Masteroppgaver 2024

NTNU
Norges teknisk-naturvitenskapelige universitet
Institutt for elektrisk energi

Summary of Master's Theses 2024

Department of Electric Energy

NTNU
Norwegian University of
Science and Technology

NTNU
Norwegian University of
Science and Technology

Fakultet for informasjonsteknologi og elektroteknikk
Institutt for elektrisk energi

Summary of Master Theses 2024

Every year in June it is a real pleasure for me to take part in the graduation event for our students and to see our class of Master students celebrate that 5 years of studies have come to an end. They are ready for their next career step.

At Department of Electric Energy we are proud to be able to present the results of the hard work that our Master students have put in under good supervision from our academic staff.

In this pamphlet you will find short summaries of the 2024 MSc theses at the department. 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!

Anngjerd Pleym
Head of Department

Mykland, Johan	Kaveh Niayesh	Investigation of Increased stresses on circuit breakers switching offshore AC cables	92
Negro El Khatib, Thamer	Olimpo Anaya-Lara	Availability Assessment of Offshore Electrical Networks in Wave Farms	93
Nordeide, Ivar Beseth	Robert Kristoffer Nilssen	Simulation and Experimental Validation of Losses in Permanent-Magnet Synchronous Machines	94
Olsen, Sveinung Berg	Steve Völler	Holistic Energy Systems Analysis for Norwegian Farms	96
Olsen, Rebekka Færøyvik	Gilbert Bergna-Diaz	Energy Synchronization of Grid-Connected Power Electronic Converters	9
Pedersen, Gard	Basanta Raj Pokhrel	Enhancing the energy efficiency of low voltage distribution grids through active voltage regulation	20
Pedersen, Henrik Engum	Hans Kristian Høidalen	Differential Protection and Distance Pilot Protection in Transmission Grids with High Penetration of Inverter-Based Resources	98
Pinderud, Jonas Henrik	Kasper Emil Thorvaldsen	Operation of an EV parking lot subject to capacity-based grid tariffs offering grid services through demand reponse	48
Rummelhoff, Stian	Ida Fuchs	Power Flow Models for Swarm Electrification - A Case Study in Rural Kenya	17
Røraas, Knut Ivar	Gro Klæboe	Assessing different balancing strategies in the Norwegian power market with high wind penetration	82
Sanden, Eirik Stenshorne	Kjetil Obstfelder Uhlen	Development and Validation of the Nordic 45 Dynamic Simulation Model for Short-Term Frequency Stability Analysis	100
Sandvik, Synne Aasvestad	Steve Völler	Comparative analysis of the Swedish and Norwegian reserve market	101
Sevang, Nicolay	Jayaprakash Rajasekharan	Long-Term Hydropower Scheduling Using Scenario Reduction and Short-Term Inflow Prediction	103
Skogen, Sander Lid	Gilbert Bergna-Diaz	Future Dutch Power System: Synthetic Modeling and Stability Analysis	105
Steen, Oscar Martinius	Gro Klæboe	Assessing the Impact of Solar Power on Calculated Water Values in a Hybrid Hydro-Solar Power Plant	106
Steiro, Hanna	Magnus Korpås	Balancing the Breeze: Offshore Grid Connectivity and Demand Flexibility in Future Power systems	108
Sølvik, Marie	Karen Byskov Lindberg	Cost-Optimal Renewable Energy System for an Industrial Area	110
Teige, Hanna	Karen Byskov Lindberg	Cost-Optimal Renewable Energy System for an Industrial Area	110
Thamotharampillai, Thivagar	Gilbert Bergna-Diaz	Developing an Impedance-Based Passivity Criterion for a Voltage Source Converter	22

Trondsen, Benjamin	Gro Klæboe	Assessing the Impact of Solar Power on Calculated Water Values in a Hybrid Hydro-Solar Power Plant	106
Umer, Muhammad	Elisabetta Tedeschi	Efficient and More Sustainable Operation of Voltage Source Converters in Offshore Power Systems through Multimode Operation	112
Vagapova, Yulia	Roy Nilsen	Control and Protection of Dual-Winding PM Machines for a Gearless Marine Propulsion	114
Vagle, Seline Tovslid	Jayaprakash Rajasekharan	Scheduling of Aggregated Electric Water Heaters for Potential Participation in the Balancing Markets	116
Valle, Astrid Elise	Magnus Korpås	Multimarket Services for an Electic Vehicle - Considering Activation of Frequency Containment Normal Operation Reserves	118
Volodin, Juri	Olimpo Anaya-Lara	Dynamic Optimization of Microgrid with Reversible Fuel Cell and Lithium Ion Battery	119
Ward, Daniel Francis Auve	Olimpo Anaya-Lara	Study on electromagnetic fields (EMFs) from submarine power cables in offshore wind farms	121
Wathne, Andreas	Arne Nysveen	An Experimental Approach on Early Fault Detection in Permanent Magnet Synchronous Machines Utilizing the Stray Magnetic Flux	123
Widzisz, Anna	Jayaprakash Rajasekharan	Scheduling of Aggregated Electric Water Heaters for Potential Participation in the Balancing Markets	116
Wikesland, Jostein August	Jonas Kristiansen Nøland	A Case Study of the Effects of Small Modular Nuclear Reactors on the Norwegian Power Grid, Utilizing the Nordic490 Model	124
Wuijts, Julian Storm	Vijay Venu Vadlamudi	Implementation of Methods for Generation Adequacy Assessment with Wind Considerations	125
Aas, Tobias	Steve Völler	Holistic Energy Systems Analysis for Norwegian Farms	96

Investigating the cost-effectiveness flexible resource in a distribution grid to mitigate voltage problems

Student: **Espen Aglen**
Supervisor: **Kasper Emil Thorvaldsen**

Problem description

The future development of the power grid is expected to see an increase of higher loads and renewable energy. Increased load demand and the integration of renewable energy sources can cause issues in the current grid infrastructure. Particularly weak distribution grids struggle to cope with the higher load demand and VRES. In the distribution grid, higher loads and PV power create voltage variations in the grid which can lead to issues with the voltage limits. Upgrading and reinforcing the grid is both a costly and time-consuming operation. Flexibility and flexible resources are a potential solution that helps reduce the severity of the issues and help stabilise the operation in the grid along with upgrading and reinforcing the grid structure.

The task

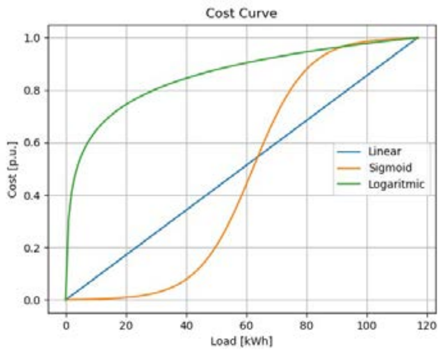
The objective for this work is to investigate the cost-effectiveness of flexible resources in a distribution grid for voltage improvements. The effectiveness of a flexible resource towards voltage improvements is spatially bounded by the location in a power grid. By introducing an operational cost on the flexible resources, the spatial dependency between the resources alters as a techno-economical perspective is evaluated.

• Build an optimisation model for a radial distribution grid based a OPF formulation. The model allows to study the voltage dynamics from activation of flexible resources. The objective is to find the optimal activation based on minimising the cost.
• Create a cost curve which describe the marginal cost of activating a flexible resource
• Perform a sensitivity for an increasing stringent voltage limit to study the voltage dynamics from activation of flexible resources.

Model/ measurements

An Optimisation model is created based on a Second Order Cone Programming (SOCP) formulation. SOCP is one approach to an Optimal Power Flow (OPF) where auxiliary variables are introduced to remove the non-linear and non-convex terms in the power flow equations. By rotating the auxiliary variables around second order cones, the OPF is changed into a non-linear and convex problem. The model is designed to find the optimal activation of flexible resources based on minimising the cost of activation. A cost curve is modelled that ties an activation cost with flexible operation of the resources. Three cost curves are tested: A linear, a sigmoid and a logarithmic cost curve. Each curve describes the willingness to be flexible.

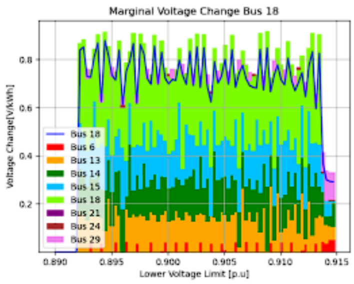
The IEEE 33 bus system is used where a sensitivity analysis is deployed on the lower voltage limit. The lower voltage limit is incrementally increased forcing the model to activate the flexible resources. With a cost curve that has an increasing marginal cost for increased activation, the analysis enables the cost effectiveness of the flexible resources to be studied. Five cases are tested where to cases have traditional methods of activation where cost is ignored, and the remaining three cases tests the linear, sigmoid and logarithmic cost curves.



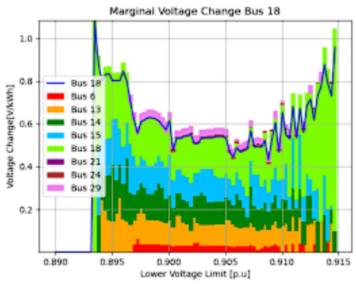
The figure displays the linear, sigmoid and logarithmic cost curve. The logarithmic have a low-cost difference where the cost is high even for small load reduction. The sigmoid have a high-cost difference, where the cost is low for small load reduction and high for high load reduction. The Linear is between the two where there is a balanced cost difference with equal trade-off of the cost and quantity on the load reduction.

Results

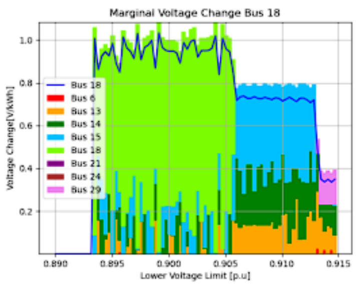
The results show that including a cost challenges the spatial dependency of the flexible resources. The three figures show the marginal voltage change on bus 18. The curve gives an indication on the effectiveness of the system, where high values represent a more efficient system. Under the curve, the voltage contribution from each flexible resource have been aggregated to highlight the cost-effectiveness from a node.



(a) Linear



(b) Sigmoid



(c) Logarithmic

The linear case the overall voltage change fluctuates as the cost-effectiveness of the resources alters for a stringent voltage limit.

The Sigmoid case allow more resources to reduce the load, resulting in a less efficient system, seen between the 0.9p.u. and 0.91p.u in the figure.

The logarithmic case results in activation of the more efficient nodes. As the cost difference is low, it favours the more efficient nodes. The voltage change is close to 1 V/kWh and drops to 0.8 V/kWh. This occurs as bus 18 has removed the maximum load capacity.

Conclusion

Including a cost of activation challenges the spatial dependency of the flexible resources. With the logarithmic case the model activates the most effective resources as the cost difference is too low for less efficient nodes to be effective. The sigmoid case has a high cost difference, resulting in less efficient nodes being activated for a higher quantity as the cost-effectiveness is more prominent. The linear case has a balanced cost difference resulting in the contribution from each flexible resource is proportional to its effectiveness.

The model also captures the value of flexibility through the marginal cost for voltage improvements [p.u./V]. The marginal cost has the potential to be used in the pricing of flexible resources and in market clearance.

Tiltak for å redusere brannrisikoen i distribusjonstavler

Student: **Mohamed Bassam Al-Najjar**
Faglærer: **Eilif Hugo Hansen**

Sammendrag
Masteroppgave handler om brannrisiko i elektriske sikringsskap og hvordan den kan reduseres gjennom effektive brannsikringstiltak og forebyggende strategier.

I oppgaven er det gjennomført en litteraturgjennomgang, Case-studier og en temperaturanalyse av automatsikringer med help av Comsol. Det for å identifisere brannårsaker, konsekvenser og risikofaktorer i sikringsskap.

Det ble også evaluert ulike brannsikringstiltak, som termisk overvåking, dimensjonering av elektrisk anlegg og ventilasjon i sikringsskap. Det ble også diskutert deres effektivitet, begrensninger og utfordringer.

