSOL Multiphysics losses due to hysteresis and eddy currents in the iron core were calculated. Losses due to eddy currents in magnets and resistive losses in conductors were calculated with loss calculation nodes.

Based on the parameter study, it was decided that a four-segment Halbach array with a magnet segment thickness of 9 mm, and a fill factor of 0.5 in the airgap windings should be used in the model. The hybrid winding machine was optimized through the optimization module in COMSOL Multiphysics. The chosen objective function was to maximize specific power kW/kg, and stator yoke thickness, inner magnet radius, slot width, and distribution of copper between airgap- and slot windings were chosen as control parameters. An illustration of the optimized machine geometry is shown in Figure 1.

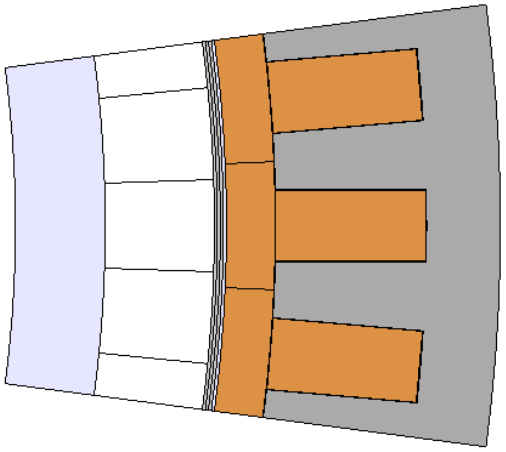


Figure 1: optimized machine geometry

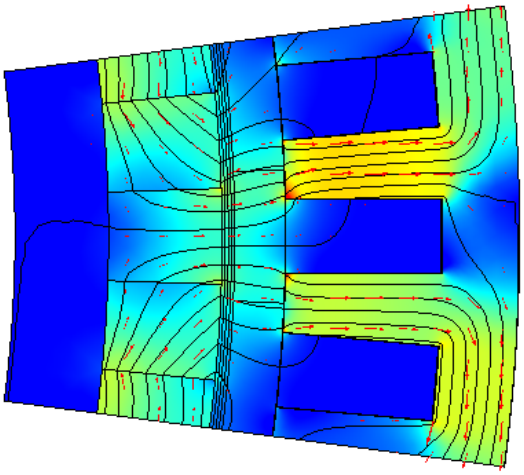


Figure 2: Flux density with nominal load in both sets of windings

Calculation

The table below summarizes the performance of the optimized hybrid winding machine when operating with peak current in both sets of windings, or only either airgap- or slot windings.

Parameter	**Value**		
Applied current	Both sets	Airgap windings	Slot windings
Average torque [Nm]	261.66	76.32	185.41
Average power [kW]	82.20	23.98	58.25
Torque ripple [%]	1.35	3.43	1.77
Efficiency [%]	96.90	94.20	95.98

During operation of both windings, the optimized hybrid winding machine achieves a peak output power of 82.20 kW, with an efficiency of 96.9%, and 1.35% torque ripple. The machine's active weight was found to be 13.51 kg, yielding a specific power of 6.07 kW/kg. Figure 2 shows the flux density of the optimized hybrid winding machine.

Conclusion

The results show promise for hybrid winding machines being suitable electric machines for the propulsion of a small electric aircraft, having both high specific power and efficiency. Having two sets of windings introduces fault tolerance through redundancy. If one set of winding experiences failure, the remaining set can be used alone to safely land the aircraft.

Modeling Optical Current Transformers in a Digital Substation.

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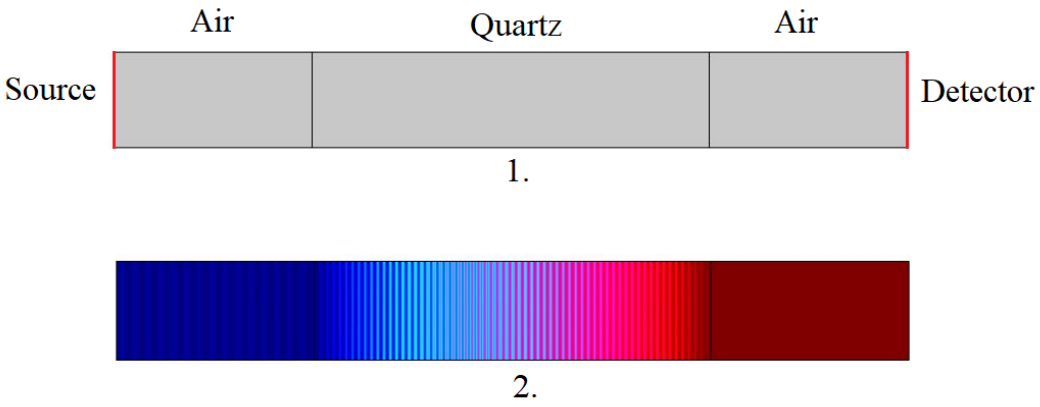
Supervisor: **Irina Oleinikova**
Contact: **andre@oppegaard.net**

Problem description
Optical current transformers (OPCT) have become a more accessible technology the last two decades. This transition from a conventional current transformer design to an optical one stimulates the need to develop a complete model of an OPCT. The model would define and showcase the performance, interoperability and error sources that could possibly occur in a digital substation.

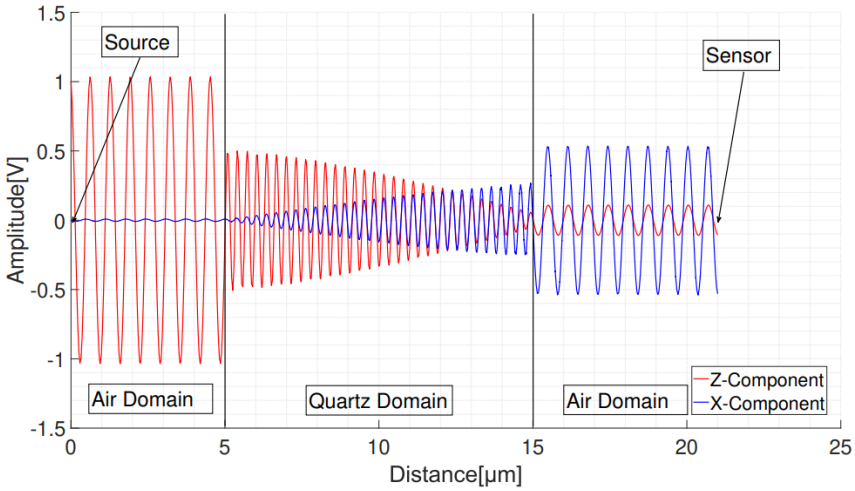
The task
The work maps the present current transducer technologies used in substations, with focus on their positive and negative aspects. Following the mapping of the present and future technology a complete model of an open-core bulk-glass optical current transformer is developed and presented. This complete model is based on an optical model modelled using a finite element method in a 2D environment, and an electrical model based on experimentally obtained frequency response data from an actual OPCT. FEM modelling is chosen as the preferred optical modelling technique, because of its ability to simulate more non-ideal and non-linear aspects of the optical current transformer.

Model/ measurements
The optical model was modelled in COMSOL, the result of the modelling is shown in the figure below.



Figur 1 1: Model Components.
2: Resulting rotation of polarization angle as a result of the Faraday effect.

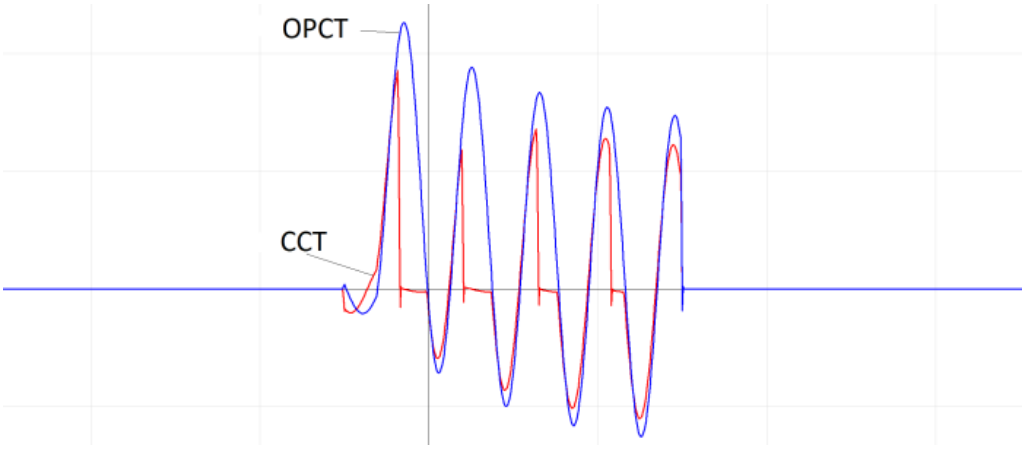
Figure 1 shows the geometry of the model in “1.” and the functionality of the model in “2.” At the source a linearly polarized light is injected. This light propagates through the air domain and into the quartz domain. While inside the quartz domain the light is affected by the Faraday effect, caused by an external magnetic field generated by the conductor current, rotating the polarization angle. When the light has completed a pass of the quartz, it propagates through the last air domain and the change in rotation is picked up by the detector. This change in rotation is proportional to the conductor current and can be related by an optical current transformer factor.



Figur 2 Optical model at high-load. T=1.3

Figure 2 shows the actual displacement of X and Z-component during the propagation through the quartz domain.
To adapt the optical model into a complete model, a curve fit function was adapted from the dynamics of the optical model. The optical model showed to be linear from 0-30kA, at a distance of 6 cm from the conductor.

Calculation
The complete model was tested in a variety of differential protection scenarios, the one scenario that showed the highest performance improvement was external transformer faults where the conventional current transformer (CCT) would saturate, resulting in an erroneous operation of the protection relay. Figure 3 shows the difference in measured current in such a scenario.



Figur 3 External Fault, Current waveforms.

Conclusion
The resulting complete model of the optical current transformer shows significant performance increase over a conventional current transformer in a differential protection setting. These results are mainly due to the increased linearity and accuracy of the optical current transformer. This performance improvement enables the protection relay parameters of the differential protection to be more conservative, resulting in a higher sensitivity and sophistication of the differential protection parameter-set. The open-core optical current transformer design is especially vulnerable to stray magnetic fields and vibrations as shown in the thesis, these effects have to be compensated for a reliable operation of the transformer.

Model Development for coordination of flexibility resources in grid connected Local Energy Communities

Student: **Pedersen, Jørgen Kipperberg**
Supervisor: **Farahmand, Hossein**
Co-supervisor: **Dmytro Ivanko**

Summary

With a rapid increase of intermittent energy resources in the European power mix, the need of new ways to control the market are present. These new renewable assets have a great effect on the environmental aspects of the power generation but can be stressful both for the market operators and the grid itself. Implementing flexibility assets can be of great help in reducing this stress.

Firstly, this thesis will perform an analysis based on the current literature about the different flexibility assets currently available. With flexibility resources present in the power market new actors come in to play, and these will also be described, and their contribution will be explained.

During the work on this thesis a model to simulate the effects of introducing flexibility assets in a Local Energy Community has been created. The way this model has been implemented and what it can do will be explained.

To showcase the model's capabilities, a case study has been created and carried out. This case study with is firstly presented before the results of the simulations are presented and discussed. The results shows that the model can simulate the effects of the integration of flexibility assets in a Local Energy community, and that it can be a useful tool when deciding which flexibility asset is most useful for a given grid.

Temporære overspenninger i 132 kV nett som følge av en nærført parallell 420 kV linje

Student: **William Pedersen**
Veileder: **Bjørn Gustavsen**
Utføres i samarbeid med: **Statnett**

Problemstilling

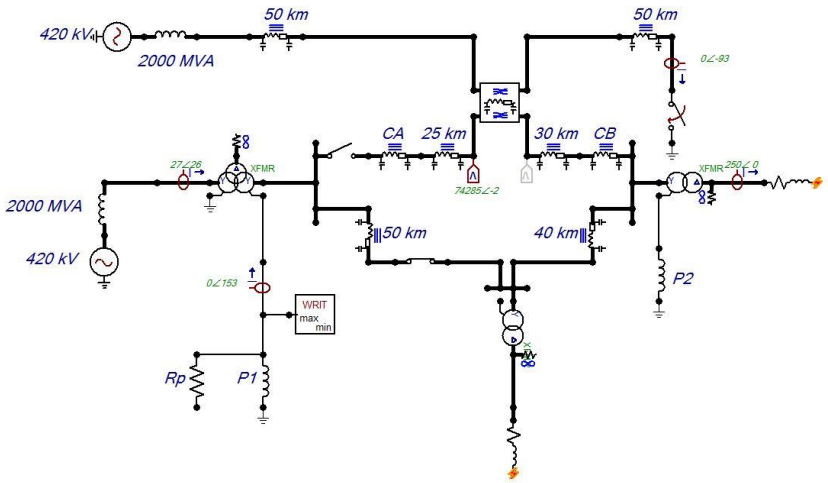
Tidligere analyser viser at temporære overspenninger kan oppstå i spolejordede nett ved feil i en nærført parallell 420 kV linje. Problemstillingen for denne rapporten er å se nærmere på hvordan og hvorfor slike overspenninger oppstår. Hovedfokuset er å se nærmere på den kapasitive og induktive koblingen. Det er også gjort en konkret analyse av et virkelig nett for å se sammenhenger mellom teori og virkelighet.

Oppgaven

Store deler av oppgaven handler om å bruke ATP-simuleringer og Matlab-beregninger i enkle modeller for å beregne og vise grafisk hvilken parameter som påvirker nullsystemspenningen. Ved å presenter nullsystemet i enkle kretser er det vist analytisk, men også gjennom beregninger at overspenninger kan overføres gjennom induktansen og kapasitansen. Det er vist at oppbygging og drift av det spolejordede nettet påvirker den resulterende spenningen. Analysen av det virkelige nettet viser hvordan det er mulig å se på virkingen av den gjensidige kapasitive koblingen ved relativt enkle resurser.