Det er kommet frem til noen konkrete anbefalinger og retningslinjer for å forbedre brannsikkerheten i elektriske sikringsskap, samt pekt på behovet for mer forskning, utdanning og bevissthet på dette området.

A Comparison of Grid-Forming and Grid-Following Control for BESS-STATCOM On Industrial Isolated Grids

Student: **Ameen, Babar**
Supervisor: **Tedeschi, Elisabetta**

Summary
The integration of renewable energy sources and energy storage systems has revolutionized the dynamics of power grids, requiring more advanced control strategies for voltage source converters (VSCs) in grid-connected systems. Particularly, Norway's increasing growing dependence on the mixture of renewable energy sources and the resulting development of isolated grids connected to these sustainable energy sources highlight the importance of efficient VSC controls to ensure grid stability and reliability. This thesis presents the comparative performance of grid-following and grid-forming control methods for a 5 MVA Battery Energy Storage System (BESS) coupled with a Static Synchronous Compensator (STATCOM) for an industrially isolated grid under varying Short Circuit Ratio (SCR) conditions.

The studies performed in this thesis include developing Simulink models for both grid-following and grid-forming controls and comparing their performance under varying grid strengths. The results obtained indicate that grid-following control with a phase-locked loop (PLL) faces issues in weak grids which results in poor power quality and instability. However, it performs well in strong grids. Conversely, grid-forming control excels in weak grids by generating its own voltage and frequency references, ensuring stable power delivery and minimizing frequency issues. However, in strong grids, its control authority is challenged, resulting in instability and reduced performance.

Additionally, the study assesses the controls during motor startup transients, revealing that grid-forming control performs better by minimizing voltage drops and maintaining system frequency more effectively than grid-following control. The research concludes that while each control strategy has its strengths and weaknesses depending on grid conditions, grid-forming control provides a more robust solution for weak grids and during transients, whereas grid-following control is better suited for strong grid environments and steady-state scenarios. The simulations show that grid-forming maintains the voltage drop above 0.9 per unit during motor startup in the implemented model, whereas in the case of grid-following, this value decreases to 0.86 per unit. Furthermore, frequency improvement was also observed in the case of grid-forming control making it a preferable choice for grids with load changes.

Model Predictive Control of a Home Energy Management System with a Rolling Horizon Strategy

Student: **Markus Andersen**
Supervisor: **Magnus Korpås**
Co-supervisor: **Salman Zaferanlouei**
Contact: **magnus.korpas@ntnu.no**

Problem description

The increased electrification of the modern society, as well as an increase in implementation of renewable energy sources has brought new challenges which requires smart solutions for energy management. One if these solutions can be found in a energy management system containing a stationary battery. Such a system turns the consumer into an active part of the grid, enabling them to benefit from being flexible in their energy consumption.

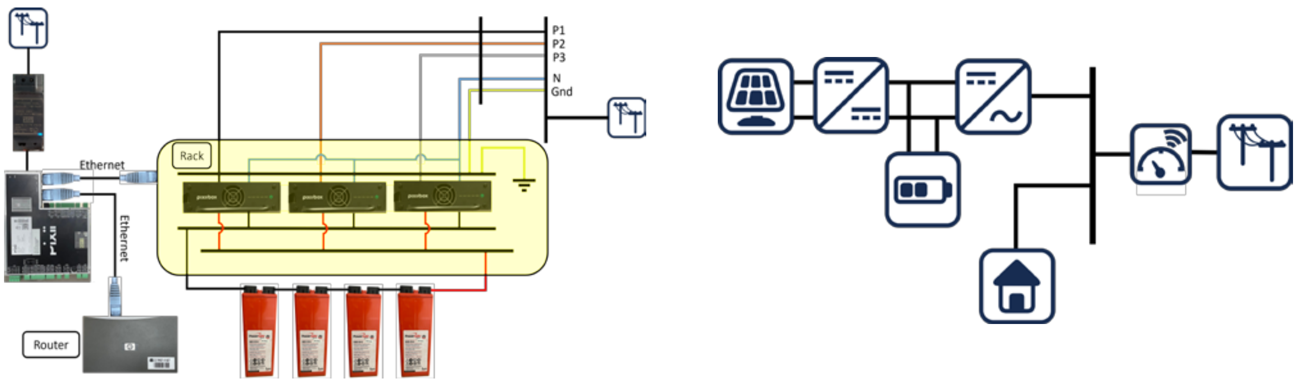
The task

This master's thesis investigates the operation of a home energy management system (HEMS) with model predictive control (MPC) and a rolling horizon (RH) strategy in a laboratory. The objective of the research was to operate the HEMS for 6 hours with real-time MPC where the objective of the control algorithm was to reduce the cost of consuming power. The research provides a detailed description of the HEMS with the control algorithm described above.

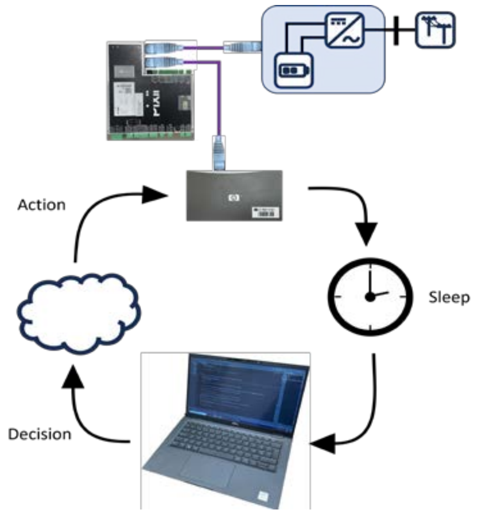
Model/ measurements

The HEMS is divided into three main components which together form the entire system. The laboratory setup is the coupling and configuration of the laboratory hardware. The Optimization model is modelled to simulate the laboratory and generates the optimal operation decisions for the MPC. Finally, the communication is the tools which makes the laboratory operate with the actions generated by the optimization model.

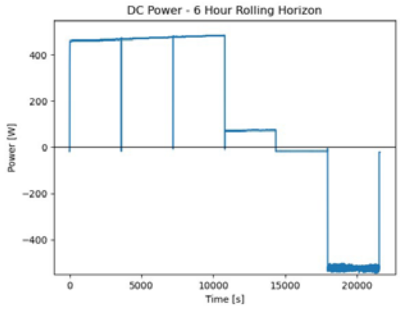
The figure below shows a picture of the laboratory configurations to the left, and a simple one-line scheme of the optimization model to the right. As can be seen from the pictures, the optimization model considers photovoltaic (PV) generation, but since the laboratory does not include any PV-module it is considered to not be any generated PV power in the research.



The Rolling horizon algorithm is described below where the computer symbolizes the optimization script, the cloud is a software tool for communication and the laboratory hardware is connected to the router. After each action, the system sleeps until the next time it generates a decision.



Calculation
The HEMS was operated with the decisions generated by the optimization script at the beginning of each hour. The figure below shows the power flow on the DC side of the converters during the entire 6 hour operation period. As can be seen from the graph, the system charges the battery in the first 4 hours, does no action in the 5th, and discharges the battery in the final hour. It is clear from the plot that the battery is charged with more energy than it discharges, and therefore the battery has stored energy at the end of the operation period. This is because the system was not instructed to end the operation in the 6th hour during the operation.



Conclusion
The system was successfully operated for 6 hours with MPC and RH. The operation cost was higher with the HEMS during the operation period. This is because the system had stored energy it was planning to discharge in the future, as it was not informed of this being the final hour. If the system had operated for a few more hours it would have proven to reduce the operation cost for the consumer.

New Environmentally-friendly Insulation Gases

Streamer Inception Probability in CO_2

Student: **Martin Tiller Andresen**
Supervisor: **Frank Mauseth**
Co-Supervisors: **Fanny Skirbekk, Hans Kristian Hygen Meyer**
Collaboration with: **Sintef Energy Research**

Problem description

The phase-out of SF_6 because of it very high global warming potential increases the need of research on environmentally-friendly gas alternatives to be used in gas-insulated switchgear. One of the relevant replacement gases is CO_2 which has shown great switching properties in earlier research. However, very little research is done with both positive and negative lightning impulses to highlight the polarity difference in streamer inception probability. Streamer inception is a very important phenomenon to investigate because it is a pre-breakdown phenomenon. Breakdown is crucial to avoid because of the potential harm it can cause to equipment.

The task

The main tasks of this thesis are:

- To establish the $U_{50\%}$, which is the voltage level with a 50% chance of a breakdown for both polarities.
- Investigate polarity differences in streamer probabilities for CO_2 during a 1.2/50 lightning impulse and compare the results to the already obtained streamer probabilities in technical air. In addition is the streamer time lag and accumulated propagation of the streamer.
- Investigate negative streamer probabilities in CO_2 and try to explain why the results are odd.

Model/ measurements

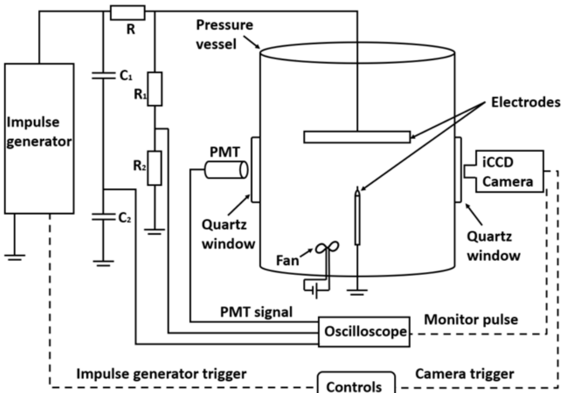


Figure 1: Schematic of the setup

Figure 1: Needle-plane gap

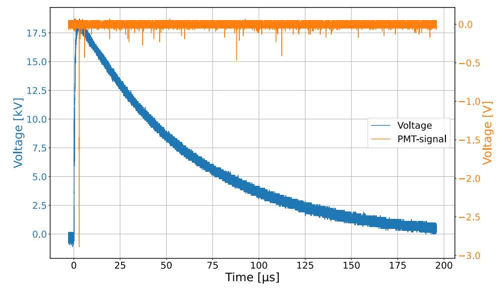


Figure 3: Lightning impulse with PMT-signal

The lightning impulse was generated by a 12 stage Marx impulse generator capable of 1.2 MV impulse output. The test object was a needle-plane gap inside a 400 L steel vessel filled with CO_2. To create a very inhomogeneous field, the tip of the needle had a curvature of 200 μm. A photomultiplier tube (PMT) in combination with a HiCam-camera was used to detect the light from the streamer. The PMT is very sensitive and can in theory detect a single photon, while the HiCam has an exposure time of 1 ms to capture the whole period in which the streamer can occur. The tests consisted of 100 impulses at each voltage level, with 10-12 voltage levels for both polarities. Up-and-down method was used to determine the $U_{50\%}$.

Results

The results of the up-and-down were varying, with negative polarity did not result in a valid $U_{50\%}$ while the positive polarity results were satisfying. However, since the main objective is to investigate the streamer inception probability, these results were not investigated any further. This was also seen during the streamer inception probability tests. The positive polarity inception probabilities were as expected a little bit higher than technical air, while it was not possible to establish a cumulative distribution of the negative inception probabilities. The reason for this is most likely accumulation of CO near the needle tip which influences the probability of a free electron existing in the region with sufficient electric field to cause an electron avalanche. In addition is ion drift a factor which dramatically can lower the density of negative ions which can release an electron in this region

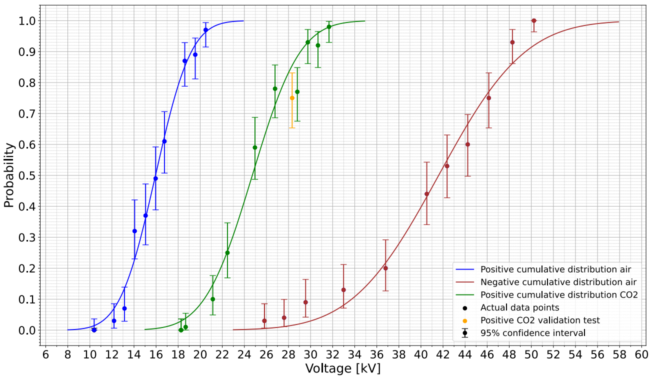


Figure 4: Streamer inception probabilities for technical air and positive polarity for CO_2

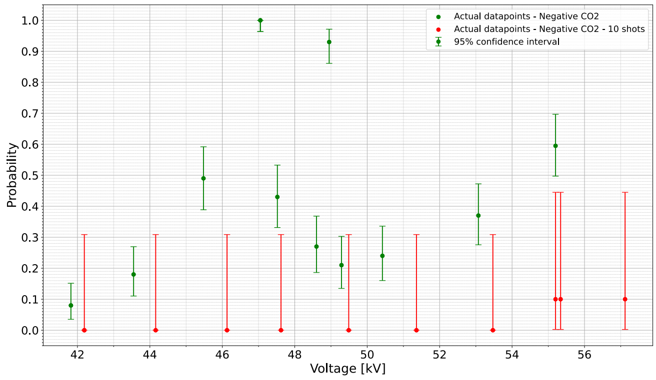


Figure 5: Streamer inception probabilities negative polarity.