Modell

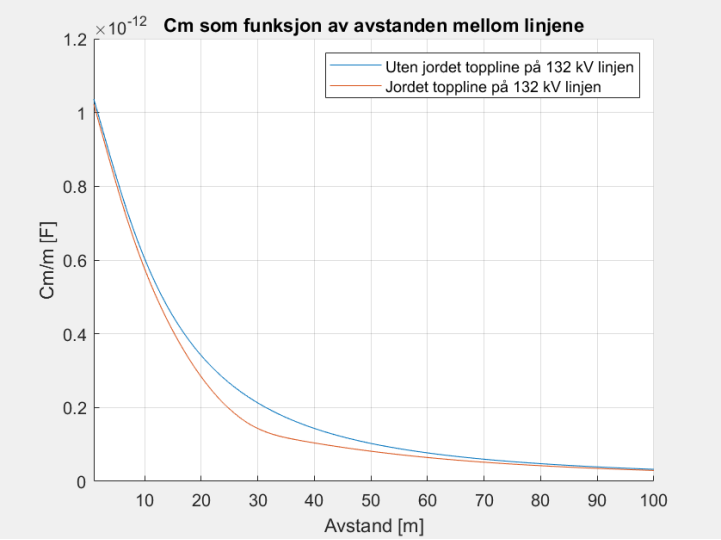
Modellen som er presentert i Figur 1, viser den generelle nettmodellen. Dette er kun et utklipp fra ATPdraw. Det er vist at en 420 kV linje er parallelført med et 132 kV nett. Koblingen mellom nettet skjer gjennom en felles kobling. I denne modellen var det mulig å gjøre simuleringer i et virkelig nett.



Figur 1: Viser ATP-modellen som ble utformet for å simulering

Beregninger

Figur 2, viser hvordan kapasitansen endres ved ulike avstander mellom linjene. Det vises også at det er forskjell mellom nett som har jordet toppline og nett uten toppline.



Figur 2: Viser hvordan kapasitansen mellom linjene endres ved endret avstand

Konklusjon

Temporære overspenninger kan overføres mellom parallelle linjer. Resultatene viser at spenninger kan overføres som en konsekvens av koblingen gjennom nullsystemet. I denne rapporten er det fokusert på overspenninger som overføres som følge av den gjensidige kapasitive koblingen og den induktive koblingen.
Resultatene viser at størrelsen til den kapasitive koblingen relativt til størrelsen på det parallellførte regionalnettet, er avgjørende for hvor stor spenning som kan oppstå. I praksis betyr dette at et relativt lite regionalnett med en relativ sterk kobling vil få de høyeste overspenningene. Grunnen til dette er at den konduktive dempningen er proporsjonal med størrelsen til nettet. Det betyr at dempningen er stor ved et relativt stort nett. Den kapasitive koblingen er derimot uavhengig av konduktansen. Dermed er det relative forholdet vesentlig for hvor store spenninger som overføres.

Spolefordelingen i nettet er en avgjørende faktor for amplituden til de resulterende temporære overspenningene som kommer av den induktive koblingen. I regionalnett der spolefordelingen er veldig ujevn, vil det være høyere overspenninger enn i nett som har jevn fordeling. Disse overspenningene kan derimot begrenses betydelig avhengig av om regionalnettet er driftet som et maskenett eller et radielt nett. Resultatene viser at overspenninger som kommer fra den induktive koblingen i nettet, vil begrenses kraftig dersom nettet driftes som et maskenett, sammenlignet med et radielt nett.

Machine Learning Methods for Anomaly Detection on Phasor Measurement Unit Data

Student: **Regev, Yuval - Vassdal, Henrik**
Supervisor: **Ümit Cali**

Summary

In a world of increased digitization and digitalization together with the increased demand of power and renewable energy sources, the cyber-physical interaction in the power system is expanding at a fast pace. This expansion requires new and improved techniques to ensure a stable and protected power system, able to deliver the necessary power demanded from the grid. Phasor Measurement Units (PMUs) provide the ability to improve monitoring and protection capabilities in power systems. These measurement units allow for precise high frequency measurements throughout the power system, increasing the situational awareness for system operators. However, these units require multiple components and systems working in unison, as well as data transmission over long distances. This makes the measurement system vulnerable for anomalies originating in the system itself, as well as external malicious cyber attacks. It is therefore crucial for rapid and effective anomaly detection schemes to protect and hinder instability in the power system.

This thesis investigates and proposes an anomaly detection method using machine learning and artificial intelligence models. Prediction based machine learning models together with error thresholding is used to locate and label anomalous data provided by PMUs. Two different data sets with PMU measurements are analyzed. The data sets contain real measurements from the power system in Norway and Texas, USA. The hybridization of machine learning models based on Convolutional Neural Network (CNN) and Long Short Term Memory (LSTM) architecture proved more effective in detecting anomalies in the tests completed, with a higher percentage of anomalies detected together with fewer false positives. The models lacked in performance detecting drift anomalies, however showed promising results for anomaly detection for injected noise, spikes and offset anomalies, laying a good foundation for further model development and real-time model deployment.

Investigation of polymer ablation and AirPlus™ for load current interruption of medium voltage systems

Student: **Kristoffer Rustad**
Supervisor: **Kaveh Niayesh**
Co-supervisor: **Paul Monceyron Røren**

Problem description

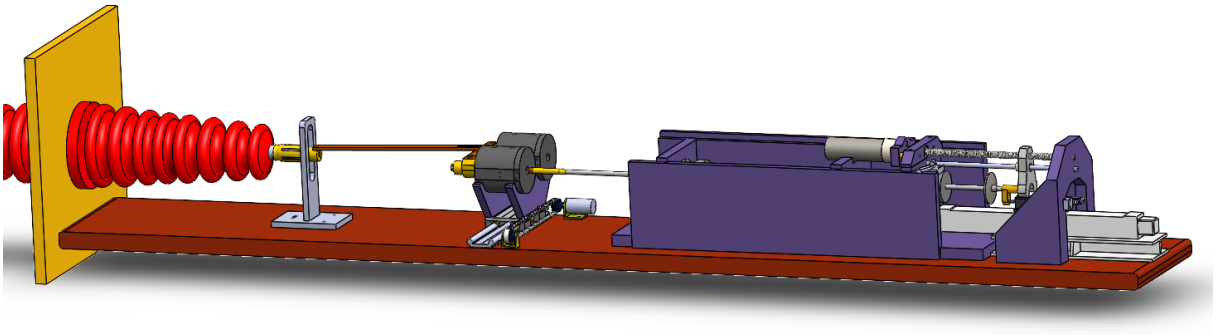
The use of switching devises is inevitable in any electrical system, as they control the power flow of the system. The work of this thesis has mainly focused on current interruption of load currents in medium voltage (MV) systems. Switching technologies for this purpose are today dominated by metal-enclosed switchgear filled with SF_6-gas. This gas acts as a more or less ideal medium for current interruption, but it is a very potent greenhouse gas with its high global warming potential (GWP) of 23900 times higher than that of CO_2 for a time horizon of 100 years. Increased environmental knowledge and awareness have in recent years led to a political desire to reduce and eventually stop the use of SF_6-gas. In the years to come, regulatory measures to limit the use of SF_6-gas are therefore expected. This has put pressure on switchgear manufacturers and research institutions to develop new switchgear technologies. One possible alternative is the use of polymer ablation and AirPlus™ for current interruption.

The task

The main objective of this thesis is to investigate the use of polymer ablation and AirPlus™ as an alternative to the non-environmentally friendly SF_6-gas for load current interruption of medium voltage systems.

Model/ measurements

Experiments have been conducted for four ablative polymers in the high current/circuit breaker laboratory at NTNU. The following polymers were selected for study; natural PTFE, natural PP, natural PEHD and natural POM-C. Experiments have been conducted for all the above-mentioned polymers with two different designs of the arcing chamber. A design constricting the arc within a limited volume, and a design constricting the arc within the same limited volume in addition to allowing for enhanced gas-flow at current zero. The experimental setup is shown in the figure below.



Conclusion

With the design, allowing for enhanced gas-flow at current zero, all ablative polymers achieved successful current interruption for experiments in AirPlus™ for all tested current levels. No major differences were detected in the number of successful current interruptions. However, PP and PEHD showed occurrence of undesired post-arc currents. PP and PEHD

also seem to be incompatible with AirPlus^{TM} for current interruption. The formation of large amounts of an unidentified substance during experiments with the two polymers in the gas raises major questions about the lifespan of a potential switch with this mix. Of the polymers tested, PTFE and POM-C therefore seem to be the best candidates for polymer ablation assisted current interruption in AirPlus^{TM}.

Baseline Estimation for Flexibility Validation

Students: **Simran Jit Kaur Sandhu and Marthe Vågen**
Supervisor: **Jayaprakash Rajasekharan**
PhD-student: **Surya Venkatesh Pandiyan**

Problem description
To deal with challenges posed by intermittent energy resources and the implementation of distributed energy resources, distribution system operators require flexible loads and energy sources that support the balancing of electrical energy supply and demand. An aggregator, acting as an intermediary, may purchase flexibility from consumers to aggregate and sell to a buyer, such as distribution system operators. The settlement process between aggregator and distribution system operator requires validation of the activated flexibility, which can be challenging as this activated flexibility can not be physically measured.

The task
The main research question of this master's thesis includes how the distribution system operator can validate this demand-side flexibility at substation level activated by the aggregator in the settlement process and how validation can be implemented in a realistic scenario using consumption data available to the distribution system operator. Load forecasting methods for baseline estimation can be implemented for this purpose, as they estimate what consumers would have consumed in the absence of flexibility activation. Two regression methods were proposed in this thesis: artificial neural network and multiple linear regression.

Model/ measurements
Two strategies were implemented with the regression methods: recursive and rectifying. The recursive strategy was chosen to improve the estimation results and make the simulations reflect a real-world scenario, as only data available to the distribution system operator was used. The rectifying strategy was implemented to improve the accuracy of the recursive strategy. Artificially created substation data with both 1 and 5-minute frequency from Austin, Texas, were used. Baseline estimation of individual households was also conducted to examine whether more information regarding the flexibility validation could be determined at a lower level.

Calculation
The implementation of the recursive strategy showed more accurate results in artificial neural network than multiple linear regression. Both methods followed the trend of the actual baseline, but neither method was able to capture the high fluctuating frequency. The rectifying strategy improved the baseline estimation results to some degree. The accuracy of the methods after implementing the strategies is moderate. However, it has scope for improvement in the future by using appropriate explanatory variables and advanced machine learning algorithms, among other factors.

The frequency adjustment had little or some effect on the accuracy of the methods, and neither of the two frequencies might therefore be more favorable for the DSO. As baseline estimation is challenging on residential data, the contribution from the individual house estimations might be negligible to the DSO in the settlement process.

Conclusion

The complexity of validation using baseline estimation has been proven, where even the most common regression methods fail due to the nature of the problem. Further work should research the factors affecting the strategies and examine different strategies.

Analyse av magnetiske tap i stålarmeringer ved å benytte en kompleks permeabilitet

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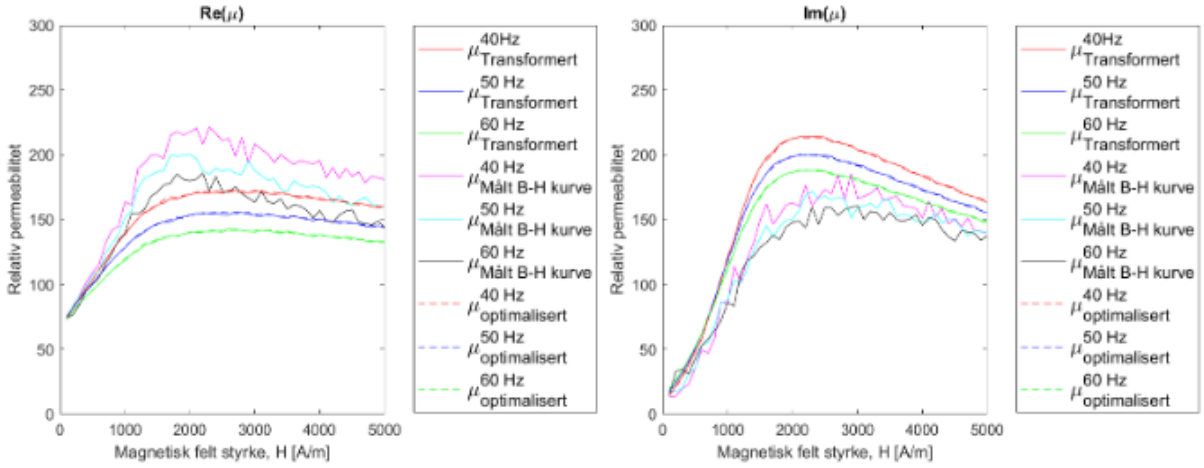
Veileder: **Bjørn Gustavsen**
Medveileder: **Arne Nysveen**
Utføres i samarbeid med: **NEXANS Norway**

Problemstilling
Sjøkabler konstrueres ofte med ytre stålarmering av magnetisk materiale for å oppnå tilstrekkelig mekanisk styrke. Armeringen gir tilleggstap som følge av hysterese i armeringen, hvilke øker oppvarmingen og derav reduserer overføringsevnen. Tapenes størrelse avhenger i stor grad av trådens permeabilitet. Beregningene av tapene blir ofte gjort ved formlene beskrevet av IEC-normer, hvilke er kjent for å overestimere tapene vesentlig. Ved å bruke hensiktsmessige modeller av kabler kan man beregne tapene med høyere presisjon ved å benytte Finite Element metoden (FEM). Denne metoden er imidlertid avhengig av å kunne bestemme materialets magnetiske egenskaper i avhengighet av påtrykt magnetisk feltstyrke og retningen på feltet. Dette kan oppnås ved å foreta fysiske målinger på armeringstrådene, som vil gi B-H kurver eller kompleks permeabilitet.

Oppgaven
Denne avhandlingen omfatter en studie om bruken av en kompleks permeabilitet til å beskrive et ikke-ledende material som erstatter et ledende material. Den komplekse permeabiliteten er basert på fysiske målinger gjort for fem ulike armeringstråder, og brukes til å beregne det totale tapet analytisk og ved å benytte FEM-beregninger i COMSOL. Det ble også utført målinger hvor B-feltet ble variert som funksjon av frekvens for åtte ulike armeringstråder. Hensikten var å se hvordan instrumentet målte og separert det totale tapet inn i hysterese- og virvelstrømstap. Den modifiserte Steinmetz metoden ble benyttet til å analytisk separere de totale tapene.

Modell/målinger
Målingene ble gjort ved måleinstrumentet Brockhaus Messtechnik og den tilhørende programvaren MPG100D. Målingene gjort for å finne de separerte tapene ble implementert i et Matlab-script som separerte og sammenligna de målte og de analytisk separerte totale, virvelstrøms- og hysteresetapene funnet ved å benytte Steinmetz metoden. Videre ble det gjort nye målinger hvor den magnetiske feltstyrken ble bestemt ved ulike frekvenser. Disse målingene ble benyttet til å beregne den komplekse permeabiliteten på 3 måter; 1) Ved å optimalisere faseforskjellen mellom B og H, 2) Ved å finne faseforskjellen mellom B og H for de målte B-H kurvene og 3) Ved å finne faseforskjellen mellom B og H for transformerte B-H kurver funnet fra reluktiviteten. Til slutt ble den optimaliserte komplekse permeabiliteten og den komplekse permeabiliteten funnet for de transformerte B-H kurvene brukt til å beregne de totale tapene ved analytiske formler og ved et fint, et medium og et grovt mesh i COMSOL.