The streamer time lags were also recorded and is presented in figure 5. This shows a larger spread in time lag for positive streamers compared to negative. Ion drift can be a cause of this where negative ions are drawn towards the critical volume for positive polarity, extending the period where a free electron can cause an electron avalanche.

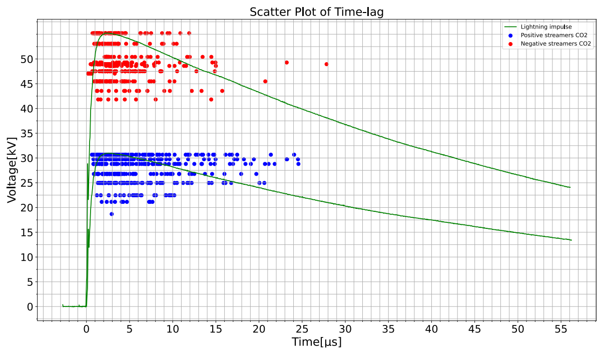
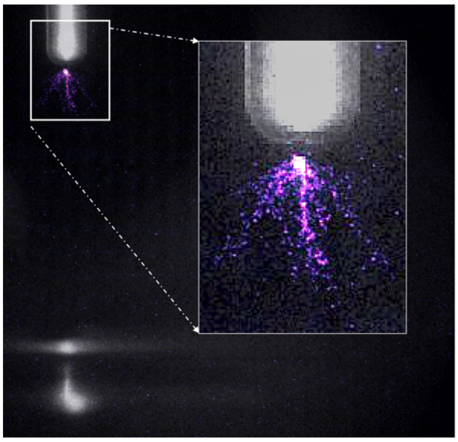
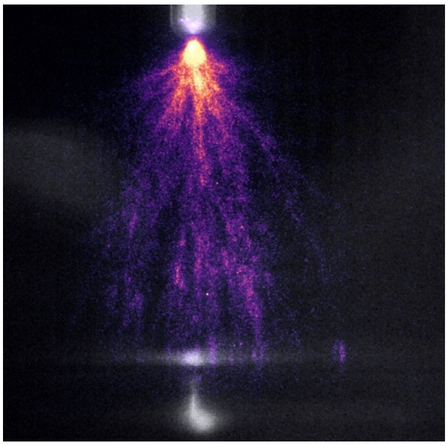


Figure 2: Streamer time-lag CO_2



Streamer picture of 18.27 kV positive polarity to the left and -56.16 kV negative polarity to the right. Contrast, colour and background image are added after picture is taken.



Conclusion

1: CO_2 needs higher voltage for streamer inception than technical air. 2: The smaller critical volume increases the inception voltage for negative polarity vs positive. 3: Byproducts makes the negative streamer inception probabilities hard to predict. 4: Lack of photoionization reduces the propagation length of positive streamers in CO_2 vs technical air. 5: Ion drift is contributing to a larger scatter for positive polarity streamer time lag.

Energy Synchronization of Grid-Connected Power Electronic Converters

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Supervisor: **Gilbert Bergna-Diaz**
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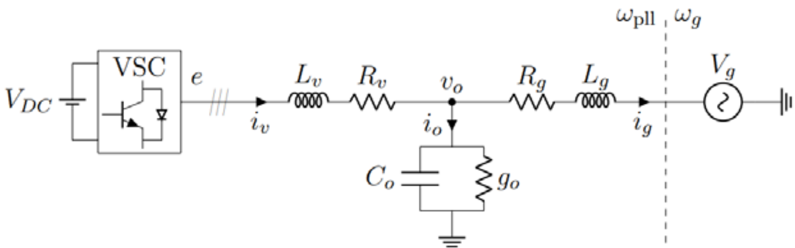
Problem description
Investigate the challenges when synchronizing power converters with power grids, especially weak grids, and to replace the standard PLL with synchronization alternatives with large-signal stability certificates.

The task
This thesis aims to revisit and challenge the well-known synchronization method known as the Phase-Locked-Loop, commonly used when interfacing renewable energy sources via power converters to the grid. Unfortunately, this established synchronization method lacks global stability guarantees, particularly when the converter is synchronizing to a weak grid. With the higher penetration of renewable energy sources, and the decommissioning of large synchronous power generation, the inertia of many grids worldwide is shrinking, making the grids weaker. Caused by this, an extensive and time-consuming (often small-signal) stability analysis has to be performed when new power electronic-based generation is deployed. Thus, this thesis wants to reevaluate the way the power electronic converter synchronization mechanism is designed, working towards replacing the standard PLL with alternative controllers with promising large-signal stability features by relying on passivity arguments. Our alternative controller is based on energy conservation principles, given its advantageous properties of additivity and preservation across non-linear systems. Although our theoretical global stability proof associated with our synchronization alternative suggests that a nonlinear observer is needed–leading to an increased control complexity–we show via practical time-domain simulations that this requirement can potentially be relaxed. In addition, we provide a regional theoretical stability proof for our alternative, arguably relaxing the theoretical observer requirement, verified by time-domain simulations.

Model/ measurements
A weak grid-tied converter model was implemented in Simulink for the time-domain simulations. A single line diagram is provided below.



Calculation
The grid model was presented using the pH formalism. This approach was selected for its ability to preserve the essential physical properties of energy conservation and dissipation, effectively representing the electrical system. Building on the passivity of pH systems, we defined the passive output, forming the foundation for our synchronization alternatives. By combining industry-standard PI controllers with the incremental and shifted passive pH-models, we applied PI-PBC to the closed-loop pH-system. In addition, we introduced a P+LI controller, which offered additional robustness to parametric uncertainties, and enabled our

controller to operate in grid-forming mode. Both grid-forming and grid-following operating modes were investigated. The key aspect of our work was to ensure the stability of the synchronization alternatives. Primarily, we proved that a modification of the closed-loop incremental pH representation, with either PI or P+LI control, satisfies global asymptotic stability. This provided a large-signal stability certificate, although with the implication of an observer. However, despite the fact that our theoretical global stability proof suggested that a nonlinear observer is needed–leading to an increased control complexity — we showed via practical time-domain simulations that this requirement could potentially be relaxed. The results showed that our contributions significantly outperformed the standard PLL, surpassing its limits by a considerable margin. The global asymptotic stability proof was also verified by simulations. In addition, we showed that a modified closed-loop shifted passive pH representation satisfies regional asymptotic stability. This provided a large-signal stability certificate, with the implication that an observer can estimate the states in the grid when the converter synchronizes. After the converter has synchronized, we argue that the converter can operate without an observer, due to a proposition of an estimated region of attraction. This proposition relaxed the requirements of the observer compared to the global stability proof. The estimation was validated by simulations.

Conclusion

This thesis successfully revisits and challenges the standard PLL-based synchronization method, presenting a more robust alternative, with large-signal stability features. If an observer is implemented, we have proved by relying on passivity arguments and Lyapunov stability that large-signal stability can be ensured.

Simplified steady-state model for probabilistic operational planning of a power system

Student: **Anne Wiig Arnesen**
Supervisor: **Vijay Venu Vadlamudi**
Supervisor: **Sigurd Hofsmo Jakobsen**
Contact: **awa@lyse.net**

Problem description

SINTEF Energy Research has investigated probabilistic operational planning using dynamic programming and time-domain simulations in the RaPid project. However, this approach used by SINTEF Energy Research in the RaPid project is time-consuming. It would be useful to see if there are less time-consuming probabilistic approaches for operational planning.

The task

In this Master's thesis, probabilistic operational planning using steady-state modeling with DC approximation is used to find the most cost-efficient operational strategy for a 25-bus system. The results of this Master's thesis are compared to the results from the RaPid project from SINTEF Energy Research with time-domain simulations of the same 25-bus system.

Model/ measurements

To obtain the results of this Master's thesis, an algorithm from SINTEF Energy Research is implemented in Python using pandapower to find the most cost-efficient operational strategy. The time-domain simulations in the algorithm are replaced with DC load flow (DCLF) and DC optimal power flow (DCOPF). The algorithm is first tested on a 4-bus system to demonstrate the algorithm in detail, as well as test the correctness of the implemented Python algorithm before applying it to the 25-bus system. The algorithm using steady-state modeling with DC approximation is tested on seven various cases of the 25-bus system in this Master's thesis. In the different cases, different combinations of ramp rate limits and system protection schemes (SPS) will be introduced to test the choice and the cost of the most cost-efficient operational strategy. The operational costs and the total costs of the operational strategies tested will be plotted as a function of the line flow on line 11 for the 25-bus system. This is the most critical line of the 25-bus system.

Calculation

The most cost-efficient operational strategy of this Master's thesis was having a line flow of 164 MW on line 11. This represents 90% of the thermal rating of the line. This can be observed in Figure 1 which shows the results for the case containing the most cost-efficient operational strategy in this thesis.

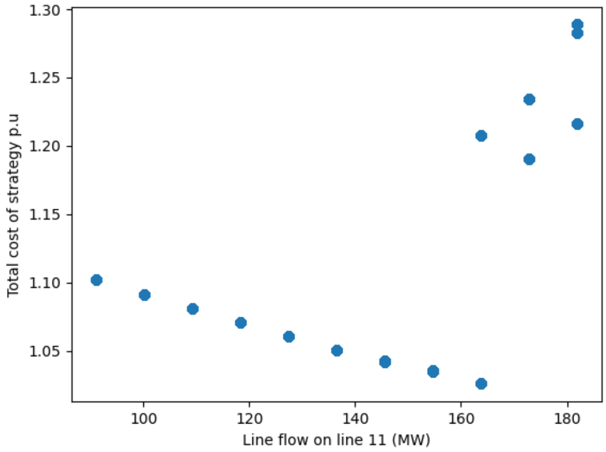


Figure 1: Total cost of operational strategies in p.u. as a function of line flow on line 11 in MW. These are the results for the case of this thesis which contains the most cost-efficient strategy.

Conclusion

The most cost-efficient operational strategy among the cases that can be assumed to be realistic, is chosen to be compared to the most cost-efficient strategy from SINTEF Energy Research. It is observed that the steady state modeling gives some differences in the choice of strategy, while the total costs of the chosen strategy are almost similar. The computational time is approximately 8 times lower with steady-state modeling compared to the time-domain simulations from SINTEF Energy Research.

Investigating Sum of Squares Applicability for Large Signal Stability Certificates in Electrical Systems

Student: **Eline Teigland Bakke**
Supervisor: **Gilbert Bergna-Diaz**

Problem description

The imperative need to integrate new renewable energy sources like wind power into the power grid has become increasingly evident in recent years. As society shifts towards sustainable energy solutions, the demand for harnessing wind energy has surged, posing unique challenges to the stability and reliability of the grid. Moreover, the advent of plug-and-play systems introduces additional complexities, necessitating robust stability measures to ensure seamless integration and operation.