Beregninger
Her er den reelle og imaginære delen av den komplekse permeabiliteten plottet som funksjon av påtrykt magnetisk feltstyrke ved 40 Hz, 50 Hz og 60 Hz. Dette er gjort for de tre tilnærmingene for å finne den komplekse permeabiliteten.



(a) Re(μ) (b) Im(μ)

Konklusjon

Resultatet fra de separerte tapene viste at det var godt samsvar mellom de beregna og de målte separerte tapene. Det ble derfor konkludert med at både målingene og beregningene baserer seg på samme tilnærming om at hysteresetapet endres proporsjonalt med frekvensen, og at virvelstrømstapet endres proporsjonalt med kvadratet av frekvensen.

Resultatet for den komplekse permeabiliteten funnet for de målte B-H kurvene stemte godt overens ved lave påtrykk av H-felt, da kurvene her var lineære elliptiske kurver. Ved høye påtrykk av H-felt ble B-H kurvene ikke-lineære, som gjorde at fasevinkelen ble for lav og dermed ble den reelle delen av den komplekse permeabiliteten for høy og den imaginære delen for lav, sammenlignet med de optimaliserte verdiene for kompleks permeabilitet. Den optimaliserte komplekse permeabiliteten hadde en veldig god overenstemmelse med den komplekse permeabiliteten funnet for de transformerte B-H kurvene. Når de optimaliserte og transformerte komplekse verdiene ble benytte i beregningene ble det et maksimalt avvik på 5% for de analytiske beregningene. Dette viser at man ved å benytte enkle analytiske formler sammen med en kompleks permeabilitet kan beregne de totale tapene for et ledene materiale.

For de ulike meshene i COMSOL ble det 0% avvik for både det fine og medium meshet, mens for det grove meshet ble det et makismalt avvik på 0.09%. Det resultatet viser er at man ved å bruke et ikke ledende materiale med en kompleks permeabilitet i COMSOL kan bruke veldig grove mesh uten at dette påvirker resultatet. Dette vil for stor og avanserte geometrier redusere beregningstiden.

Konklusjonen fra dette er at bruk av kompleks permeabilitet til å beskrive de totale tapene for et ikke ledende material som erstatter et ledende material er en effektiv og veldig presis tilnærming. Med minimale avvik og enkle formler kan en forutse tapene i en armeringstråd uten å være avhengig av å ha kunnskap om materialets egenskaper. Utføres det mange målinger på samme tråd og man finner en form for gjennomsnittsverdi for kompleks permeabilitet ved ulike påtrykk av H-felt og ulike frekvenser, kan man bruke dette til å forutse de totale tapene i avanserte geometrier for sjøkablene.

Energy Control of Complex Cyber-Physical Microgrids: Robustness against Cyber Attacks

Student: **Cornelia Skaga**
Supervisor: **Gilbert Bergna-Diaz**

Problem description
This master thesis presents an overview of the modelling and design of complex cyber-physical (CP) microgrids (MGs), further extending the work carried out in the associated specialization project. More precisely, the model of the closed loop CP microgrid is finalized and represented with the port Hamiltonian (pH) formalism, emphasizing the energy preservation and dissipation within the system dynamics, facilitating energy-based control design.

Following a hierarchical control perspective, the power generating units have a *decentralized* primary control behaving according to a droop characteristic, current surveillance and as a result regulating the voltage and thereby limiting the deviations from the pre-defined nominal voltage. Consequently, the primary controller ensures the sub-optimal operation of the MG and is shown to be globally asymptotically stable with respect to a new equilibrium point. However, the controller is not able to restore the initial operating conditions and the ability to steer the MG to desired optimal operation is therefore stymied. Motivated by this shortcoming, an outer loop distributed secondary controller is proposed, allowing for optimal operation of the MG.

The secondary controller incorporates decentralized droop control and *distributed* control compiled in a new distributed control network. The distributed control dynamics are characterized by the consensus protocol. It is by exploiting the communication between the neighbouring generating units that the MG is able to operate as desired. Hence, this additional control network constitutes the cyber layer of the cyber-physical MG. However, the use of communication links makes the distributed control system prone to cyber attacks. Cyber attacks perturbing the power systems may threaten the control operations and thereby prevent optimal behaviour of the MG. The cyber attacks may infiltrate the control dynamics in different locations, thereby causing different operational challenges.

The task
This thesis includes both finalizing the model of the CP MGs and analyses the control performance when the MGs are prone to cyber attacks. The cyber-physical microgrid is analysed with respect to three different types of cyber attacks: *false data injection attacks* in the control actuators, *stealth attacks* in the current sensors and *man-in-the-middle attacks* in the communication links. The problems emerging from these attacks are then studied with respect to the ability to still achieve the desired optimal steady state operations despite the attacks. The final objective is then to design a novel resilient control system, robust against all types of cyber threats: i.e., almost completely mitigating the negative consequences of the attacks, regardless of where, when, and how the attacks perturb the MGs.

Model/ measurements
The physical layer of the CP MG is first mathematically modelled by interconnecting generating units, transmission lines and power consuming loads through (skew-symmetric) power preserving interconnections. The model of the physical network characterizes the

electrical power system and is shown to admit a pH representation, facilitating the second outer loop control design and interconnected MG.
Secondly, the distributed control network dynamics are characterized by the consensus protocol. It is by exploiting the communication between the neighbouring generating units that the MG is able to operate as desired. Hence, this additional distributed control network constitutes the cyber layer of the cyber-physical MG due to the use of communication. It is shown that the cyber network admits a pH representation -- in a similar fashion as the electrical network.

The control objectives are secondly defined, and MG's secondary controller is implemented with the intention of bringing the system to desired optimal stable operations while satisfying the control objectives given as*: proportional current-sharing* and *average voltage regulation*. Proportional current-sharing is ensured by solving a convex optimization problem, formulated with the objective function summarizing the cost of generation. Lagrangian duality is then applied in order to rewrite the problem formulation and solve the convex optimization problem with the Karush-Kuhn-Tucker conditions. The secondary controller is then finalized with dynamics based on the stationary conditions of the optimization problem, providing proportional current-sharing. Average voltage regulation is guaranteed by adding weightings in the interconnections between the two networks, ensuring that the weighted sum of all the generating unit's voltages is equal to the pre-defined nominal voltage of the MG.

The two layers (cyber and physical) admit the pH system representation and are then interconnected through an interconnection pattern–including added weightings and modified dissipation–constituting the final cyber-physical MG. The perturbing cyber attacks are then individually implemented with equal system-dynamics corresponding to the location of the attack of the studied cyber threat. The finalized resilient control system is then modified with sufficient tuning of both primary and added secondary control parameters in order to remove the influence of the attacks and then optimally operate the MG.

Conclusion
Incremental energy modelling and Lyapunov stability criteria are used to conclude that the linear CP MGs always converge to a steady state equilibrium regardless of the potential attacks. However, the three different cyber attacks perturb the controller's ability to ensure the two control objectives at this converged equilibrium. The finalized secondary controller, combined with the appropriate resilient tuning of the control parameters, is then concluded to be sufficient in almost completely remove the influence of the attack for a variety of cyber threats. However, the controller is not robust against the very discrete implemented stealth attacks, and the controller needs to be further modified in order to ensure complete novel robustness.

Utprøving og samspill mellom ulike smarthus-løsninger

Student: **Jonas Skaadel**
Veileder: **Eilif Hugo Hansen**

Problemstilling
Kommuniserende enheter får stadig større plass i mange deler av samfunnet, og spesielt i hjemmene våre. Et hjem med flere kommuniserende enheter kan kalles et smarthjem. Eldrebølgen, det grønne skiftet og generell effektivisering er områder hvor smarthjem bør utnyttes, men for at dette skal skje kreves det stor tilpasning og derfor er det essensielt med gode og brukervennlig løsninger. Formålet til masteroppgaven vil være å svare på spørsmålene som er presentert nedenfor:

- Hva slags problemer og utfordringer oppstår under design av et smarthjem og hvilke løsninger kan hjelpe?

- Hvordan fungerer kommunikasjonsprotokoller og komponenter fra ulike produsenter sammen i et smarthus?

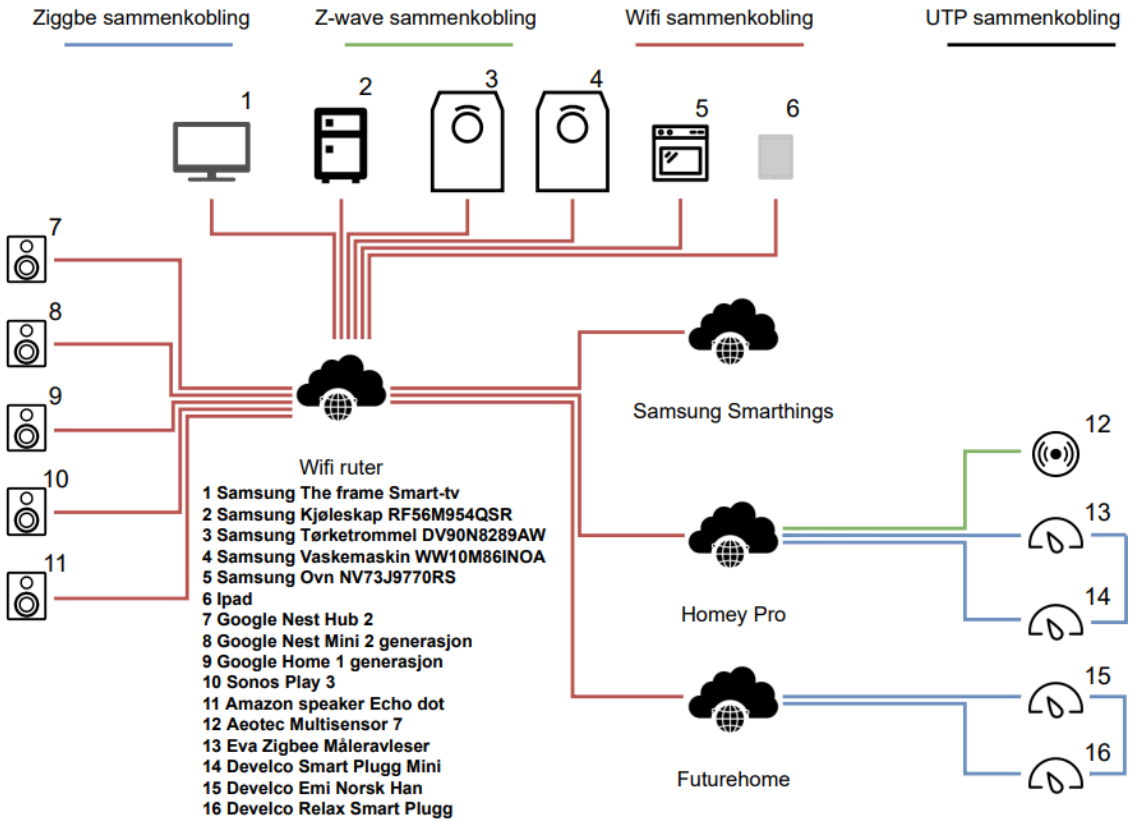
- Kan det formes en generell guide for å bygge opp et smarthjem?

- Hva er nytteverdien til dagens smarthjem-løsninger i forhold til eldreomsorg og det grønne skiftet, og hvordan fungerer løsningene?

Oppgaven
Masteroppgaven blir hovedsakelig delt opp i to deler; en grundig teoretisk del bestående av bakgrunnskunnskap og relevant litteratur og en praktisk del som består av viderebygging og design av et smarthjem, hvor hele prosessen blir nøye og stegvis forklart fra innkjøp til vedlikehold. Alle typer utfordringer i de forskjellige delene av prosessen vil bli belyst sammen med hva som blir oppnådd.

Modell

Illustrasjon av sammenkoblingen av enhetene i siste konfigurasjon kan sees nedenfor. Rød strek er en sammenkobling med Wi-Fi protokollen, grønn er Z-wave, blå er Zigbee og svart er UTP, Wi-Fi ruteren er koblet til internett.



Konklusjon

- For et smarthjem med kommunikasjonsprotokoller og komponenter fra ulike produsenter er funksjonaliteten til hjemmesentralen helt sentral for sammenkoblingen og virkemåten. Utfordringer med sammenkobling i smarthjem skyldes oftest mangel på integrering av smartenheter i hjemmesentralens programvare.

- Når det kommer til det grønne skiftet blir bruksområde energisparing ansett som relevant. Uttestingen av smartleiligheten har vist at det er mulig å overvåke og automatisk styre den elektriske effekten til leiligheten med riktige komponenter.

- De største utfordringene under design av smarthjem kommer av lite samarbeid mellom produsenter og at smarthjem generelt har en høy kompleksitet. Dette byr på utfordringer som: flere ulike metoder for å koble sammen smartenheter med hjemmesentralen, krav om flere ulike brukerkontoer og apper, og en komplisert innkjøpsfase som krever erfaring med hver spesifikk enhet som skal implementeres i smarthjemmet.

Statisk UPS i strømtilførsel til CT - Vurdering av pålitelighet og reduksjon av kostnader

Student: **Vegard Solberg**
Veileder: **Eilif Hugo Hansen**
Utføres i samarbeid med: **COWI AS**

Problemstilling

I de senere år har det blitt et økt fokus på avbruddsfri kraftforsyning til elektromedisinsk utstyr, slik som den avanserte røntgenmaskinen CT (computertomografi). Til dette formålet benyttes ofte en dedikert, statisk UPS. I denne oppgaven undersøkes denne problemstillingen: *Kan investeringskostnadene for avbruddsfri kraftforsyning til CT-maskiner reduseres, uten at strømforsyningens pålitelighet blir merkbart svekket?*

Oppgaven

Målet med denne oppgaven er å utfordre gjeldende praksis hos COWI, som er å dimensjonere UPSen ut fra summen av dimensjonerende effekt for samtlige CT-maskiner tilknyttet denne.

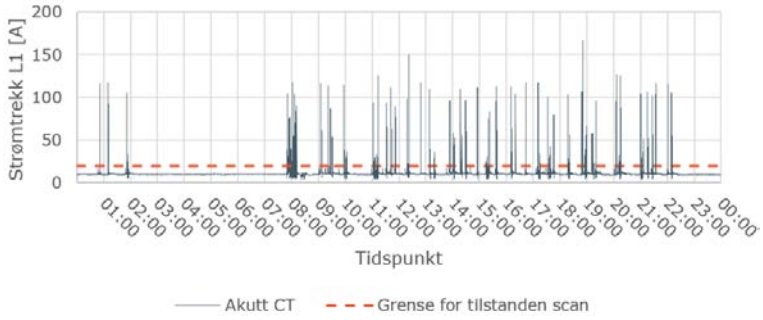
Modell/målinger

Oppgaven består av både innsamling av bruksdata for 5 CT-maskiner ved St. Olavs hospital og modellering av påliteligheten for strømforsyningen frem til CT-maskiner ved et tenkt/generelt sykehus. Den består også av innsamling og analyse av kostnader for avbruddsfri strømforsyning fra tidligere gjennomførte sykehusprosjekter.

Strømtrekket til CT-maskinene ble målt med dataloggere påkoblet respektive kursavganger i de ulike hovedfordelingene ved St. Olavs hospital. Disse dataene ble etterbehandlet basert på at CT-maskinen befinner seg i en av to valgte tilstander:

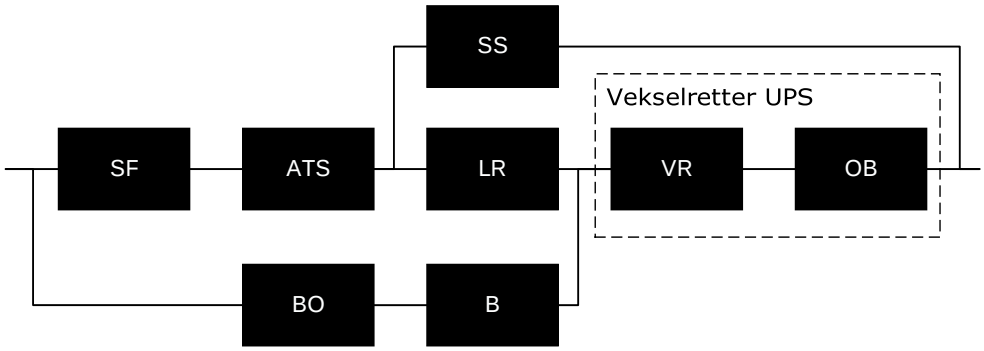
- *Skann* (Høyt strømtrekk. Pasient blir bestrålt med røntgenstråling)
- *Standby*. (Lavt strømtrekk. Røntgenrør genererer ikke røntgenstråling)

Basert på disse to tilstandene kunne gjennomsnittlig tid mellom *skann* og gjennomsnittlig varigheten av *skann* beregnes. Disse behandles som ekvivalente til MTBF og MDT i pålitelighetsanalysen for å beskrive muligheten for overbelastning av UPSens vekselretter. Typisk strømtrekk/bruk for en CT-maskin for en dag er vist i følgende figur:



Strømforsyningen frem til CT-maskinene modelleres som en hybridmodell. En Markov-modell beskriver strømforsyningen frem til hovedfordeling nødkraft og hvordan denne veksler mellom forsyning fra nettleverandør og nødstrømsaggregater, mens et pålitelighetsnettverk beskriver resterende strømforsyning frem til CT-maskinene. Et forenklet pålitelighetsnettverket består av strømforsyningen inn på hovedfordeling nødkraft (SF), omkoblingsautomatikken inni denne (ATS), samt UPSens: Likeretter (LR), statiske switch (SS), batteriomformer (BO), batteri (B). UPSens vekselretter består av to blokker, hvorav VR

beskriver svikt i selve vekselretteren, mens OB (overbelastning) beskriver en bruk av *k-av-n* mulige CT-maskiner som fører til overbelastning av vekselretteren. Forenklet pålitelighetsnettverket sees påfølgende figur, hvor feildata for de fleste komponentene stammer fra OREDA eller IEEE Std. 493.



Resultater

En rekke forutsetninger gjelder for følgende resultater for påliteligheten til strømforsyningen, hvorav en av de viktigste er at den statiske switchen ikke kan bli overbelastet. Resultatene gjelder for 1 til 5 tilkoblede CT-maskiner på en og samme UPS. For avbrudd i strømforsyningen fås bl.a. disse resultatene:

- Dimensjoneres UPSen iht. gjeldende praksis hos COWI fås en MTBF på 10 147 år
- Dimensjoneres UPSen for 3 av *n* CT-maskiner fås en MTBF på 3025år til 6155år
- Dimensjoneres UPSen for 2 av *n* CT-maskiner fås en MTBF på 599 år til 67 år.

For den målte bruken av CT-maskinene ved St. Olavs hospital, deles disse opp i bruk innenfor normal arbeidstid (hverdager kl. 7 til 15) og utenfor normal arbeidstid. Resultatene fra disse målingene sees i tabellen:

	gjennomsnittlig tid mellom *skann*	gjennomsnittlig varigheten av *skann*
Innenfor normal arbeidstid	5 min 51 s	14 s
Utenfor normal arbeidstid	13 min 15 s	16 s

Konklusjon

UPSens installerte effekt kan reduseres slik at MTBF for strømforsyningen forventes å være lengere enn byggets levetid (60 år). Dette gjelder bare om visse betingelser er oppfylt:

- Antall tilkoblede CT-maskiner må være 3 eller flere.
- Hvis 3 til 5 CT-maskiner er tilkoblet en UPS, kan denne dimensjoneres for å dekke det dimensjonerende effektbehovet for 2 av disse.

Ved en slik dimensjonering kan forventet besparelse direkte knyttet til selve UPSen bli i størrelsesorden 100 000 kr til 600 000 kr. Det er dermed en begrenset økonomisk gevinst for prosjektet ved å neddimensjonere UPSen på denne måten.

Anbefalingen til fremtidige sykehusprosjekter blir bl.a. at ev. avbruddsfri kraftforsyning til CT-maskiner ikke bør tas av budsjettet til den generelle elektroinstallasjonen, men isteden være en del av budsjettet for medisinteknisk utstyr. Dette åpner for at det medisintekniske personalet selv kan gjøre de mest rasjonelle disponeringene ut fra tilgjengelige midler. Da kan gevinsten for pasienten bli hovedfokuset, noe som gjør at avbruddsfri kraftforsyning kan vurderes mot andre tiltak, slik som eks. anskaffe av flere CTer.

Undersøkelse av tekniske utfordringer ved bruk av DC forsyning til veibelysningsanlegg

Student: **Solbrekken, Gustav Georgescu**
Faglærer: **Eilif Hugo Hansen**

Sammendrag er ikke tilgjengelig på grunn av båndlegging.

DC insulation materials for a modular HVDC generator

Electric stress testing of epoxy with and without silica filler

Student: **Sofie Barmen Stein**
Supervisor: **Pål Keim Olsen**
Co-supervisor: **Frank Mauseth**
Collaboration with: **SINTEF**

Problem description

A modular HVDC generator (ModHVDC) has been developed to meet offshore wind energy production challenges. It introduces a segmentation in the stator by dividing it into different modules and offer higher reliability, reduction of components, and DC at its terminals, making it desirable for an evolving HVDC transmission network. However, the entire design of the machine is not completed and is still in research. A challenge regarding the machine is the insulation system due to a DC potential in the stator, making it more complex than an AC insulation system. No suitable DC insulation materials have yet been developed for the modular machine.

The task

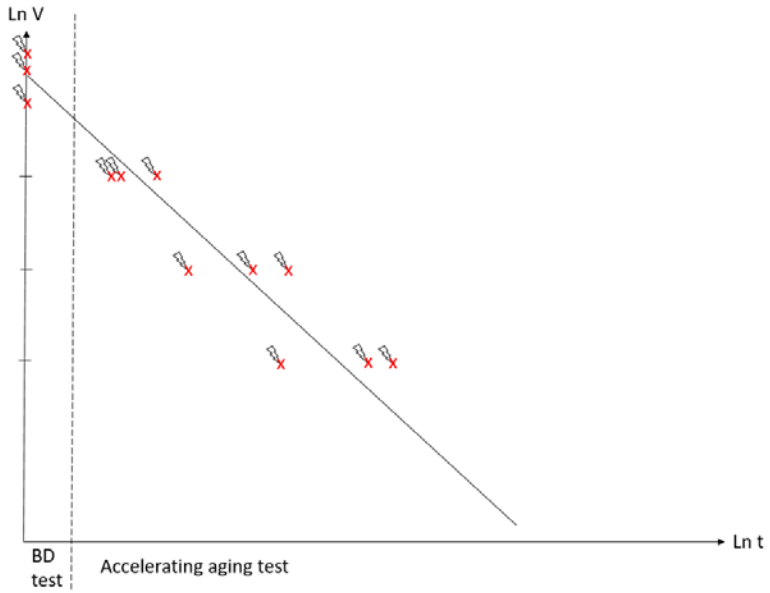
This thesis investigates the modular HVDC machine's electrical DC insulation system design. Electric stress testing was performed on epoxy cups with and without silica filler to obtain lifetime curves. Due to DC complexity and the capacitive field when turning on/off the machine, AC was applied.

Model/ measurements

IEC 60505 suggests the inverse power law model when making lifetime curves.

$$L(V) \propto xV^{-n}$$

The principle of how to obtain a lifetime curve with the help of BD and accelerated aging tests as a function of time and voltage is shown in the figure below. From the breakdowns (lightning) at different voltage levels, a linear graph can be drawn in a log-log representation of the axis, showing the life of an insulation system. The illustration has three tests at each voltage level.



Calculation
The table presents the results obtained from the breakdown tests in the epoxy cups with and without silica filler. The average BD voltage was calculated from the BD voltage at each cup.

	Breakdown voltage [kV]						Average breakdown voltage [kV]	
	Room temperature			70 °C			Room temperature	70 °C
Cup	**2A**	**1B**	**3C**	**4B**	**4C**	**1D**		
Epoxy cup without silica filler	46.5	34.1	44.2	33.9	33.8	36.4	41.6	34.7
Cup	**2A**	**3A**	**1B**	**5A**	**2B**	**3B**		
Epoxy cup with silica filler	37.0	26.8	31.9	35.8	31.0	38.7	31.9	35.2

As the test temperature at 70 degrees Celsius coincides best with the actual operating state of the modular HVDC machine, how the cups preformed at this temperature weights more compared to the tests performed at room temperature. However, no significant deviation in the average BD voltage between the epoxy and epoxy with silica flour cups was found at 70 degrees Celsius. Hence, it is difficult to conclude the best performing cup configuration.
It must, however, be addressed that the epoxy cups with silica filler withstood the temperature increase better compared to the epoxy cups without silica filler. It could be assumed that a further increase in temperature will give an even poorer average BD voltage in the epoxy cups without silica, and that adding silica flour will resist the temperature change better.

Conclusion
This thesis aimed to establish lifetime curves for a DC insulation system for a modular HVDC generator. However, due to the time limitation, it was not accomplished. Poor painting of the semiconducting layer and several voltage interruptions gave invalid results. When the corners of the cups were coated better, the time to breakdown increased both at 95 % and 90 % of the average BD voltage at 70 degree Celsius, giving no results that could be used in the further development of lifetime curves.

Despite this, other results from PD and BD tests were obtained at AC. In addition, was a methodology made. They can be used in further developing the DC insulation system for the modular HVDC machine.

A Study of Internal Temperature Dependency in Norwegian Railway Transformers

Student: **Aurora Paulsrud Stenvig**
Supervisor: **Hans Kristian Høidalen**
Co-supervisor: **Yared Samson**
Collaboration with: **Bane NOR**

In step with modern technological advancements and developments, electried railways have bloomed throughout the past century, spreading across state borders and making for complicated interconnected systems. The need for better and more intelligent railway systems has snowballed with increasing traffic- and freight loads, causing a domino effect for expansion, modernization, proliferation, and infrastructure improvement. The trend of increasing traffic load on the electrified railway infrastructure poses an increase of stresses affecting the electrotechnical systems and their components. This development has motivated a renaissance in the railway sector, with record-high governmental investments intended to increase the capacity of the Norwegian railways. Since the Norwegian electrical railway network operates at a different nominal voltage and frequency than the regional grid, energy conversion is required. This is managed by frequency converters and voltage transformers.

The interrelationship between economic, safety and security, environmental, and technical interests make insight into the actual state and life of the electrotechnical railway installments attractive studies. The transformer responsible for the voltage transformation to appropriate railway levels is among the most costly single-component installations in the ERPSS, making their investment and longevity highly desirable. Thermal limits have traditionally established the dimensioning criteria for such transformers, but recent advances have established advanced loading pattern simulations as a more accurate decider. This development has reduced the overdimensioning of electrotechnical arrangements, which have yielded both technical- and economic advantages.

This master's thesis aims to evaluate the relationship between real-life loading and the internal temperature of railway transformers and the consequences that the railway-specific stresses impose. Furthermore, the transformers' importance and role in the railways' reliability and security are investigated. The exploratory portion of this thesis is based on collecting and examining recorded data from three transformers installed in two different converter station arrangements. Through the exploration of relevant laws, standards, and regulations, this thesis’ findings find a definite dependency relation between the internal temperature of a railway transformer and the load it is exposed to, as well as its relation to its surroundings, which in further works can be useful as a basis for transformer dimensioning evaluations.

Comparison of droop-based grid-forming and PLL-based grid-following control of VSC during symmetrical fault

Student: **Ole Amund Storlien**
Supervisor: **Kjetil Obstfelder Uhlen**

Summary

This thesis is about controlling of voltage source converters during a fault scenario. More specifically it is about comparing two different control methods, namely droop-based grid-forming control and PLL-based grid-following control. The fault conditions are varied in order to uncover the performance characteristics of the two control methods and quantify their advantages and disadvantages. During the simulation study the difficulty of limiting fault currents in grid-forming control was discovered. Two simple methods of limiting the fault current was discovered, and compared with each other, as well as with the grid-following control.
The comparison was done in a scenario provided by Siemens Energy - Offshore Marine Center. They have field experience with operation and control of droop-based grid-forming converters, through their work in delivering power system solutions to electric passenger ferries in Norway. Their challenges related to handling of faults in the outer-lying grid during charging, is the background for the simulation study in this thesis. The scenario was modelled in the Matlab/Simulink environment, and the simulation study performed in the time-domain.
The main difference between the control methods ability to handle a symmetrical fault is related to their control objectives. The grid-forming converter injects large reactive currents to prevent the voltage from dropping, whereas the grid-following converter allows the voltage to drop. The fault current limitation was done through saturating or removing the feed-forward term in the voltage control loop. This came at a large cost of performance for the grid-forming control, resulting in a superior ability to handle the fault for the grid-following control.
The grid-forming converter had less robustness when it came to varying fault duration, and had a smaller critical clearing time than compared to the grid-following converter. The effect of increasing the fault magnitude, i.e fault current, was less detrimental than increasing the fault duration. The grid-following converters point of weakness was discovered when increasing the line impedance, as it highly dependant on a strong connection to the power grid. It was therefore concluded that without proper fault current limitations techniques in the droop-based grid-forming converter, the PLL-based grid-following converter performs better whenever not exposed to a high impedance grid

Small-Signal Stability Analysis of GridVille's Microgrid

Student: **Kjell Petersen Synstad**
Supervisor: **Mohammad Amin**
Collaboration with: **GridVille**

Problem description and the task
The objective of this thesis is to use small-signal analysis on the microgrid of GridVille, a student project trying to build a microgrid for a village in Nepal, to come with practical suggestions for improving the stability of the energy system. The practical suggestions that is mentioned are concretised by investigating changing the parameters voltage, droop gain, interconnecting lines and load distribution.