The task

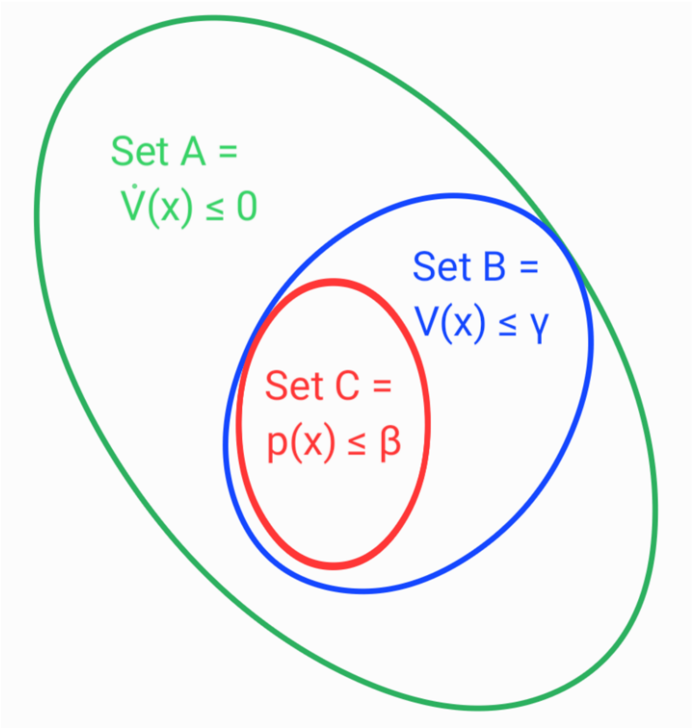
Against this backdrop, this thesis builds upon prior research conducted in the associated specialization project. It delves deeper into exploring the efficacy of the Sum of Squares (SOS) method as a potent tool for securing large signal stability certificates, with a specific focus on estimating the region of attraction for pertinent electrical systems.

Model/ measurements

To address the aforementioned challenges, our study adopts an innovative approach by directly analyzing nonlinear system dynamics. Leveraging convex optimization techniques, particularly the SOS method, we endeavor to estimate a region of attraction that serves as a robust stability certificate. This estimate ensures system stability within a defined boundary, mitigating the risks associated with unforeseen disturbances and operational uncertainties.

Calculation

Central to our investigation is a comprehensive elucidation of the SOS method's underlying principles and methodologies. We meticulously detail its background and definitions to enhance accessibility and reproducibility for future research. Leveraging a set containment equation derived from the Positivstellensatz theorem, we ensure that the estimated region of attraction satisfies Lyapunov stability criteria. The set containment is shown in the figure below. Additionally, a V-s iteration scheme is employed to iteratively refine the estimated region of attraction and its associated Lyapunov function, optimizing system stability.



Conclusion
In conclusion, this thesis presents a robust framework for implementing the SOS method in analyzing the stability of complex electrical systems. Addressing the pressing need for integrating renewable energy sources and accommodating plug-and-play functionalities, the research contributes to advancing the resilience and reliability of modern power grids. By continuing to explore and refine stability analysis techniques, we can pave the way for a sustainable energy future characterized by enhanced system performance and operational efficiency.

Oppgradering av en eldre bolig, med forsyningsbegrensning fra distribusjonsnettet, til et smarthus.

Student: **Adrian Flatmo Bakken**
Veileder: **Eilif Hugo Hansen**

Problemstilling

Boliger som har begrenset forsyning fra distribusjonsnettet vil ha utfordringen å henge med på utviklingen til et stadig mer elektrifisert samfunn. Derfor kan smarthusløsninger som er tilgjengelig på markedet benyttes til å balansere det elektriske effektforbruket i en bolig med forsyningsbegrensing fra distribusjonsnettet. Dette skal bidra til at boligen kan dekke beboernes behov for elektrisk effekt med eksisterende infrastruktur.

Oppgaven

En eksisterende eldre bolig har, på grunn av forsyningsbegrensing fra distribusjonsnettet, kun en hovedsikring på 25A ved 3~230V systemspenning. Dette gir et maksimalt effektforbruk på ≈ 10kW. Ved å implementere smarthusløsninger som kan integreres med de forskjellige elektriske ikke-, semi- og fleksible lastene i en bolig skal lasttopper som genereres jevnes ut. Slik kan beboernes behov for elektrisk effekt bli dekket uten at hovedsikringens kapasitet overstiges, som resulterer i sikringsutfall. Samtidig skal smarthusoppgraderingen, om mulig, kunne redusere fastleddskostnaden knyttet til effektforbruk som vil gi et økonomisk insentiv til å investere i et smarthus. Under oppgraderingen til et smarthus vil også andre funksjoner implementeres om kan være nyttig for en bolig med geografisk av.

Oppgaven vil gi et realistisk eksempel som belyser utfordringene ved å ta i bruk smarthusløsninger på markedet i dag til å oppgradere en eksisterende bolig til et smarthus.

Modell/målinger

Ved å bruke smarthuskomponenter til å styre de fleksible elektriske lastene etter et tidsbasert system modellert etter beboernes hverdagsrutiner ble effekttoppene holdt nede slik at deres behov for elektrisk effekt ble dekt. Oversikt over forbruket ble hentet fra strømabonnementets app.

Konklusjon

- Lastbegrensningsfunksjonene i smarthuset klarte å balansere den elektriske effektforbruken bra nok til at beboernes behov ble dekket uten utfall av hovedsikringen. Dette er selv med et fritt bruk av laster fra beboerne.

- De enkleste av fleksible lastene å integrere i laststyringssystemet var panelovnene som kun trengte en smart stikkontakt. Fleksible laster burde kontrolleres direkte, enten fra eksisterende funksjon i enheten eller en komponent som gir enheten denne funksjonen.

- De semi-fleksible lastene var de største bidragsyterne til å produsere lasttopper.

- Tidsbaserte styringssystemer som følger beboernes rutiner, er mindre fleksible enn systemer som baserer seg på deteksjon av effektforbruk i den elektriske installasjonen og justerte lastforbruket.

- Det er fortsatt et uløst potensial ved bruk og tilgang til sanntidsmåling og spotpris funksjoner. Dette burde være enklere å implementere i et smarthus en dagens situasjon.

Power Flow Models for Swarm Electrification - A Case Study in Rural Kenya

Student: **Audun Bangsund and Stian Rummelhoff**
Supervisor: **Ida Fuchs**

Problem description

The primary objective of this master's thesis will be to investigate the possibilities of energy sharing between nanogrids in the area surrounding Kilifi. By developing a power flow algorithm, this research will explore how the interconnection of rural nanogrids can enhance the system performance, and analyze how it affects economic parameters. Specifically, this research will be anchored in a detailed case study of the Eco Moyo Educational Centre located in Kilifi, Kenya, and how energy surplus from the electrification of the school kitchen can be used for swarm-grid purposes. Due to the nature related to electric cooking, an excessive amount of surplus energy is produced by the system entertaining the idea of selling surplus energy to neighbors to finance the installation's investment cost.

The task

• Modeling of Realistic Load Profiles: This involves developing detailed load profiles for electric cooking at Eco Moyo using the RAMP load profile modeling tool. The modeling will be based on data collected during the field trip, existing literature, and previous work at the property. Development of in-depth load profiles for the surrounding properties is beyond the scope of this thesis and a predetermined appliances list will be utilized.

• PV Generation Profiles: This thesis will develop realistic PV generation using PVsyst, based on a detailed analysis of irradiation, soiling effects, and shading. These profiles are specifically designed to meet Eco Moyo's cooking needs. For other microgrid-connected nanogrids, the generation profiles will be scaled-down versions of this system, as detailed modeling is only conducted on Eco Moyo.

• Development of a Power Flow Algorithm: A power flow algorithm will be developed using Python and the Pandapower library to facilitate the analysis of active power distribution within the Eco Moyo nanogrid and the interconnected nanogrids. The choice to neglect the reactive power flow was made due to the insignificant amount of reactive power flowing through the short lines. To simplify algorithm complexity charging, discharging, and self-discharging losses in the battery are also neglected.

• Power Flow Calculations: The developed algorithm will be utilized for both the Eco Moyo nanogrid and the microgrid, determining the distribution of power throughout the community. Extensive stability analysis will not be conducted, however, voltage quality will be briefly presented and discussed.

• Economic Analysis: Using economic parameters, an economic analysis will be performed, calculating how selling electricity to neighbors can help finance Eco Moyo's investment in a PV/battery system for the school kitchen. Since this thesis is primarily a case study for Eco Moyo, the economic effect on neighboring properties will not be extensively analyzed.

Model

To investigate the upsides with swarm electrification an end-to-end model is developed to investigate system performance and cost. The model consists of five main steps:

• Step 1 - Data acquisition: Acquiring data through interviews, existing literature, and previous work.

• Step 2 - Rural load profiles: The data gathered in step 1 was utilized together with the Python package RAMP to generate load profiles.

• Step 3 - PV generation profiles: The peak load demand found in step 3 was used to dimension a PV/battery system in PVsyst and generate PV generation profiles.

• Step 4 - Power flow analysis: Running power flow calculations on load demand and solar generation using Pandapower, an open-source Python package.

• Step 5 - Results: Results are read to CSV files and system performance and economic parameters are evaluated.

Results

This thesis demonstrates that the interconnection of nanogrids is highly beneficial for a large PV system producing large amounts of surplus energy. Maintaining the same security of supply, Eco Moyo can decrease its levelized cost of energy from 0.078 EUR/kWh to 0.015 EUR/kWh through the sale of excess power to other interconnected nanogrids. For the remaining nanogrids, this thesis concludes that the connection to the swarm grid can greatly decrease the initial investments, as well as increase the security of supply. Furthermore, it is highlighted that the battery parameters are crucial for the optimal utilization of the microgrid, as there is still a lot of unused surplus power. A brief analysis of the bus voltages also underlines the stability of the systems. Future work entails analysis of transient stability, real-life comparisons, and finer load- and generation-profile resolutions.

Conclusion

It is evident that swarm electrification is highly beneficial for a large PV system with a lot of surplus energy. This thesis has shown how the interconnection of buildings, and nanogrids, can help finance an energy system in rural communities, without decreasing the security of supply for the initial system. The increase of participants in the swarm electrification also helps reduce the cost of energy, under the condition that there is surplus energy yet to be utilized. This is a valuable observation to include, also to existing systems, as a low use rate of an already installed system should serve as an incentive for swarm electrification. This is deemed beneficial for all parts.

Steady and Dynamic interactions of Kalman Filter based Grid-Following and Droop & VSM based Grid-forming Inverters with conventional Grid and in 100% inverter-based power system.

Student: **Barua, Pollen**
Supervisor: **Uhlen, Kjetil Obstfelder**

Summary

The global energy landscape is undergoing a transformative shift towards renewable energy sources, driving the transition from traditional synchronous machine (SM) based grids to inverter-based power systems. This transition necessitates the integration of Grid Following (GFL) and Grid Forming (GFM) inverters, each with distinct advantages and challenges. As the future power system will be predominantly inverter-based, a comprehensive understanding of the steady-state and dynamic interactions between GFL, GFM, and SM-based grids is crucial for ensuring a reliable and efficient energy supply.

This thesis delves into the investigation of steady-state and transient state responses in various scenarios of the future power system. For GFL inverters, the Phase Lock Loop (PLL) plays a pivotal role in determining their behavior. While existing PID controller-based PLLs perform well in strong grids with smooth voltage and angle, this research adopts a Kalman Filter-based PLL to enhance the suitability of GFL inverters for weak grid conditions. On the other hand, GFM inverters are modeled using two existing techniques: Droop and Virtual Synchronous Machine (VSM) as their primary controllers.

The research employs a range of inverter capacities, from 2.5 MVA to 10 MVA, in different case studies. To form the conventional grid, synchronous machines of both weak and strong types, ranging from 2.5 MVA to 200 MVA, are modeled. This dissertation meticulously scrutinizes the interactions between grid-GFL, grid-GFM, and GFL-GFM, both in steady-state by assigning small disturbances and in transient state by introducing bolted symmetrical faults.

The findings of this research highlight superior performance of the Kalman Filter-based PLL for GFL inverters against transient disturbances, the spontaneous transient response of GFM inverters compared to GFL, and the promising potential of GFL-GFM interactions to form a 100% renewable energy-based power system.
Through rigorous research, this thesis contributes to some extent in the field, providing a pathway for the successful integration of renewable energy sources.