Model/ measurements
To analyse the microgrid, the paper *Reduced-order model and stability analysis of low-voltage DC microgrid* by Sandeep Anand and Baylon G. Fernandes was used as the foundation. The model in the paper is recreated and a new model is developed for GridVille's microgrid with the same procedure as the paper. The line currents and source currents have the same response, except for a difference in the time scaling for the paper recreation. For GridVille representation, the response follows similar patterns compared to the papers' response and is therefore used for further analysis.

Calculation
The results generally show that there are no big variations in position of the rightmost eigenvalue. All the scenarios are stable and well damped. The biggest difference in eigenvalues comes from the scenario where two interconnecting lines are added to the microgrid. There is a significant movement of the rightmost eigenvalue towards the y-axis. The scenario with the rightmost eigenvalue the most to the left is where the scenario where two power sources are placed in one node, and not two different.

Conclusion
The suggestions for improving the GridVille's microgrid is summed up in the points: 1) Increasing the voltage 2) One bigger power source is better than two equally big 3) Reduce the number of nodes. Based on the results, it seems that the system is more stable when the microgrid is simpler. To achieve that, the Battery Energy Storage System (BESS) or loads can be placed on more than one node and power sources can be put together. However, due to the geographical location of the microgrid, this may not be possible if there solar photovoltaic (PV) array and wind turbine do not produce their maximum at the same location or that there only one place that the load can be placed.

Optimal Integration and Control of Distributed Batteries for Multiple Grid Services

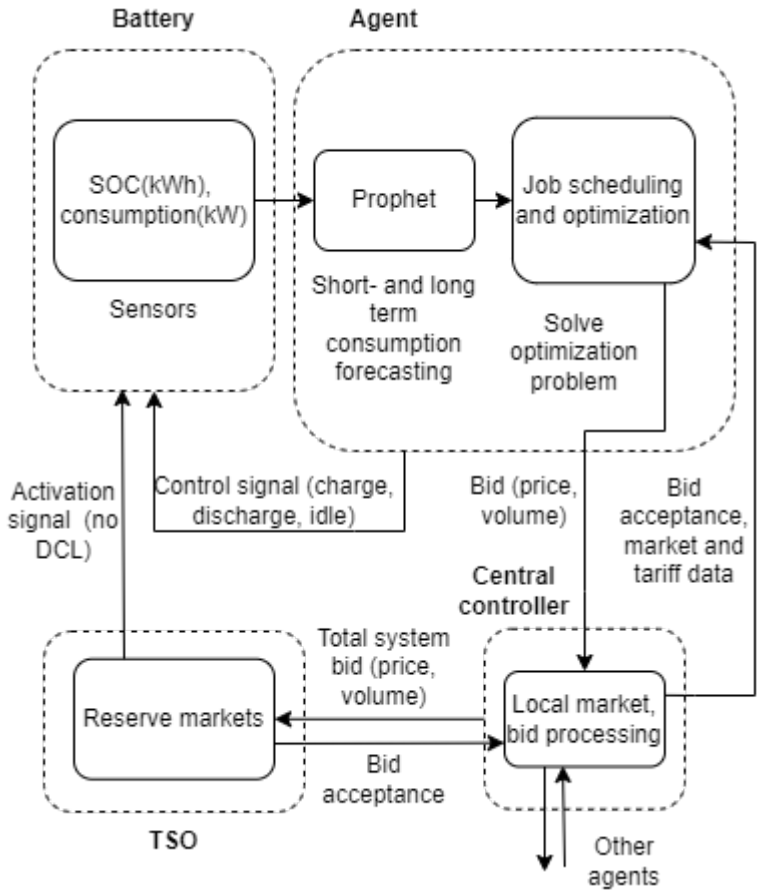
Student: **Abraham Paulsen Sørdalen**
Supervisor: **Jayaprakash Rajasekharan**
Collaboration with: **Pixii AS**

Problem description
The electrification of society and the increased power generation from highly variable, intermittent and distributed Renewable Energy Resources (RES) can cause imbalance, instability, and congestions in the transmission- and distribution system. Typically, Battery Energy Storage Systems (BESS) have been deployed for only one or two flexibility services. Can a control model be implemented for distributed BESS to provide multiple grid services? How can agent-based modeling be utilized to control BESS?

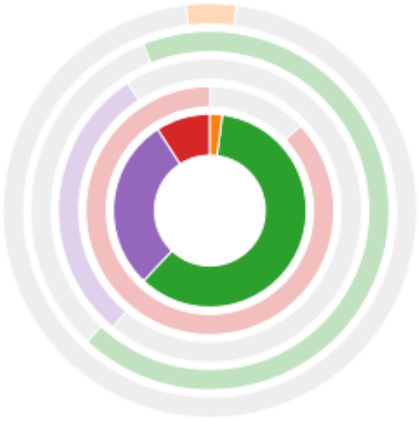
The task
To answer the research question, the master thesis aims to:

- Identify relevant services that BESS can provide, and the market driven economic incentives.
- Study the characteristics of energy arbitrage, peak-shaving and reserve market participation services and research the constraints in the FFR-, FCR-, energy markets and the utility tariffs that are relevant for these applications.
- Research power consumption forecasting and optimization methods to determine service priority for distributed BESS.
- Develop a model that acts as a proof of concept for the feasibility of distributed BESS providing multiple grid services. Implement the Prophet forecasting algorithm and utilize forecasts to optimize service allocation 48 hour ahead. Create a central control system that performs market clearing and promotes agent cooperation to increase flexibility.
- Evaluate the flexibility of the proposed model on several scenarios and determine the operational feasibility of the implemented model.

Model/ measurements
The model is divided into four segments. The battery segment collects consumption from the battery owner and SOC data from the battery. The agent segment performs forecasting, job scheduling and optimization. It is in the agent segment where most of the calculations and optimization is done. It is in the central controller segment where agents can communicate with each other by trading services and obligations.



Calculation



(a) Service allocation with max. agent service proportion.

(b) Service revenue.

Service	Jobs [%]	Rev. [%]
Peak-shaving	9.0	5.2
FFR	28.9	40.0
FCR D-2	59.9	52.4
FCR D-1	2.1	0.6
Energy arb.		1.8

Metric	Values
Total energy rating	1514kWh
Total power rating	757kW
Monthly revenue	13263€
Rev./energy	8.76€/kWh
Rev./power	17.5€/kW

Peak-shave success	Tot. energy traded	Avg. price of flex
10.0%	62.0MWh	0.65€/h

Traded hours	Rev. inc. from trading	Trading val.
19.8%	0.26%	2256€

Conclusion

Based on simulations in a developed and implemented model, it can be concluded that agent-based models can be utilized to increase BESS flexibility and revenue. The results indicate that the developed model increases revenue when providing multiple services compared to single-service applications. The results also show that trading of service obligations between agents slightly increase revenue and increases the overall system flexibility

Optimal Operation of Flexible Assets in a Residential Energy System: A Rolling Horizon Approach

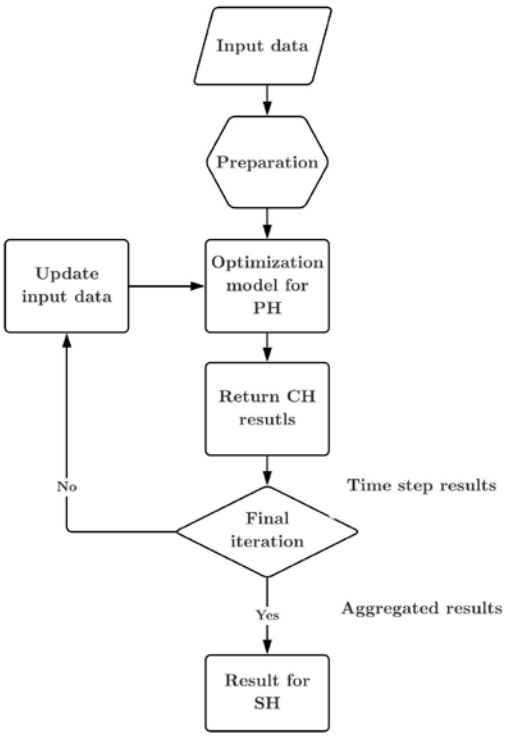
Student: **Mikal-André Tvedt**
Supervisor: **Magnus Korpås**
Co-supervisor: **Kasper Emil Thorvaldsen**

Problem description
In order to meet the increasing fluctuations in electricity prices, Norwegian domestic end-users are expected to implement flexibility solutions in order to balance their demand on the power grid. Flexibility assets such as batteries can shift end-user load on the grid away from the expensive power peaks to other hours of the day. Operation of these assets can play a key role in reducing the financial burden of increased prices placed on the end-user. However, to generate value in the long-term, these assets must be operated in a cost-optimal manner.

The task
The objective of this thesis is to develop an optimization algorithm with the goal of optimal operation of flexible assets with respect to costs, in conjunction with inflexible household load. The flexible assets examined are battery energy storage, electric vehicles with bidirectional charging capabilities, and domestic hot water, supplemented by a PV system. The algorithm will be applied to a case household to investigate cost optimality and the long-term value of the flexible assets.

Model/ measurements
The algorithm is developed within a rolling horizon framework. In each iteration, a linear programming model solves the optimal operation of assets under a prediction horizon, and returns the state variables to be used as initial conditions for the next iteration. The prediction horizon consists of forecasted demand load and prices based on the patterns observed during the previous week.

The assets are simulated in configurations of both individual and simultaneous operation for each moth of 2021. The price signals that determine the cost are Real Time Prices, and a grid tariff consisting of Time of Use and Capacity Subscription components.



Calculation
To determine the vale, the costs incurred during operation is compared to a reference case where the assets are in static operation. Under this approach, the battery system could reduce yearly costs with 2% compared to a reference case, and flexible water heaters provided up to 2.55% yearly cost reduction. Smart charging of the eclectic vehicle yielded a reduction of 5.7%, and 6.1% if bidirectional V2H charging was applied.

Some months yielded lower cost savings when bidirectional charging was enabled compared to ordinary smart charging. With the applied charge/discharge efficiency, high price variations are required in order for bidirectional charging to be profitable. In the case where all assets were present, yearly cost reductions were 7.93%.

Conclusion

The total costs were reduced for all cases in all months of the year, illustrating the long-term value of optimal operation of flexible assets. The most benefit results from shifting load to less expensive hours, thereby reducing the electricity purchase cost and the grid tariff expenses. Periods with large price variations resulted in large cost reductions in costs, while periods with stable prices resulted in relatively low reductions. However, the flexibility potential of the assets is limited by the load limit imposed by the Capacity Subscription scheme, which penalizes high loads regardless of the time of day. Seasonal variations also impact the cost saving ability of the flexible assets. The summer months are characterized by high PV input and low household heating demand, which allows for grater flexibility potential.

Advanced Control Scheme Development for Single-Stage Solar PV System

Student: **Hyginus Sunday Ugwuanyi**
Supervisor: **Mohammad Amin**

Problem description

The greatest ever-expanding installed capacity of solar photovoltaic (PV) energy sources has drawn the attention of the worldwide electrical electricity generating market within the last few decades. Because of the widespread use of grid-connected PV systems, robust grid codes have been developed to ensure the stable and secure operation of existing grids. Solar PV systems' unpredictable characteristics and tight grid-codes demand power electronic-based energy conversion devices. Also, as the power levels generated by the solar PV systems rise, multi-level voltage source converters (VSC) and their control mechanisms become more necessary for effective energy conversion.

The task

This Thesis investigates the grid integration of solar PV system into electricity network to improve the power quality and achieve less total harmonic distortion (THD) for the system. The work done focused on implementing advanced control approaches for single-stage PV system. The maximum power point tracking (MPPT) algorithm controls the switching of the dc-dc converter to extract the maximum power while the dc-ac converter provides a constant dc voltage for the boost converter. If the PV system is implemented in the single-stage, i.e., the dc-dc converter is removed, it will improve the efficiency and minimize the cost and size of the PV system. To achieve this goal, an advanced control technique that can extract the maximum power from the PV, and also, maintain the stability of the system has been proposed. The advanced control approach for the single-stage PV system adopted for this project is based on the artificial neural network (ANN) and model predictive control (MPC).

Model/ measurements

The ANN control and continuous control-set model predictive control (CCS-MPC) are the two main advanced control schemes implemented on MATLAB/Simulink environment for a single-stage grid-connected solar PV system. The CCS-MPC is used as an expert/ a teacher to generate the data required for off-line training of the neural network controller. After the off-line training, the trained ANN can fully control the inverter's output voltage and track the MPP without the need for CCS-MPC during testing. A single-stage CCS-MPC has been simulated for a two-level converter. For this project, a single step prediction horizon for CCS has been adopted because of its fast-forecasting horizon with precise and more repeatable solution. The system configuration and setup diagram is shown in figure 1.

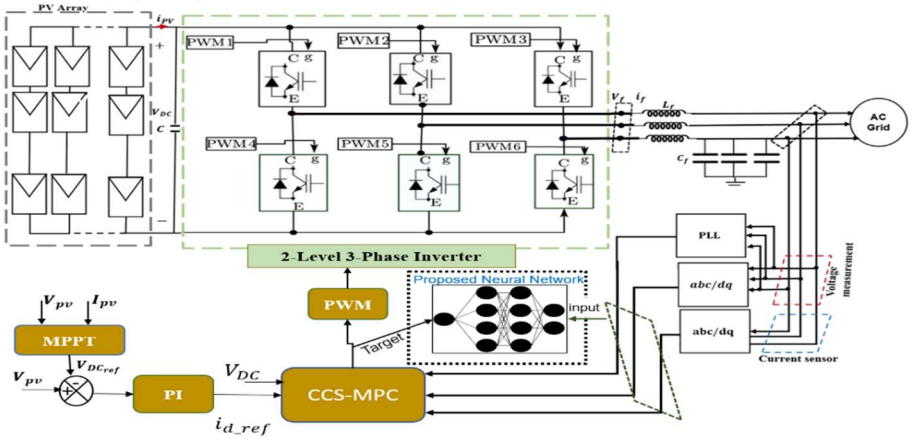


Figure 1: CCS-MPC with Artificial Neural Network training phase

Calculation

The results obtained from the two main control schemes are similar. It can be observed from Figure 3 that the proposed controllers have been able to track the maximum power point within few milliseconds and send power to the grid according to the PV irradiance profile in Figure 2. The accuracy of the controllers can also be measured from the results in Figure 5 on how the V_{dc} was able to track the reference, and how the output current in Figure 4 was able to follow the MPP tracking profile in Figure 2.