Enhancing the energy efficiency of low voltage distribution grids through active voltage regulation

Student: **Mathias Aak Berg and Gard Pedersen**
Supervisor: **Basanta Raj Pokhrel**
Co-Supervisors: **Irina Oleinikova, Kjell Sand, Arnt-Magnar Forseth**
Contact: **mathiasaakberg@gmail.com, gard1999@hotmail.no**
Collaboration with: **TENSIO TS**

Problem description

In the last few years, the world's energy demand has increased significantly. Industry and individuals are transitioning their energy consumption from fossil fuels to electric energy. For instance, the electrification of cars and trucks is reducing carbon emissions significantly. However, the increased energy demand and power peaks are causing higher losses in the power grid, especially in the distribution grid. The high power peaks, in addition to distributed energy sources, such as photovoltaic panels, are causing bigger variations in the supply voltage, which must be regulated.

The task

As mentioned in the problem description, distribution system operators are experiencing higher losses in their grid as a consequence of the energy transition. Therefore, this master's thesis investigates how the losses in the distribution grid vary with different voltage levels. In addition, it will study the impact of voltage variations on smart home appliances and their energy consumption.

Model/ measurements

The measurements for this master's thesis are divided into two parts, i.e., an analysis of the real grid through simulations and laboratory setup. The simulation model reconstructs a segment of the low voltage distribution grid provided by TENSIO TS, which is illustrated in figure 1. The model is further divided into two scenarios and 5 cases, including one base case and four cases investigating the implementation of electric vehicles (EVs), photovoltaics, and batteries. The two scenarios were winter and summer, where the former represents the most significant loading during the year, while the latter represents the least significant loading. Additionally, the load type composition differs between the two seasons. In the summer scenario, the load is equally distributed among constant power, constant current, and constant impedance. In contrast, the winter scenario has 60% constant impedance, with the remaining 40% evenly split between constant power and constant current, reflecting the increased heating demand during winter.

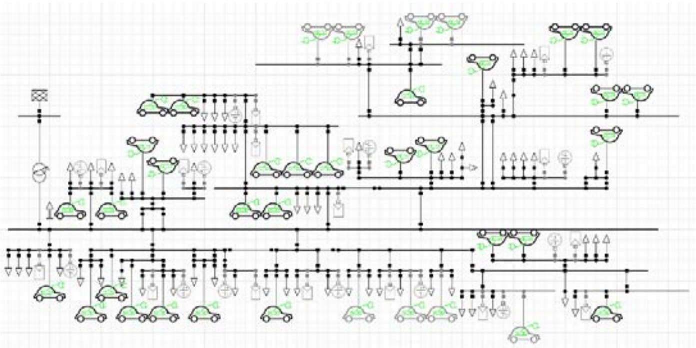


Figure 1: Simulation model

To validate the concepts discussed in the simulations, a laboratory setup was essential for investigating the tasks under real-world dynamics. A small network was established by connecting the National Smart Grid Laboratory to the smart home at NTNU. These were connected via two small distribution lines and a low voltage transformer, as illustrated in figure 2. In the smart home, various loads were measured to represent a typical smart home consumption pattern. The measurements were categorized into three distinct scenarios: morning, afternoon, and evening.

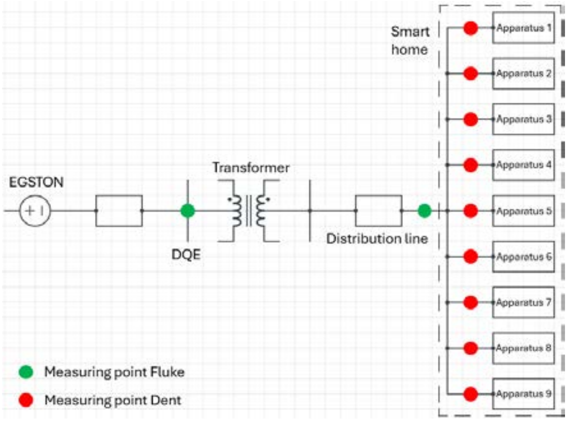


Figure 2: Laboratory measurements.

Calculation

The simulations show that, for most parts, the voltage level should be lowered to reduce both load consumption and power losses. However, with the large-scale implementation of EVs, constant power becomes the main load type during summer, thus changing how load losses vary with voltage level. However, this makes it more difficult to conclude on the individual apparatus behaviors to lower the voltage level, as it reduces the total energy usage in the system. Similarly, the laboratory measurements indicate that the voltage level should be reduced to improve energy efficiency, mainly due to the transformer entering saturation and causing severe power losses at regular high voltage. Interestingly, many of the smart loads can be observed to deviate from their expected behavior, possibly due to internal controllers. Inaccuracies in measurement details do, however, make it more difficult to draw conclusions about the individual apparatus's behavior.

Conclusion

Both the simulations and the laboratory work indicated that reducing the voltage level at the distribution transformer would decrease both power consumption and losses, with two exceptions. The morning case in the laboratory showed an increase in power consumption, while the EV case during summer in the simulations exhibited increased power losses. Nevertheless, all cases and scenarios exhibited increased energy efficiency with lower voltage levels.

Developing an Impedance-Based Passivity Criterion for a Voltage Source Converter

Student: **Marius Tomasgård Bjørgan & Thivagar Thamotharampillai**
Supervisor: **Gilbert Bergna-Diaz**
Contact: **Raymundo Enrique Torres-Olguin**
Collaboration with: **SINTEF Energy AS**

Problem description

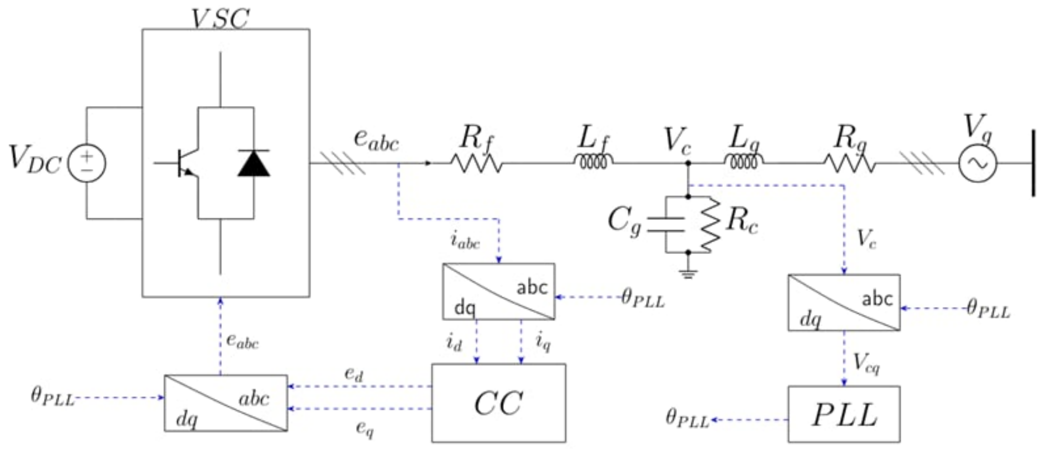
With the rise and increase of renewable energy sources, such as photovoltaics and wind farms, the integration and demand for power electronic converters in the power grid has risen. The rise of the converts in the power grid has caused stability issues, due to the design of the converters not being released by the manufacturers due to intellectual property concerns. This causes an issue for the system operators of the grid, due to the operators only knowing the input and output of the converters. This raises the question as to why operators cannot ensure full interoperability between system components.

The task

The main task of this thesis focuses on proving passivity for a two-level voltage source converter (VSC) connected to the grid through small signal impedance-based stability analysis, along with a passivity-based analysis. Proving passivity for a converter through small signal impedance based analysis is proven to be advantageous due to the perk of having infinite scalability of integrating converter to the grid. Additionally, small signal impedance analysis with an estimation of grid impedance would give several advantages for stability analysis, such as being well suited for a distributed control system, being suitable for real-time applications and enabling plug- and play characteristics.

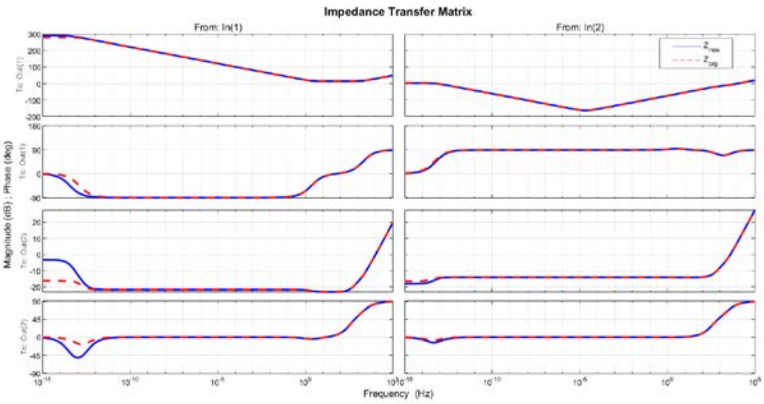
Model/ measurements

The modelling in this thesis focuses on the linear small-signal analysis, which necessitates the need for validation of the non-linear equations. To verify the equations, two independent models has been developed in Simulink, and compared in a time simulation after a step in the current reference. The first model incorporates physical signals and acts as a representation of the physical system, and the second model is implemented numerically through MATLAB functions containing the mathematical equations. After the non-linear equations were verified, a respective state-space model was derived which allowed for further research in both transfer matrices and Lyapunov equations.



Calculation

The state-space model follows into the main contributions and results of this thesis. Additionally, a new storage function has been found that would make the VSC passive.



This thesis uncovered the potential passivity of impedance/admittance, yet caution is advised on solely relying on the frequency domain analysis, due to potential erroneous conclusions, which can be seen in the figure. The figure shows some small deviations in the small frequency regions. This small deviation in phase and magnitude equates to the difference between a passive and a non-passive transfer matrix, simultaneously as both of the transfer matrices are positive real. This is supported by the prerequisite of controllability and observability for the Kalman-Yakubovich-Popov lemma, which is usually lost in electrical circuits. Additionally, results in this thesis indicated contradictions between the frequency domain and the time domain in regards to passivity. This also highlights why using matrix analysis in the time domain is more intuitive for researching passivity, rather than using bode plots in the frequency domain. Consequently, while impedance measurement remains a reoccurring method for assessing passivity, our findings suggest a necessary revision to ensure accuracy in industry practices.

Conclusion

The results of the study conducted in this thesis are an applicable state-space model with a storage function that would make a VSC passive, additionally contradicting results between the frequency domain and the time domain was found in regards to passivity. Thus, highlighting the need for a possible revision to ensure accuracy in industry practices, as impedance measurement remains the predominant method for assessing stability.

Grid forming control for inverter-based resources

Student: **Sander Braaten**
Supervisor: **Kjetil Obsfelder Uhlen**
Contact: **Kamran Sharifabadi & Atle Rygg**
Collaboration with: **Equinor**

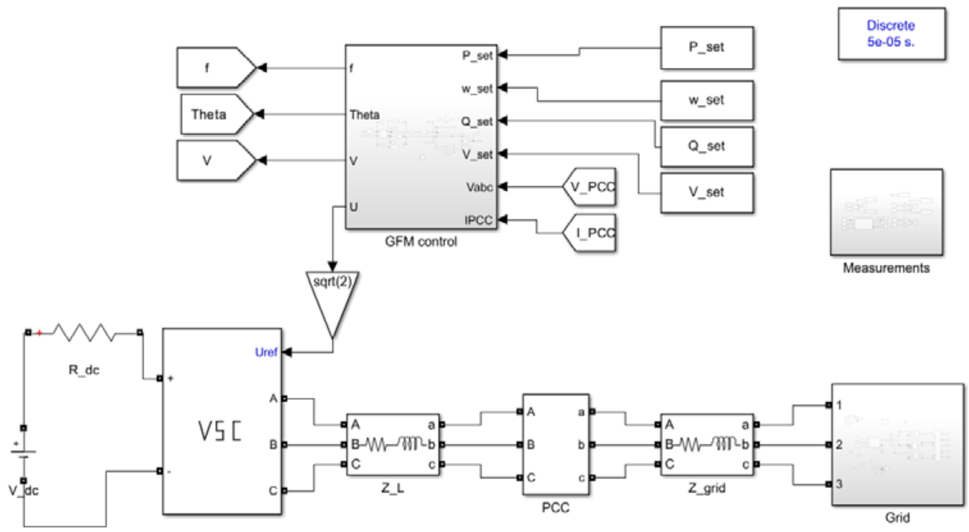
Problem description

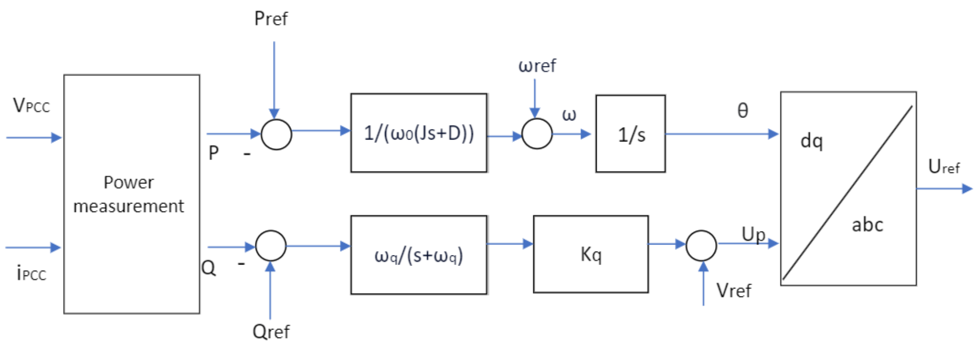
As the integration of inverter-based resources increases, lower system inertia becomes a bigger problem. The inverters used in renewables have two main operation modes, grid-following (GFL) and grid-forming (GFM). GFL is the state-of-the-art mode, but it often encounters several limitations due to the absence of ancillary services. The GFM control is a promising solution to the upcoming challenges since it can actively control active- and reactive power, and also provide virtual inertia. This thesis aims to explore various GFM strategies and analyze the impact of using different inertia values in GFM converters.

The task

- Design a realistic network model of a voltage source converter (VSC) connected to an external grid in MATLAB Simulink.
- Design different GFM control strategies in Simulink and compare the dynamic characteristics.
- Choose one GFM control concept and analyze the effect of using different inertia constants by running simulations based on specified operating tests in grid code standards.
- Discuss and conclude how the designed GFM converter is affected by different inertia values and its ability to solve challenges caused by high IBR penetration.

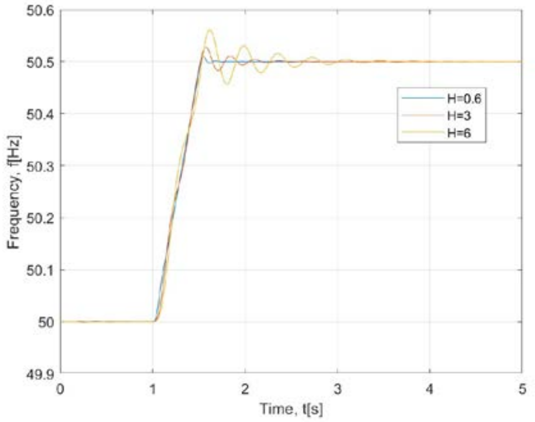
Model/ measurements

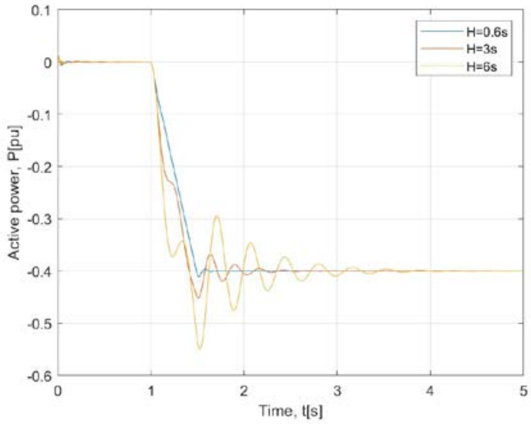




A network consisting of a VSC with GFM control and connection to an external grid was designed in Simulink as shown in the first figure. Three GFM methods were designed and tested, synchronous power control (SPC), virtual synchronous generator (VSG), and droop with low-pass filter (LPF). From block-diagram manipulation and simulations in Simulink, it was found that all three of the chosen GFM methods could have the same dynamic characteristics, depending on the parameters. It was therefore decided to choose one main GFM method to analyze further. The main GFM method was chosen to be the SPC with an LPF droop in the voltage loop, the control concept is shown in the second figure above.

Calculation





Simulations were done for a set of 7 scenarios based on standard tests in GB grid code GC01037, with constant inertia H=0.6s, 3s, and 6s.

Conclusion

From the results, it was discovered that the designed GFM converter was able to actively control active- and reactive power generation. It was also concluded that it could function as a synchronous generator and provide virtual inertia. It showed on the other hand lack of performance during high disturbances as in scenarios 5 (extreme phase jump) and 7 (three-phase short circuit fault). The overcurrent observed in these scenarios was determined to be a result of a lack of current limitation in the control. Overall the thesis confirmed that a lower inertia value is disadvantageous for the power system. It also confirmed that the GFM methods: SPC, VSG, and LPF droop are promising solutions to this steadily increasing problem.

Design- and Optimization Analysis of a Modular Thermal Storage System for a Nuclear Power Plant

Students: **Anders Olai Grotle & Simen Dyrkolbotn**
Supervisor: **Prof. Magnus Korpås**
Co-supervisors: **Martin Nødland Hjelmeland & Jonas Kristiansen Nøland**
Collaboration with: **Quantified Carbon Limited**

Problem description

In the pursuit of achieving the Net Zero goal by 2050, the United Kingdom (UK) is constructing a new 3200 MWe nuclear power plant (NPP) known as Sizewell C. The background for the thesis is to investigate the potential operation of the planned Sizewell C power plant, as well as the potential impact of implementing a thermal energy storage (TES) system. In collaboration with Quantified Carbon, a python software of the plant was provided. A modular TES system is to be designed, with focus on the thermodynamics, and implemented to analyse economical aspects to determine the feasibility of such a system. Implementation of a TES system have the potential to increase the flexibility of the power plant, making it more capable of responding to sudden demand changes. In addition, a TES system could also contribute to increase revenue by storing thermal energy in periods with low demand and low electricity prices, before utilizing it during peak periods.

The task

The main objectives for the thesis:

- Design and implementation of a thermal energy storage (TES) system for the Sizewell C with focus on the thermodynamics
- Present several phase shifting materials (PCM) used for heat storage and choose the most suitable
- Determine the impact and the feasibility of the TES system
- Investigate the operation of the system
- Analyse the economical aspects

Model build up and measurements

The model used in this thesis is an optimization model written in Python. The base model of the power plant is provided by Quantified Carbon, and this model has been the main tool for the study conducted in this paper. By making use of this model, a modular thermal energy storage (TES) system is developed and implemented to further analyse the potential economic and operational impact of such a system. The base model includes detailed modelling of the Sizewell C nuclear power plant reactor and its belonging steam flows, but also modelling of related services that utilize the high temperature steam, such as direct air capture (DAC) and both low and high temperature electrolyzers (LTE & HTE). However, these applications will not be analyzed any further, as these are beyond the scope of this thesis.

Model results

The spot market price curve, illustrated as a duration curve in Figure 1, is elemental when running the model after the implementation of TES. As the TES system bases itself on a modular structure, simulations are done with 1 to 5 modules implemented. The most beneficial results of this is illustrated in Figure 4, where the case utilizing 3 modules proves to be the most beneficial from an economical point of view. When running the model with 3 modules implemented, results such as the ones presented in Figure 3 and Figure 2 illustrates how the power plant utilizes the TES system through the year with the given spot price market.

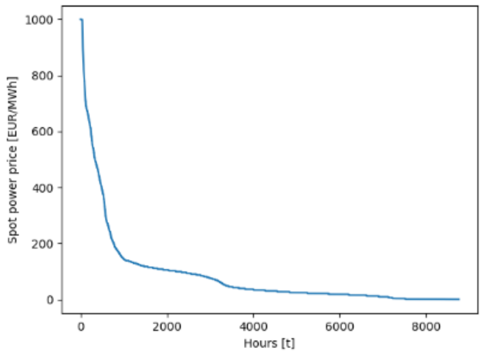


Figure 1

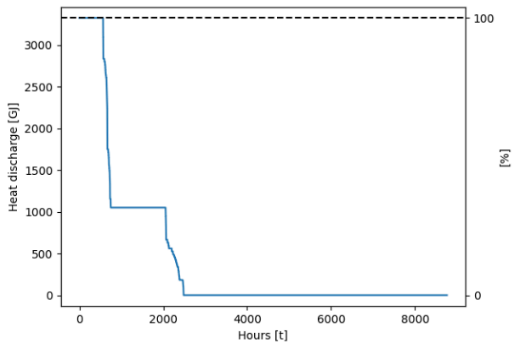


Figure 2

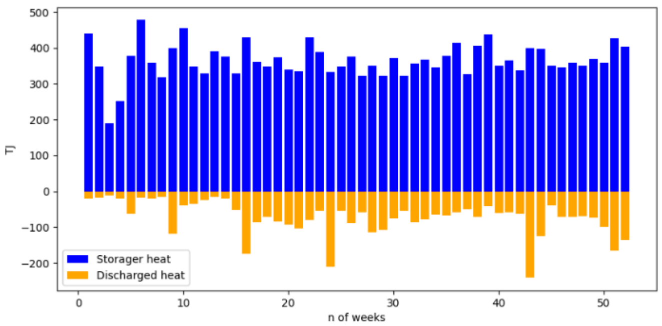
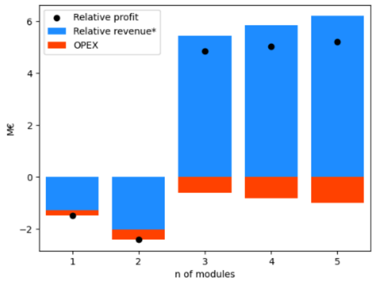


Figure 3



The relativity in this context is to the electricity sales (i.e. revenue) of the system without the implementation of TES.

Figure 4

Conclusion of the thesis

The results show that the implementation of TES system modules provides a rather small impact on the overall operation. The inclusion of TES in itself has the potential to greatly affect the operation, however, due to the low volatility of the spot price market used in the model, its potential is not fully utilized. Running the optimization model presents various results, such as the concluding results with 3 implemented TES modules as the most beneficial solution, considering the spot price market in this model. The 3 module-case results in an approximated increased revenue of 5.44 MEUR/y, and a payback time of 7.46 years. Compared to 5 modules, which is the highest number in this analysis, the revenue is lower (5 mods ⇒6.20 MEUR/y), however the payback time increases (11.05 years), due to the higher capital expenses following an additional number of modules.