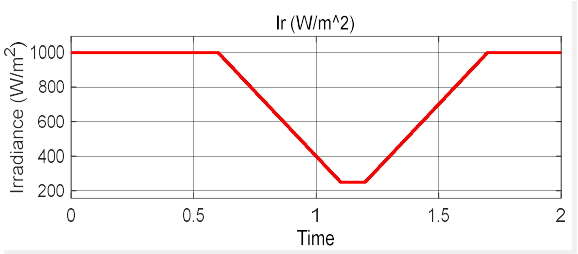


Figure 2: Irradiance profile applied for Verification

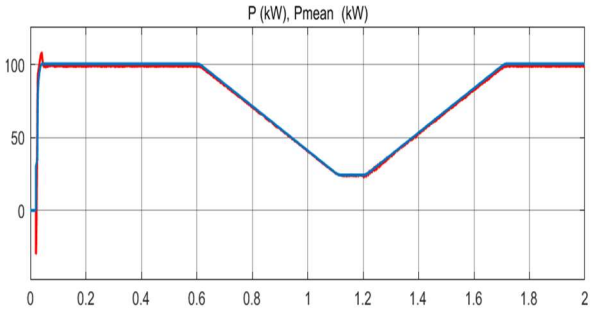


Figure 3: DC-AC power simulation results under linear irradiance

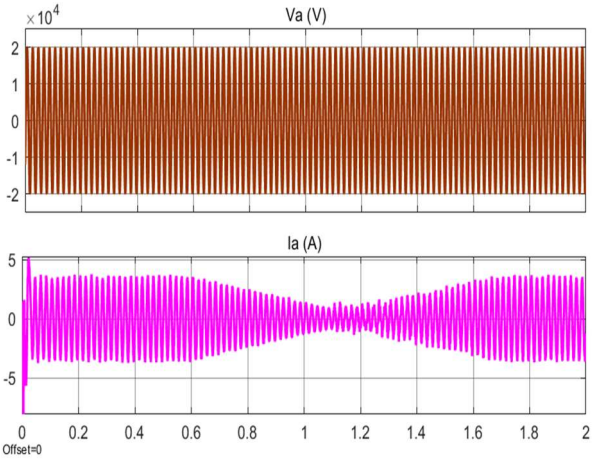


Figure 4: Simulation results under linear irradiance change: a) output AC voltage, and b) AC output Current.

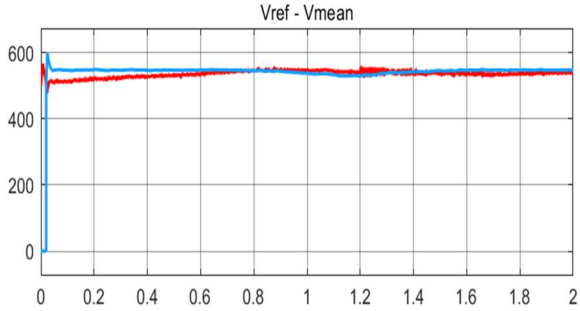


Figure 5: DC-AC power simulation results under linear irradiance change.

Conclusion

The proposed controllers have been able to ensure high power quality extraction within the range of the irradiance and even with the step changes in irradiation. Both controllers have an improved capability to track the reference current during transients and a decoupled current control function. The current and voltage THD values recorded shows that the system performance satisfied the 5% grid interconnection standard. The proposed model can be an excellent option to build a greener environment for the future by improving the current power generating PV system by minimizing current THD and power loss.

Norwegian Day-ahead Electricity Price Forecasting using AI Models

Student: **Gajanthini Vamathevan**
Supervisor: **Ümit Cali**
Contact: **Marthe Fogstad Dynge**

Problem description

The adoption of the Energy Act in 1991 in Norway led to the liberalization of the electricity market which has caused competition among the supplier, consumers and brokers as the electricity price depend on the bids and offers processed in a trading. Thus, it is vital for these market participants to make the most optimal decisions in the light of minimizing economic losses in the auction and exploiting forecasting tools may provide with the answer.

The task

The day-ahead electricity price in 2021 of the five bidding zones in Norway is to be forecasted. Essential input data will be assembled from various entities, appropriate preprocessing actions such as feature extraction, restructuring and cleansing of data, normalization and clustering may be incorporated to the input data. These will further be injected to the two disparate DL models, ANN and LSTM, implemented in Python, and necessary postprocessing techniques like de-normalization and de-clustering may be applied before inserting the results into model output statistics (MOS) for visualisation and analysis of the performance of the various models through evaluation metrics.

Model/ measurements

The presented flow charts in Figure 1 and Figure 2 is illustrating the methodology that is to be conducted in this thesis.

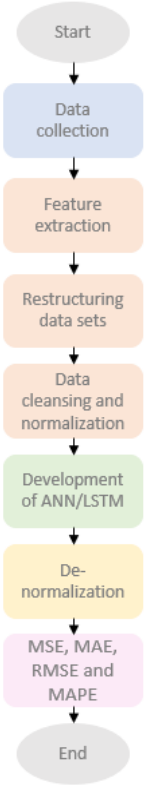


Figure 1: No clustering

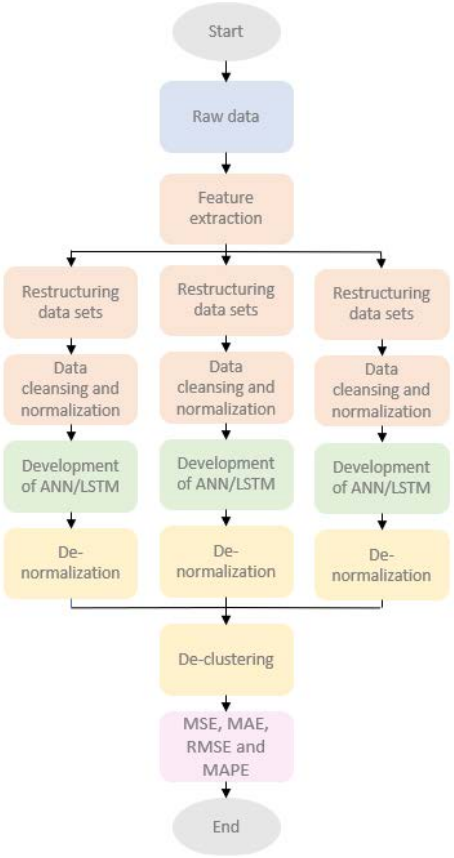


Figure 2: With clustering

Calculation
The batch size, timesteps and activation functions along with certain model modifications. A sensitivity analysis is performed by removing certain input parameters as to see how this affects the forecasting accuracy. Hybrid solution of clustering and ANN/LSTM is also investigated.

Conclusion
Electricity price forecasting has achieved much attention lately for the tremendously growing price detected in 2021. It has thus, emphasized the importance in having well-performing forecasting models which indeed has been noticeable as a vital need among the market participants. Therefore, this thesis was decided to encompass the electricity price forecasting of the bidding zones in Norway, which in turn has led to the discovery of connectivity among certain areas and the usage of ML method. Although the employed modifications in this report did not enhance the DL models, there is still quite a potential of improving the models through other methodologies that may be explored.

Mitigation of Wind Turbine Induced Sub-Synchronous Oscillation by Implementation of Wide Area Monitoring and Control

Student: **Cornelis Albert van Vledder**
Supervisor: **Olimpo Anaya-Lara**
Collaboration with: **TU-Delft**

Abstract is not available due to delayed publication.

Local flexibility market – TSO and DSO coordination

Student: **Ine Solsvik Vågane**
Supervisor: **Hossein Farahmand**
Contact: **ine.vagane@lyse.net**

Problem description
The European power system is changing. An increasing amount of energy is provided by renewable energy resources and distributed generation. This imposes a number of problems for the grid operators. The power production becomes uncertain and unpredictable, making the operation of the grid difficult. A solution could be to incorporate more flexibility resources into the local flexibility market. A model for clearing the market called Hybrid AC/DC-OPF was made. However, the model could only handle one distribution grid and was only tested on a simulated grid.

The task
The task in this master thesis is to review existing publications on utilisation of the flexibility resources, functioning and coordination of the local flexibility market, and modelling approaches that can be used for the market clearing, and to analyze which of them is suited for the tasks of the master investigation. The second part is to develop a Hybrid AC/DC-OPF ADMM model, that can be used for clearing the flexibility market with coordination of TSO and multiple DSOs. The third part is to create the test case based on a Pandapower grid and a synthetic grid generated by Ding0 package to test the Hybrid AC/DC-OPF ADMM model. Using the model and the test case, the aim of the fourth part is to answer the question: how can the flexibility resources benefit the TSO and DSOs operation. The final part is to answer the researching question: Can the DSOs help each other with grid issues in a flexibility market?

Model/ measurements
The extended model is based on Alternating Direction Method of Multipliers (ADMM). The method is based on coordinating the solutions of the separate local subproblems for TSO and each of DSOs to find the solution for the global problem of entire flexibility market coordination. The procedure is called decomposition-coordination. The ADMM method attempts to unify the benefits of dual decomposition and the augmented Lagrangian methods for constrained optimization. The iterative approach of the ADMM method can be seen in Figure 1. The model was tested with voltage violations, congestion in the distribution grid, congestion in the transmission grid and economic dispatch.

Calculation
The results suggested that the use of FRs are partly beneficial for the DSOs and TSO. For the case of voltage violations, FR helps with the voltage profile, costs and active losses. When introducing congestion in the DS, the costs and load shedding amount are lower only when FRs are located in the DSO with the congestion. For the case of congestion in the TS, the costs are reduced for the TSO when more FRs are included in the distribution grids. In addition, the FRs make the TSO more resilient to congestion in the TS. When there are no grid issues, as in the case Economic dispatch, the results show that FRs only help the DSO where they are located and the TSO. The active losses are increased for DSO 1 when FRs are

included in DSO 1, but decreased for DSO 2 and 3 when located in their grid.

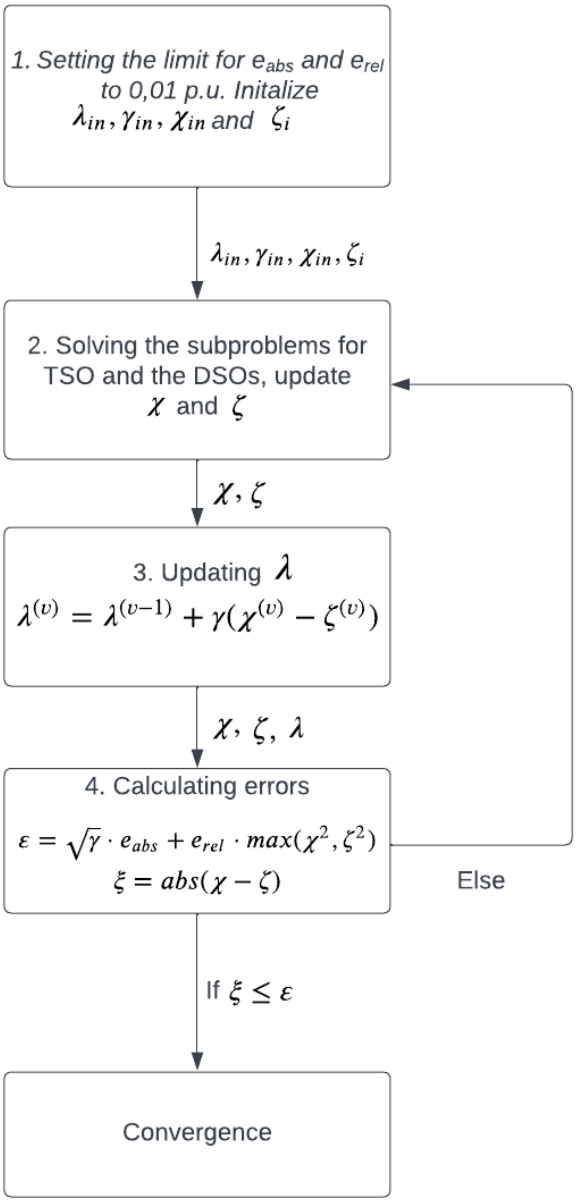


Figure 1 : The iterative approach of ADMM method

Conclusion

The thesis reviews several coordination schemes for a local flexibility market and its participants, and modelling approaches used for market clearing, and chosen decomposition method as the best suited method. In addition, the results showed that the develop Hybrid AC/DC OPF ADMM model can handle several DSOs. The test case was developed from Pandapower and Ding0. The results also imply that flexibility resources help the grids where they are located, in addition to the TSO. Lastly, there was a researching question if the DSOs could help each other with the grid issues in a flexibility market. In this case the answer was no, they only help themselves.

Analysis and Testing of Ground Fault Protection Function Performance in Compensated Distribution Grids

Student: **Pål Wagner**
Supervisor: **Hans Kristian Høidalen**
Contact: **paalwagner@gmail.com**
Collaboration with: -

Problem description
Traditionally, overhead lines have been used to build the electrical distribution grid due to long distances and low costs. High voltage levels with low current have been used to transfer the electrical power across long distances such that electrical losses could be reduced, as well as the quality of power increased. To maintain a secure delivery of power, the distribution grid has to be secured against electrical faults, the most common being single line to ground fault, which is responsible for 70%-80% of electrical faults in the distribution system. Today, the most common ground fault protection function in arc suppression coil grounded electrical grids in Norway is the Wattmetric-based function, which utilizes three different vectors to identify and disconnect a ground fault. Fault direction is made by measuring the active component of zero sequence current compared to zero-sequence voltage, which has also to exceed a pre-determined threshold. If the direction is determined, both zero-sequence voltage and current have to exceed their threshold values for the ground fault to be disconnected.

In recent years, the trend in electrical supply systems around the world has been to replace traditional overhead lines with underground cables, partly due to the expansion of the renewable energy arsenal. There are many advantages of such a decision, such as increased public support for electrical grid expansion, as well as technical and economic advantages, such as lower voltage drop, lower maintenance cost as well as longer lifetime Even though increasing cabling in the distribution grid provides many advantages, it also introduces a large disadvantage for today's ground fault protection scheme. On average, cables contribute 40 times more capacitance per length than overhead lines. The increased capacitance of a protected feeder will have a large impact on the angle between the zero-sequence voltage and current. Too much capacitance on a protected feeder can compromise the Wattmetric-based protection function, due to large capacitive current, and relatively small resistive current. In addition, increasing amounts of cable result in fault current that does not extinguish by itself. This means that in today's ground fault protection scheme, the Wattmetric-based ground fault protection function is one of the limiting factors in grid expansion using cables.