A Modular Single Active Bridge Converter to Supply Low Voltage Loads from MVDC Grids

Student: **Kaja Eide**
Supervisor: **Beatrix Veronika Weiss**

Problem Description

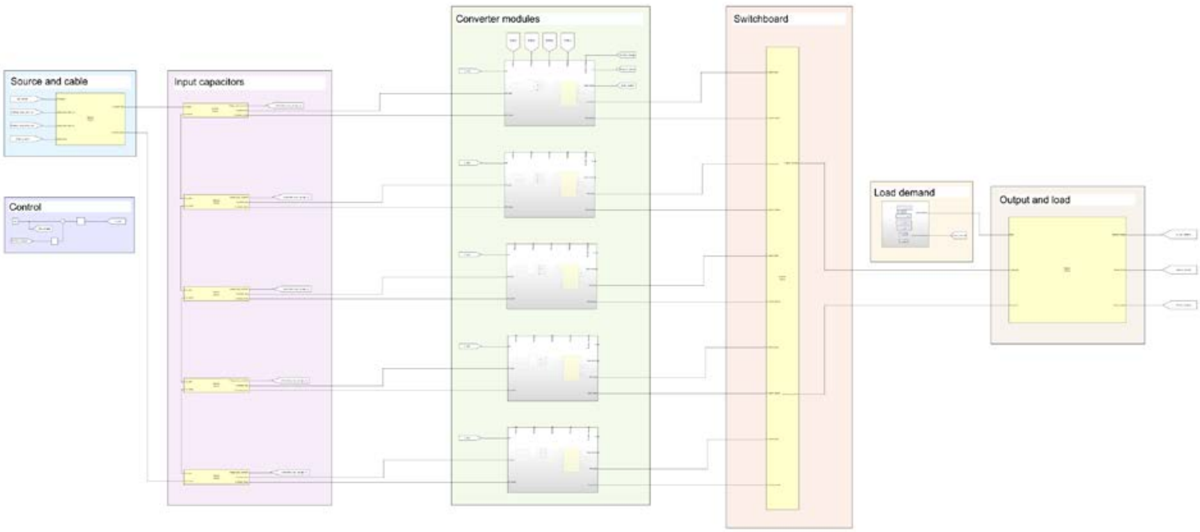
DC-DC converters are fundamental components in the conversion and management of DC power. The development of converter technology is crucial for optimising and expanding the possibilities of DC power. This thesis investigates the development of a modular DC-DC converter for use in an MVDC grid. By utilising a modular structure, the idea is to divide the input voltage between converters, so that each converter is operated with a low input voltage. In that way, the converter can use components of lower voltage ratings. Components of lower ratings can usually reduce overall cost, save space, and be more energy efficient. The goal is to develop and test a converter model that can step down a medium voltage and deliver a stable output voltage.

The Task

The developed model of the modular DC-DC converter steps down a 6 kV DC voltage source to 800 V using an input-series output-parallel topology. This approach distributes the 6 kV input across five serialised converters, enabling the use of power semiconductor devices with lower voltage ratings. Power semiconductor devices of the materials silicon carbide (SiC) and gallium nitride (GaN) were investigated, and SiC devices were chosen due to the possibility of higher blocking voltages. A SAB converter is unable to transfer bidirectional power flow for applications involving battery and energy storage, making it a unidirectional modular converter suitable only for supplying loads.

Model

The converter model is built in MATLAB Simulink with PLECS Blockset. The control system consists of an outer loop for output voltage control, and an inner loop controlling the inductor current in each converter. Pulse width modulation which adjusts the phase shift between the switches in the SAB converter is applied to get the desired output voltage. If the system is subjected to a load variation, the controller takes action and adjusts the phase shift.



Calculation
Several simulations are conducted under different conditions. The results show that the DC-DC converter is capable of handling a full load of 100 kW in steady state. The capacitors in the system are charged up to nominal voltages, and a full load is connected. The capacitance of the input and output capacitors is increased to stabilise the controller and reduce the voltage drop during load transitions. The output voltage response becomes acceptable with a voltage drop of less than 3% of the set voltage for a rapid load change from 0 to 100% power. The controller responds well to instantaneous and slower linear changes, as the output voltage response stays within a 3% deviation. However, for a step in load, it is suggested that the input capacitance is increased further to reduce oscillations in the converter input voltage and the cable current response. To further improve the converter model, an option for a no-load condition, where the current demand can become zero, should be implemented.

Conclusion
A modular SAB DC-DC converter model is successfully built and tested under several conditions. The results show the potential of how modular converters can be utilised for voltage conversion in MVDC grids.

Techno-Economic Analysis of Large-Scale e-Fuel Production Powered by Nuclear Energy

Student: **Erik Oscar Riis Enander**
Supervisor: **Jonas Kristiansen Nøland and Martin Nødland Hjelmeland**

Problem description

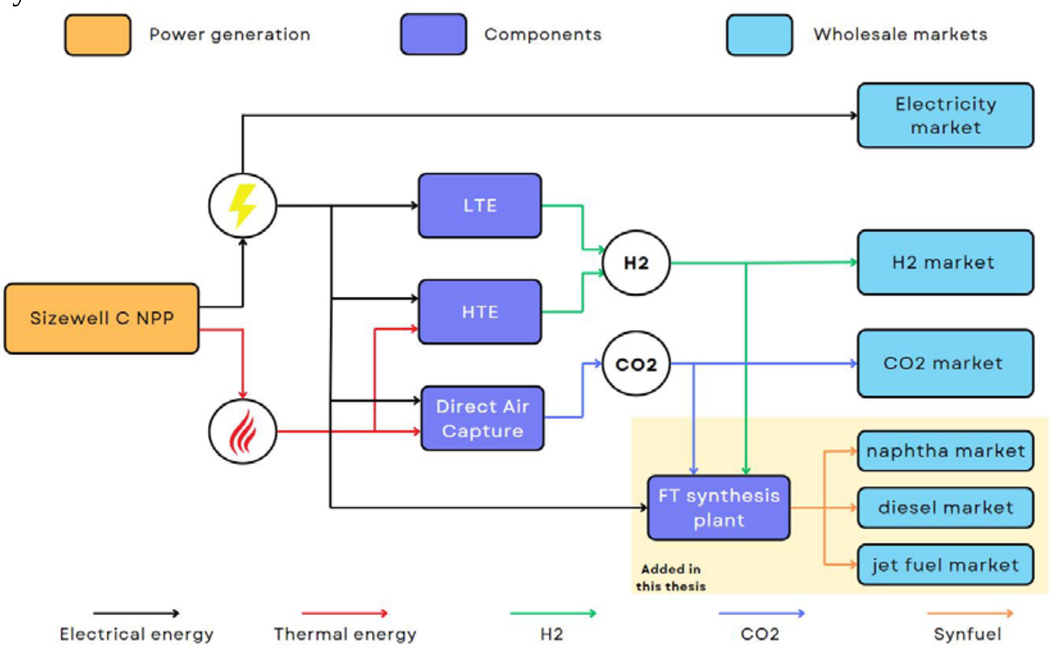
Through simulations carried out in the OptiNuc software, the thesis will explore the behaviour of a synthetic fuel production facility in an integrated energy system powered by nuclear energy. The simulations will provide information on what it takes for the energy system to produce synthetic fuels instead of being used for alternative uses, like provide electricity to the grid or sell hydrogen or CO2 to the market.

The task

To understand the challenges and benefits of synthetic fuel production powered by nuclear energy. The thesis is also aimed to provide a real-life example of how this energy system could provide synthetic aviation fuel to Norway's largest airport.

Model/ measurements

Implementation of a separate module in the OptiNuc software, representing a Fischer-Tropsch synthesis plant. The module was designed to take inputs of electricity, H2 and CO2 from already existing modules, and produce synthetic fuels. It was created to visualize optimization of synfuel production and see what criteria has to be met in order to produce synfuels.



Calculation

Considering electricity price of 70 EUR/MWh:

Type of levelized cost	Value [€/kg]
LCOH	3.852
LCOD	0.248
LCOFT	0.150
LCOEF	4.249

Electricity price of 30 EUR/MWh

Type of levelized cost	Value [€/kg]
LCOH	1.852
LCOD	0.230
LCOFT	0.120
LCOEF	2.202

Other results are stored in an excel file from simulations done in OptiNuc

Conclusion
Results show that the levelized cost of hydrogen (LCOH) accounts for the biggest portion of the levelized cost of e-fuel. Since hydrogen production consumes large amounts of electricity, it was found that the price of electricity highly affect the LCOEF.

Another key finding is that it was estimated that the market price of synthetic fuel must be around 2.5 euro/kg to prioritize production of synthetic fuels over delivering electricity to the grid, when sale of H2 and CO2 is not accounted for. When the energy system is able to sell H2 and CO2, the market price of synfuels must instead reach around 6 euro/kg in order for it to beneficial to produce synfuels. A cost of 2.5 euro/kg are in line with the projected price of e-kerosene in the EU-market for 2050, according to the International Council on Clean Transportation (ICCT).

Distributed SOC-weighted droop control in DC microgrid

Student: **Eriksen, Erlend Brask**
Supervisor: **Bergna-Diaz, Gilbert**

This thesis will not be published, and abstract is not available.

Fault Detection on Large Induction Motors on Oil and Gas Platforms

Student: **Kristian Erlandsen**
Supervisor: **Arne Nysveen**

This thesis will not be published, and abstract is not available.

Integrating Electric Vehicles into the Norwegian Power Grid: A Case Study

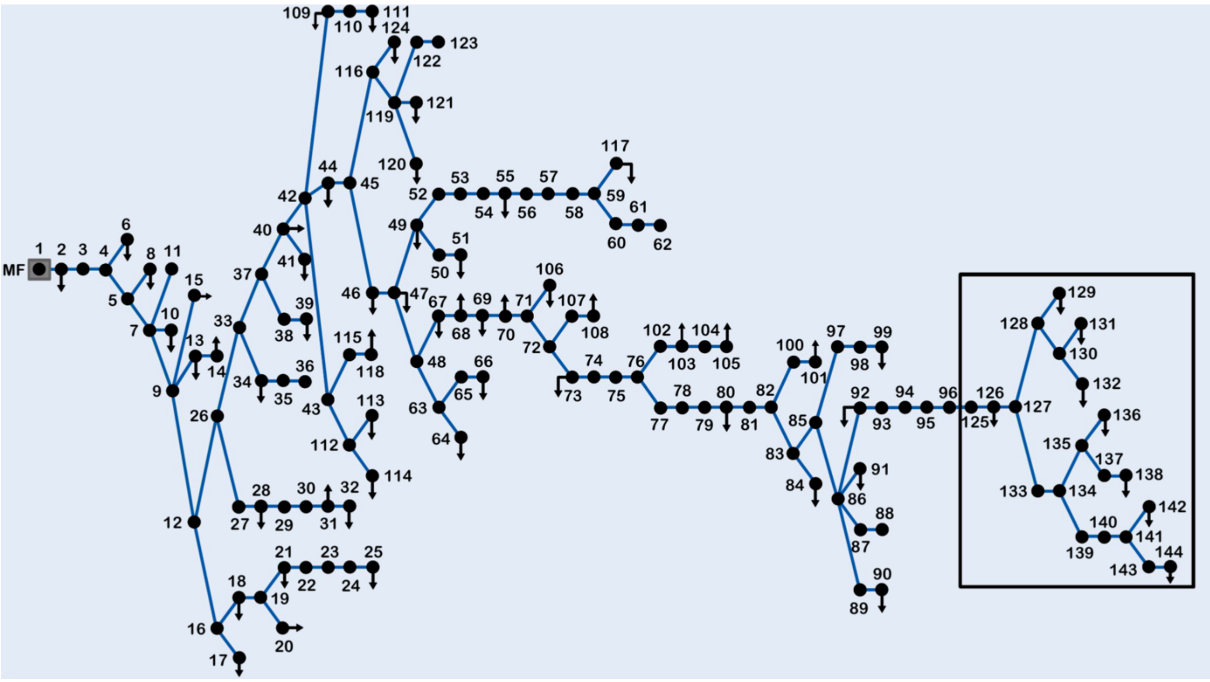
Student: **Espnes, Egil**
Supervisor: **Oleinikova, Irina**
Co-Supervisor: **Sperstad, Iver Bakken (SINTEF)**
Contact: egil.esp@hotmail.com
Collaboration with: **FME CINELDI**

Problem description

As the electrification of transport increases, it significantly raises the stress on the grid, necessitating solutions to prevent problems such as overloads and power outages. This thesis explores the impact of electric vehicles (EVs) on the Norwegian low-voltage distribution grid and how different charging strategies can alleviate the grid strain to facilitate the integration of electric transportation. The charging strategies include coordinated and bidirectional charging methods, which can contribute to flexibility in the power grid.

Model

Python was utilized for grid simulation, using the Pandapower package for power system modelling. The modelling involved implementing power lines, transformers, generators, loads, and buses, with properties like voltage rating, resistance, and load consumption stored in dataframes for easy configuration. The reference grid from CINELDI, a 22 kV distribution grid with 124 buses and 53 loads, included aggregated loads and Evs. In addition, a low-voltage distribution grid was created and connected to the aforementioned grid through a transformer. The low-voltage distribution grid had 20 buses and 8 loads. Each load contains a household and an EV. Load data for the households and EVs were retrieved from relevant articles. Various charging strategies were modelled, including a base case, constant charging, smart charging, and vehicle-to-home (V2H), to analyze flexibility potential and grid impact, with simulations revealing insights into load behavior and voltage levels. The figure below shows an overview of the modelled grid. The box shows the low-voltage grid, which was the main focus area of the thesis.