Modern commercially available relays contain both Wattmetric-based ground fault protection function, as well as alternative protection functions, such as Admittance based and Transient based. The functionality for ground fault detection of modern ground fault protection functions is different from Wattmetric based, enabling the possibility for these ground fault protection functions to perform better in highly cabled networks.

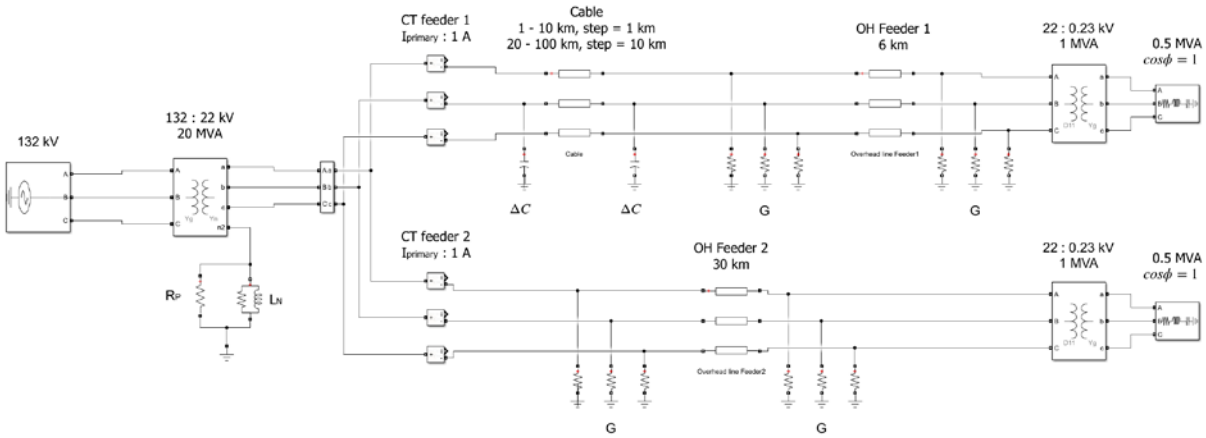
The task
The objective of this master thesis is to perform practical testing and analysis of three ground fault protection functions - Wattmetric, Admittance, and Transient based ground fault protection functions, such that their performance and limits due to increasing cable length and fault resistance can be established.

Model/ measurements

Three models were used to perform the task described above:

1. Small Simulink model, where both feeders were relatively short, was used to investigate how the change in ground fault protection function settings affect the ground fault protection function performance.
2. Large Simulink model, where cable length of the protected feeder increased greatly, was used to investigate ground fault protection function performance due to large capacitances in the protected feeder.
3. An existing Norwegian distribution grid, where ground fault protection function performance was analysed and tested on a realistic distribution grid.

Figure below demonstrates the Simulink model that was established.



Calculation

The results have shown that during permanent ground faults, Admittance based ground fault protection function has superior performance compared to both Wattmetric based and Transient based ground fault protection functions. The same conclusion was made when performing analysis and testing in realistic distribution grid.

Conclusion

By taking ground fault protection function performance from both simulated and real distribution systems into consideration, the Admittance-based ground fault protection function appears to be the optimal ground fault protection function for achieving optimal protection from single line to ground faults. However, it has been demonstrated that both Wattmetric and Transient based ground fault protection functions can detect an acceptable percentage of ground faults, such that if arc suppression coil grounded distribution systems are designed to meet the limits of chosen ground fault protection functions, satisfactory ground fault protection performance can be achieved by using either ground fault protection function. By taking the results from a real Norwegian distribution grid into consideration, if the Admittance based protection function is taken into use, the lower limit of G0 > setting should be used, such that unintentional drop out of ground fault detection can be avoided. In cases where the Transient based ground fault protection function is taken into use, the zero-sequence voltage threshold value, V0 >, should be set to approximately 5% of secondary transformer voltage value, such that satisfactory ground fault protection performance can be achieved.

Flexibility assessment in a Distribution Grid

Student: **Walderhaug, Jon Roaldsøy**
Supervisor: **Oleinikova, Irina**

Summary

Increasing electrification in all facets of society, along with louder calls for variable renewable energy (VRE), and with the emergence of distributed energy resources, creates a challenge for the modern power system. This thesis presents how flexibility as a resource in the grid has the potential to be beneficial for the system operator. Inspired by the pilot project Linja at Bremangerlandet, a case network with real residential consumption data from the DSO was analyzed. Flexible resources such as Battery energy storage solutions (BESS) and load shifting were discussed. Three scenarios were created for the highest-demand day in 2021, with different levels of flexibility solutions implemented. The results showed an improved voltage profile for the high demand day, but did not manage to alleviate voltage limit violations on the longest radials.

QUANTIFYING THE CAPACITY VALUE OF WIND POWER IN COMPOSITE POWER SYSTEMS

Student: **Widding, Martin**
Supervisor: **Vijay Venu Vadlamudi**

Summary

Renewable power is a growing resource, and is an important factor in the future of power system planning. The last decade, wind power and solar photovoltaic power has been the largest growing renewable energy source on the market. However, both wind and solar power are intermittent power sources, and are not possible to schedule in contrast to hydro power and power produced by burning fossil fuels. To accurately value the contribution renewable energy sources have on the power system, a method of quantifying their integration into an existing power system is needed.

This thesis presents and explains a method to quantify the Capacity Value (CV) of wind power generation integrated in an existing composite power system. It is intended as an addition to the ongoing Power System Reliability project at the Department of Electrical Power Engineering at NTNU. The power system's probabilistic nature is simulated though the State Sampling Monte Carlo Simulation method, and the CV metric Effective Load Carrying Capability (ELCC) is determined using the bisection method.

An in-house software tool capable of quantifying the ELCC of added wind power generation to an existing composite power system is developed through this thesis work. The tool is able to base the ELCC calculations on two adequacy reliability indices, namely the Loss of Load Expectation (LOLE) and the Expected Energy not Served (EENS). Using two different indices to calculate the ELCC of added generation to a composite power system is shown to present different perspectives on potential power system expansion.

Through a literature review, the thesis presents a comprehensive explanation of Power System Reliability studies. Both sequential and non-sequential Monte Carlo Simulation methods are explained in detail. The State Sampling method is used in the software developed through this thesis work, as it is found to need fewer simulation years to converge on a result compared to the State Duration and State Transmission methods.

Impedance Modelling and Stability Analysis of Virtual Synchronous Machine-based Wind Energy Conversion System

Student: **Claysius Dewanata Widjaja**
Supervisor: **Mohammad Amin**
Contact: **claysius@ieee.org; mohammad.amin@ntnu.no**

Problem description

As the number of power electronics converters increases due to the proliferation of variable renewable energy, a significant impact has brought changes to the dynamics and stability of power systems. Since power systems are traditionally dominated by synchronous machine-based physics and control, the dynamics are also determined by the response of the dominant synchronous machine. With how power converters are more interconnected to the grid, the conventional modelling for power system dynamics is not enough to capture all the desired phenomena available in power systems.

However, the existing method to assess the dynamics of the Converter-Interfaced Generation (CIG) by state-space analysis will be a challenge for the Transmission System Operators (TSO) since it requires a detailed control design of the converters. This control design is usually very confidential information and will not be available to other parties.

The task

The main objective of this master's thesis is to investigate the converter-driven stability of a Synchronverter-based Wind Energy Conversion System (WECS) for weak AC grid interconnections by means of impedance-based modelling and analysis. MATLAB/Simulink will be used to simulate the systems and implement the method proposed.

Therefore, the three primary objectives of the thesis are

- to analytically derive the impedance model of the WECS
- to compare the accuracy between the derived analytical model with the frequency sweep model
- to conduct the converter-driven stability analysis of the WECS connected to an AC weak grid by implementing the impedance-based stability analysis

Model

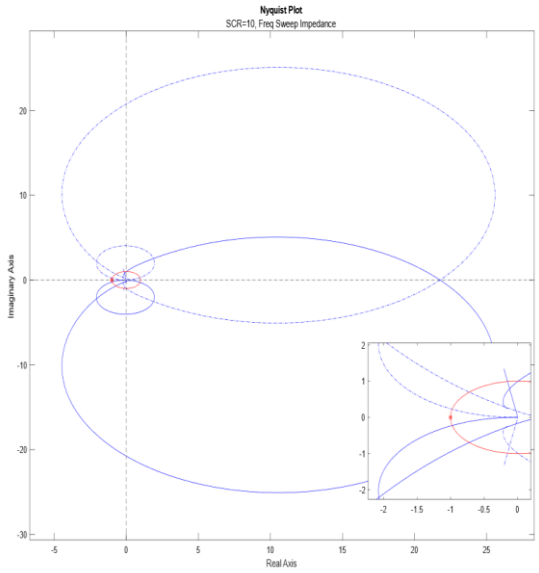
A self-synchronised Synchronverter-based WECS, which is a type IV wind turbine connected to an infinite bus, will be modelled in Simulink. Both converter controls will use Synchronverter algorithms where Rotor Side Control will control the DC link voltage, and Grid Side Control will control the active and reactive power transmitted to the grid. The model will be validated against the Texas Panhandle Wind Farm scenario.

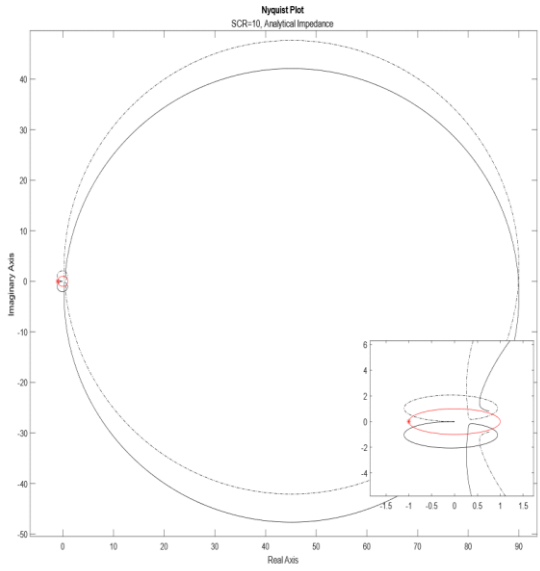
The impedance model of the Synchronverter-based WECS will be derived analytically using the mathematical model of Synchronverter. The accuracy of the impedance obtained will be compared with the impedance obtained through the Single-Tone Sinusoidal Frequency Sweep in Simulink. The impedances will be presented in the Modified Sequence Domain.

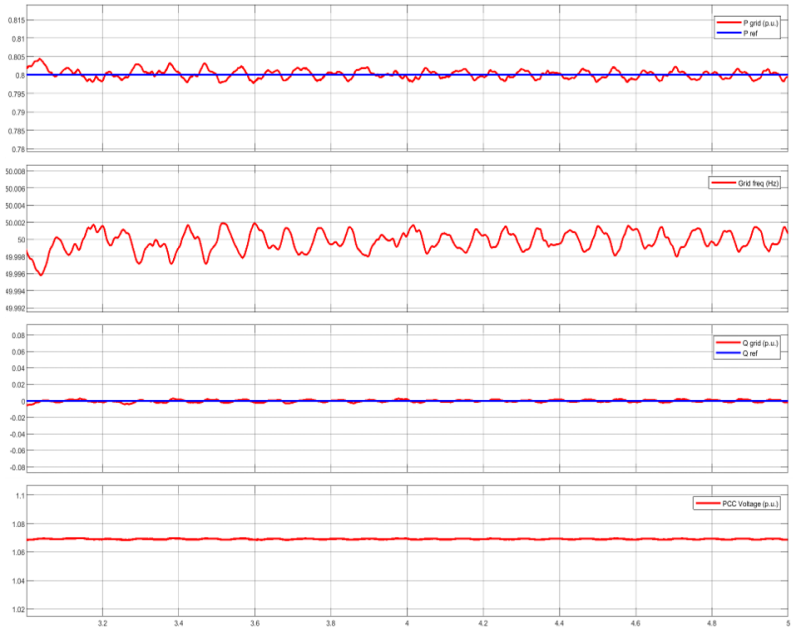
Both impedances obtained will be used to assess the converter-driven stability of the WECS for weak AC grid interconnection. Generalised Nyquist Criterion (GNC) will be used to examine the systems' open-loop-pole characteristics. Sensitivity studies will be performed, where three system parameters will be varied: *Short Circuit Ratio (SCR), virtual damping,* and *virtual inertia*.

Calculation

Examples of the converter-driven stability assessment by GNC results are given below. For detailed results, please refer to the master thesis directly.







Conclusion

The results show that variation of SCR affects the stability of the system to a large extent, and that virtual damping and virtual inertia do not really affect the converter-driven stability of WECS, especially for weak grid interconnection. The simple impedance model derived also performed satisfactorily for the converter-driven stability assessment since it captures all the desired stability phenomena.

The simulation results also managed to show that the impedance-based technique combined with GNC is a powerful tool for assessing the power system's stability in the form of BIBO stability.

Evaluation of Flexibility in Distribution Grid

Student: **Ilya Yankouski**
Supervisor: **Irina Oleinikova**

Abstract

Flexibility of distribution system is being challenged by increasing amount of Distributed Renewable Resources and Electric vehicle penetration. The main objective of this thesis is to analyze impact of EV charging on distribution system.

Artificial Neural Network-Based Control for Grid-Connected Converter

Student: **Ella Gardner Øxnevad**
Supervisor: **Mohammad Amin**
Co-supervisor: **Prabhat Ranjan Bana**
Contact: **ella.oxnevad@outlook.com**

Problem description

As the share of renewable energy sources increases, the control methods for grid-connected converters need to be improved to ensure stable and reliable operation. New control methods are replacing conventional proportional plus integral (PI) control as they have been proven to be faster, more robust, more accurate, and more reliable. Among numerous control methods, the use of artificial intelligence, specifically the use of artificial neural networks is increasingly drawing attention in research for improved converter control.

The task

This thesis investigates different artificial intelligence-based methods for the inner-loop current control for a grid-connected voltage source converter. Based on this study, three different artificial neural network (ANN) controllers are developed, and their performance is evaluated and compared. The first ANN controller is trained offline using simulation data, which consists of control inputs and outputs, from the conventional decoupled PI controller. This controller is denoted PI-ANN. Similarly, the second controller is trained offline using simulation data from a model predictive controller (ANN-MPC). The third controller is pretrained offline but continues training online, where training is done according to the direct heuristic dynamic programming algorithm (dHDP).

Model/ measurements

The control methods are implemented in Matlab/Simulink for a system consisting of a DC source, a switching model of the two-level three-phase voltage source converter, an LC filter, and a distribution grid. Pulse-width modulation (PWM) is used for generating the switching pulses, and a phase-locked loop (PLL) is used for grid synchronization. The PI-ANN and the dHDP controllers are implemented in the synchronous rotating reference frame, while the MPC-ANN controller is implemented in the stationary reference frame. The system and the control methods are illustrated in Figure 1.

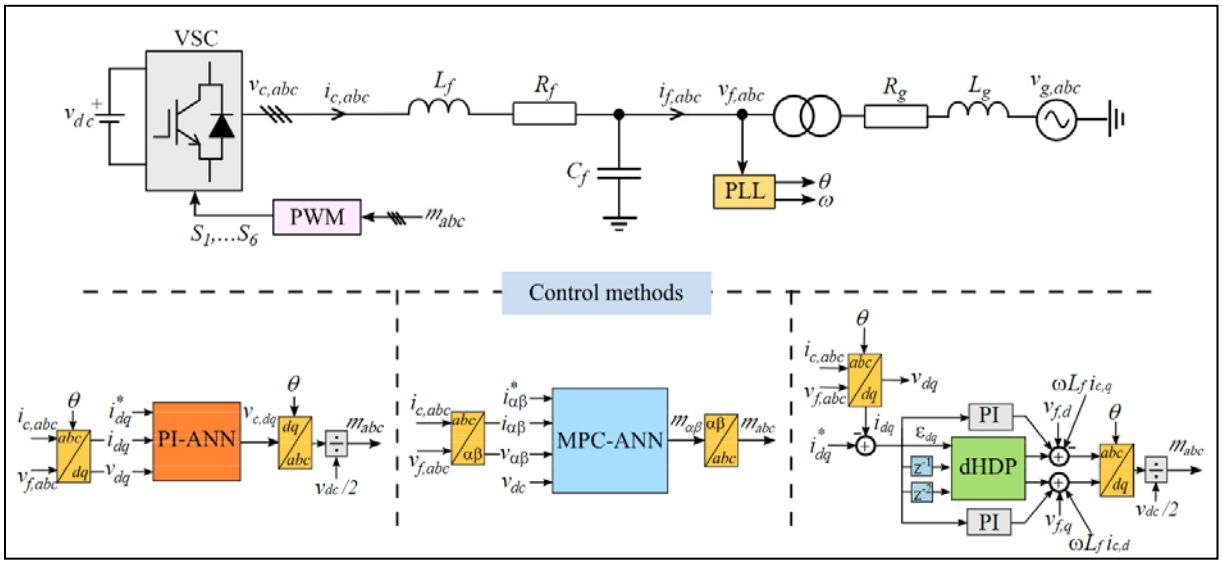
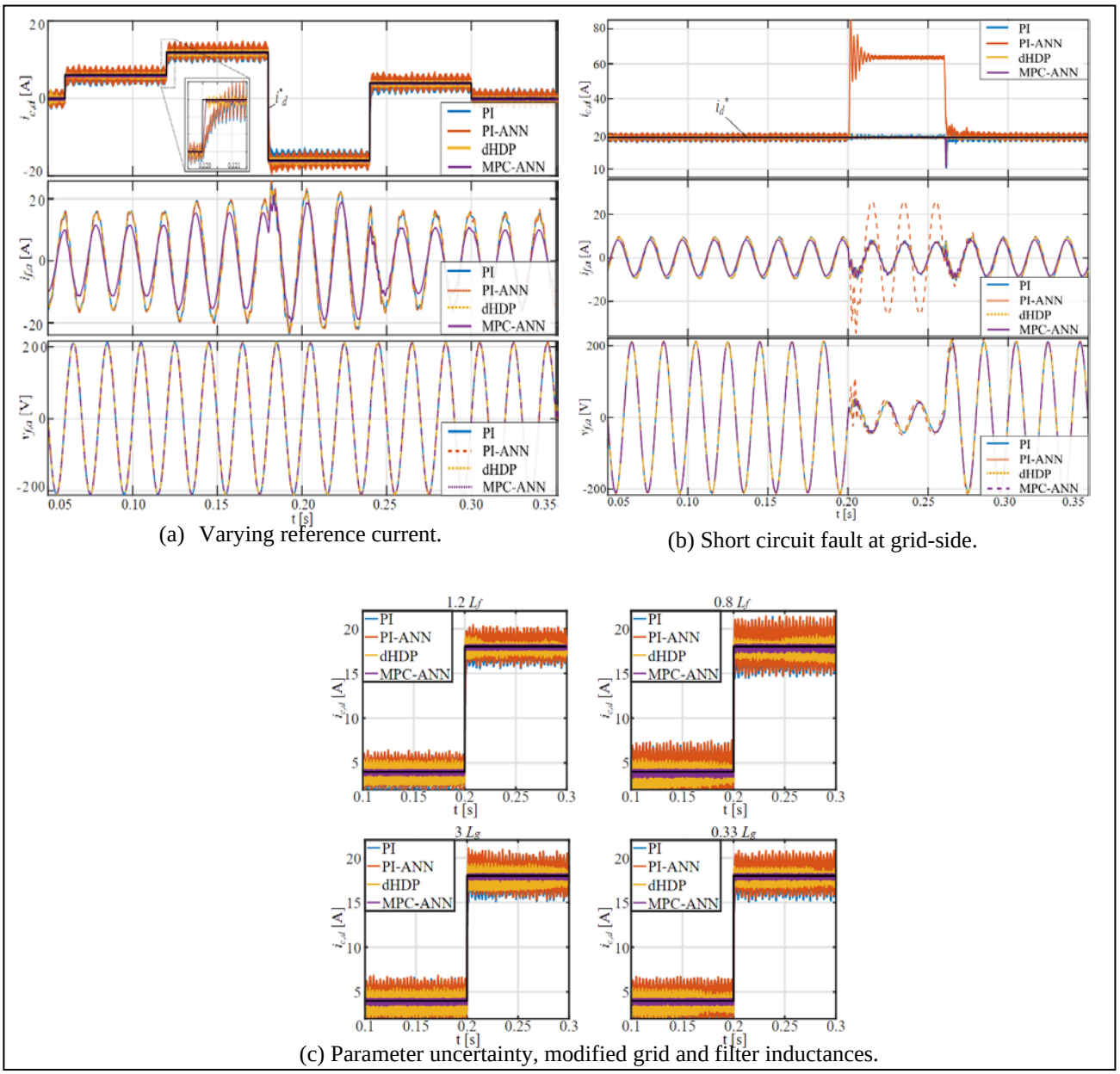


Figure 1: Grid-connected voltage source converter and proposed control methods.

Calculation

The performance is evaluated considering three different test case scenarios: continuous step-varying reference current, short circuit fault at distribution grid and parameter uncertainty. The simulation results are presented in Figure 2, where the *d*-axis converter current ($i_{c,d}$), phase-*a* of filtered output current ($i_{f,a}$), and phase-*a* of filtered output voltage ($v_{f,a}$) are plotted.



(a) Varying reference current.

(b) Short circuit fault at grid-side.

(c) Parameter uncertainty, modified grid and filter inductances.

Figure 2: Simulated performance of the proposed control methods.

Conclusion

The PI-ANN controller has similar and sometimes worse performance compared to the conventional decoupled PI controller. The dHDP controller results in significantly better performance, with more accurate tracking, faster response, and improved robustness. The MPC-ANN presents a superior performance, and compared to the dHDP it is more accurate, robust, and faster.

Transition Strategies for Smart Grid: Evaluating Future Scenarios on Distribution Grid

Student: **Alvar Øyasæter**
Supervisor: **Olav Bjarte Fosso**
Collaboration with: **SINTEF Energy**

Problem description
As a larger share of energy is produced in the distribution grid, along with more unpredictable load and generation profiles, distribution system operators face a challenging task when it comes to operation of the current and planning of the future distribution grid. This thesis evaluates transition strategies for the implementation of Smart Grids, exemplified through simulations done on a reference grid model.

The task
The thesis aims to simulate future scenarios developed by CINELDI, to illustrate how distribution grids may be impacted by various factors. The results may then be used by DSOs to develop strategies for planning and dimensioning of distribution grids.

Model/ measurements
The model used is based on the Forward-Backward-Sweep Method, which has been updated to include voltage and loss sensibilities. The model has then been expanded to span a full day, to give more accurate view into the impact of batteries and other flexible resources.

Calculation
The simulations were done on three separate scenarios, each comprised of several of the mini scenarios developed by CINELDI.

- **Scenario 1: Local Energy Communities**
  Five LECs were connected to the grid, and the impact of them staying connected to the grid versus disconnecting was simulated. The results showed that the DSO can benefit greatly from getting LECs to stay connected to the grid, given that they can use the flexibility services offered.
- **Scenario 2: Increased Local Production**
  Several PV systems were installed in the system, and the effect of weather was examined. The use of batteries to alleviate abrupt systems changes were then evaluated and was found to be synergetic in combination with the PV systems.
- **Scenario 3: Electric Transport Sector**
  Charging stations for EVs, as well as an electric ferry charger were introduced to the system. They were found to have a significant impact on the load curve. The use of distributed energy resources was then examined and showed that in combination with voltage regulating equipment like SVCs could help with the operation of the system.

Conclusion
The results showed that DSOs can use the flexibility services offered by DERs to help with the operation of the distribution grid. It also showed that without access to these services, significant grid reinforcements would be needed. The results highlighted the need for the establishment of new frameworks and roles to accommodate these changes.

A Case Study on the Grid Integration of Electric Vehicles in Norway

In combination with Solar Power, Fast Charging Stations and an Electric Ferry

Student: **Andreas Aadnøy**
Supervisor: **Magnus Korpås**
Contact: **Bendik Nybakk Torsæter**
Collaboration with: **SINTEF Energi AS**

Problem description

Norway is one of the leaders in the electric vehicle (EV) transition, with 82.9% of new registered vehicles so far in 2022 being EVs. This high addition of EVs create challenges for the grid operators, as today's power grid are not made to withstand this large electrification. The average load from an EV charging at home is low, and the power grid in Norway will withstand a relatively large transition to electric cars. However, a high number of EV charging simultaneously in one area, can create major challenges for transformers and cables in the distribution network. By using the flexibility of EV charging and other measures it is possible spread the load throughout the day, instead of high loads within short time periods.

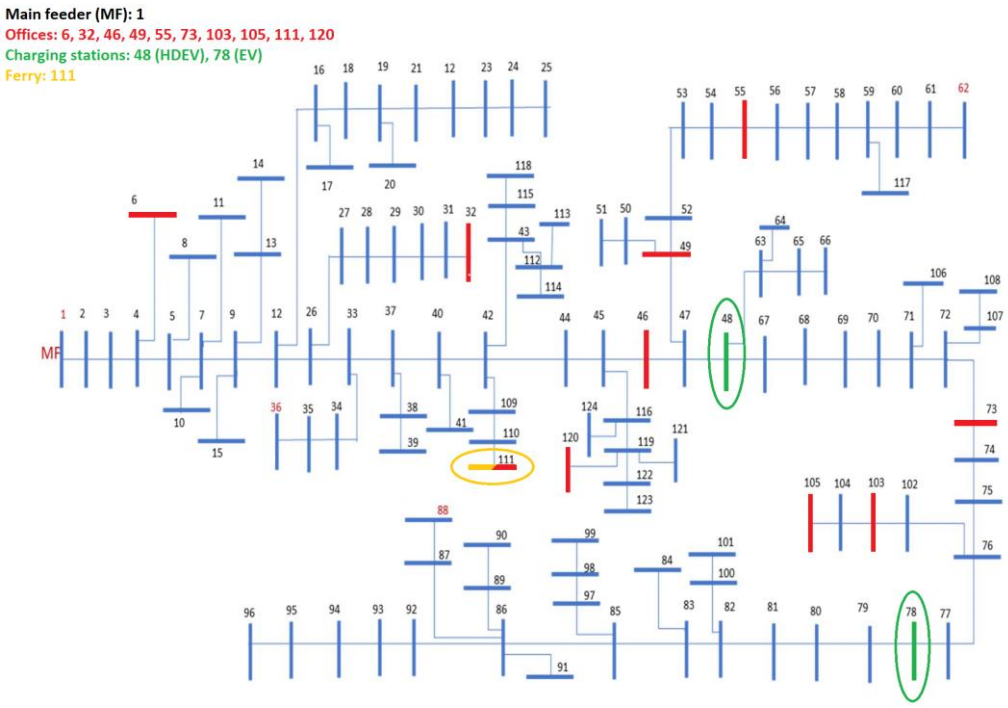
The task

In this master's thesis, impact of EV charging in a modern power grid is analyzed. Three different EV charging cases are made, to analyze how different forms of charging can affect the power system. There were made one worst case scenario where all charging happens straight after work hours, 16:00-19:00, when the grid often are congested. The two other charging cases made, were more flexible, with one having charging start at randomized time steps throughout the day, except during working hours. The last case had a slow charging approach, where all EVs charges constantly at a low power rate throughout the day, except during working hours.

To further decrease grid impacts of the high load demanding EV charging, are three additional measures added to the charging cases: A PV park with a 4.67 MW rated power, reactive power support from EVs and fast charging stations & an electric ferry, and lastly, a battery energy storage system (BESS) added to the HDEV FCS.

Model/ measurements

The power grid in this thesis is a test grid made from preliminary work done in CINELDI. To make the grid a modern grid are solar power production, two fast charging stations (FCS) and one electric ferry added to the system. This is shown in the figure below. A standard number or PV panels are added to all households and offices in the system. MF represents main feeder, i.e. the external grid.



The grid and charging cases with and without measures were analyzed by performing power flow calculations of the grid, with load inputs from the different cases, over a time series. Analyzing power flow performance of a power grid is an important tool to determine the power and voltage quality of the grid. A high power and voltage quality are crucial for a stable and reliable power grid. The power flow calculations is done in a simulation model made in the Python package 'Pandapower'.

Calculation

From the EV case studies, it is evident that utilizing the flexibility of EV charging rather than charging all EVs simultaneously over a small time period, results in a minimal grid impact. In a high load demand scenario the load peaks of the system is decreased with 6 MW from the worst case scenario to the flexible charging cases. Resulting in an increase of minimum voltage magnitudes at the weakest bus, which has been raised with 0.048 p.u. and 0.049 p.u. in the two flexible charging cases

Each individual measure did make an positive impact on the voltage quality. However, a combination of the measures made it possible to raise the voltage quality in the system sufficiently

Conclusion

In this thesis it is shown how damaging dumb charging of EVs can be to the power and voltage quality. Further, it is shown how implementing different measures, individually or in combination, may be crucial to secure grid stability with EV integration in a modern power grid. To conclude, flexible charging of EVs may benefit the power and voltage quality of the grid but will not always be enough to secure stability. Hence, implementing additional measures such as solar PV production, reactive power support, or BESS can be decisive. Especially by combining these measures in flexible charging scenarios, the voltage and power quality could be increased immensely.