Calculation

Four different scenarios were established, each with its own charging strategy. The load and voltage behavior at the bus furthest out in the system was presented for each scenario. Further, the flexibility potential was calculated and presented. The flexibility potential was based on how much load was shifted for the different scenarios.

- **Benchmark Scenario**

  The benchmark scenario refers to unadjusted charging, in which EV owners start charging immediately when they return home. The charging data is retrieved from smart meter data in a Norwegian distribution grid.

- **Constant Charging Scenario**

  Constant charging is defined as continuous charging in a predefined interval, with a charging power much lower than the regular charging level. This scenario contains two sub-scenarios; one with a 16-hour charging cycle (16:00 – 08:00), and one with an eight-hour charging cycle (00:00 – 08:00).

- **Smart Charging Scenario**

  The smart charging is based on the total demand for each residential load, where a set load threshold activates the smart charging whenever it is exceeded. If the load threshold is exceeded and the EV is charging, then the charging will be delayed to a later time.

- **V2H Scenario**

  V2H is a type of bidirectional charging in which the EV battery is discharged to transfer energy to the household if the load threshold is exceeded. For the V2H technology to be activated, the EV needs to be connected to the grid and fully charged.

Conclusion

The thesis underscores the importance of flexible charging strategies to handle the growing electricity demand from the transport sector. It concludes that implementing smart charging and bidirectional charging can offer significant flexibility potential, alleviating the stress on the grid by shifting the loads away from hours with typically high residential load demand.

Partial Discharge Characterization of New Environmentally Friendly Insulating Liquids

Student: **Mohammad Fazlalizadeh**
Supervisor: **Kaveh Niayesh and Mohamad Gaffarian Niasar**
Contact: **Kaveh Niayesh**
Collaboration with: **SINTEF Energy and TU Delft**

Problem description

Unwanted breakdown of insulation is one of the primary challenges affecting the reliability of power systems. Liquid insulation is commonly used in power grids and subsea installations due to its preferred qualities, such as heat transfer and safety. Some insulating liquids have been available since the earliest times, and some have been proven to be harmful to humans, animals, and the environment. Consequently, the search for better candidates has always been ongoing. Unfortunately, the knowledge of the quality of the insulating liquids is insufficient since numerous phenomena related to electrical discharge and breakdown in insulating liquids happen unexpectedly, often surprising the personnel involved. Therefore, gaining a deep understanding of Partial Discharge (PD) and the mechanisms leading to the degradation of their dielectric properties is crucial.

Based on this, studying Partial Discharge Inception Voltage (PDIV) is a good measure that reflects the dielectric characteristics of a liquid. There are defined standards, such as IEC 61294, for testing liquids. This work is focused on investigating the behaviour of different types of a new environmentally friendly liquid under the AC voltage stress above and below the PDIV level to determine if the defined standards reflect the dielectric characteristics of each liquid properly.

The task

The aim is to investigate the partial discharge formation in dielectric liquids more deeply. The main approach of this work is to experiment with various liquids to observe their electrical behaviour under HVAC voltage with different frequencies. Careful investigation of the process of PDIV across different liquids and the role of space charges in initiating PDs within the liquids will be studied.

PD detection with different methods to evaluate the procedure of PD is one of the goals of this work.

Model/ measurements

Three liquids have been examined under a High Voltage (HV) sinusoidal waveform with three different frequencies. Candidates were two commonly used insulating liquids in transformers and one spectroscopy standard liquid. Tests are performed in a needle-plane geometry.

In another approach, PDIV level has been tested by optical PD measurements and compared to regular measuring methods. PD patterns and the needle current passing through the liquid have also been measured and compared for this study.

Further, the test setup was facilitated, and half-cycle voltages were applied to involve only one polarity of space charges

Results

Influence of Remaining Space Charges in the Region After a PD Incident leading to an increase in the conductive current level, which remains for a certain amount of time which is shown in Fig.1. Erosion of the needle tip has been investigated in different voltage levels and

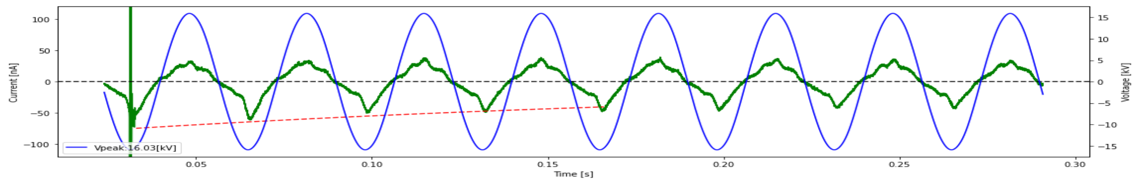
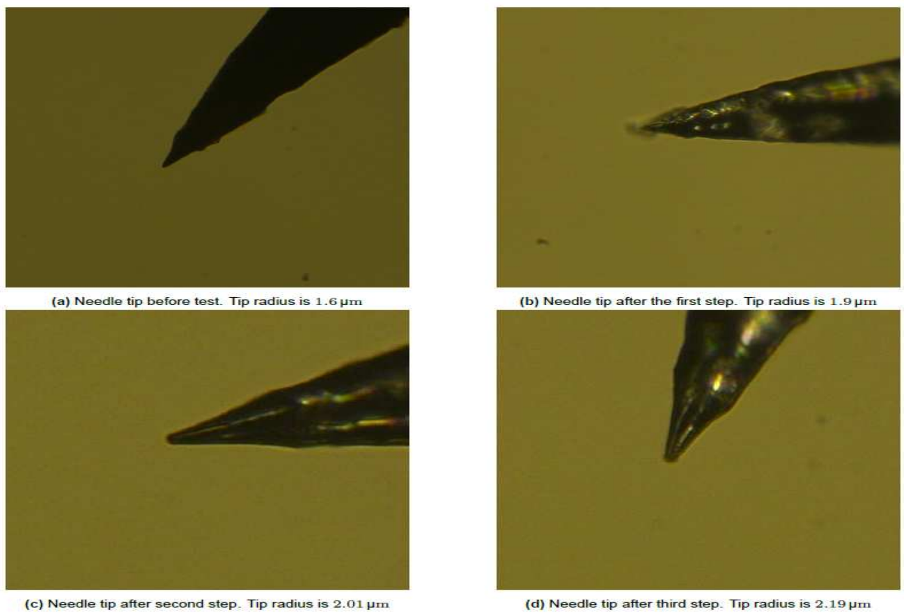


Fig.1: The conductive current versus time in Cyclohexane under 16kV, 30Hz with 3μm needle tip

time periods. The different levels of erosion due to PD is visible in Fig.2 and quantitive results have given in Fig.3(b). The liquids also measured the PDIV level and needle erosion. The results are given in Fig.3(a) and Fig.3(b).



(a) Needle tip before test. Tip radius is 1.6 μm

(b) Needle tip after the first step. Tip radius is 1.9 μm

(c) Needle tip after second step. Tip radius is 2.01 μm

(d) Needle tip after third step. Tip radius is 2.19 μm

Fig.2: Different levels of needle erosion under a microscope

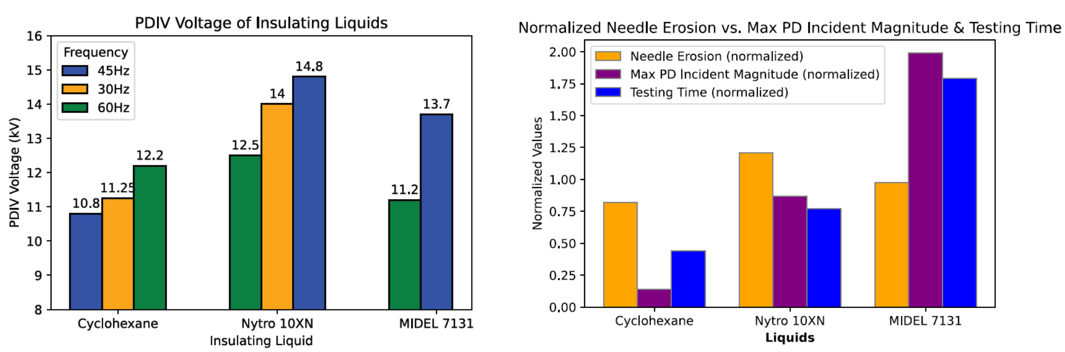


Fig.3: PDIV and normalized needle erosion test results

Conclusion

The effect of space charges on current waveforms has been successfully demonstrated in multiple cycles after a PD incident. This change decreases exponentially with the displacement of space charges. Also, observations of the asymmetry between the first and second quarters of the cycle in higher frequency have been made. The theory of the impact of space charges on the asymmetry has been developed. In addition, the results of practical tests on the PDIV level in three different dielectric liquids under three different frequencies have been reported. The effects of applying voltage and PDs on the erosion of the needle tip in a needle-plane geometry have been investigated in two different aspects. The results have been presented and compared with previous research.

Evaluating the Scenario Fan Simulation(SFS) Methodology for Local Medium-term Hydropower Scheduling

Students: **Øyvind Benno Haugland & Vegard Storeng Fjeldstad**
Supervisor: **Gro Klæboe & Viviane Aubin**
Collaboration with: **ANEO**

Problem description

As the share of intermittent energy sources like wind and solar grows, the importance of flexible hydropower in balancing fluctuating production becomes increasingly important. At the same time, hydropower also harms the ecology of rivers and lakes. The emphasis on environmentally friendly hydropower production has grown significantly, causing NVE to impose stricter restrictions on hydropower production when reevaluating old production licenses. Power producers need to be able to adapt their production according to new restrictions and need accurate hydropower scheduling models as decision support.

The task

One of the Norwegian river systems that are likely to face stricter environmental restrictions and must adapt their hydropower scheduling accordingly is Lundesokna in Melhus, Central Norway. This master's thesis evaluates two different methodologies for medium-term hydropower scheduling, through a case study of implementing environmental restrictions in the Lundesokna River system. Scenario fan simulator (SFS) is a methodology that shows promising results for long-term market simulations on the Nordic power system but has not been used for production scheduling. An SFS model is developed for medium-term production scheduling, and results are compared with an aggregated Stochastic dynamic programming (SDP) model. The SFS methodology allows for more detailed modeling of environmental constraints than an aggregated SDP model. How the different methodologies perform for scheduling production in Lundesokna is examined by comparing key metrics such as income, production, spill, reservoir management, and flexibility.

Model/ measurements

Two optimization models are developed in Julia to investigate how the different methodologies for hydropower scheduling perform for production scheduling in Lundesokna. The main model is based on the SFS methodology, while the SDP model is used as a benchmark to compare results. Both models aim to maximize income over one year of production while complying with the constraints of the watercourse. Figure 1 illustrates the procedure of the SFS methodology. The SFS algorithm is divided into two stages that run iteratively to find the optimal production schedule one week at a time. Stage 1 is the scheduling part, where the production plan is optimized. Stage 2 is the strategy part where the different scenarios represent the uncertainty in price and inflow.

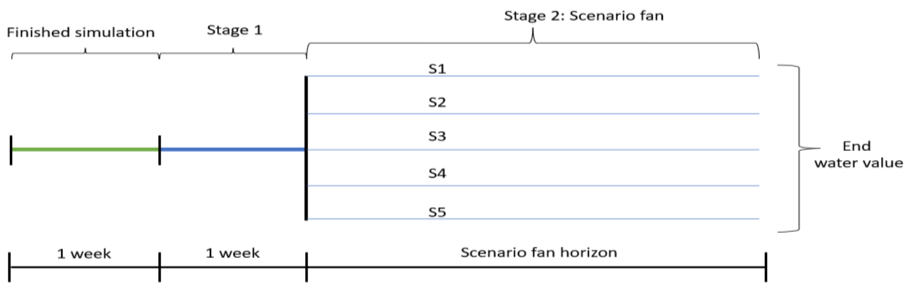


Figure 1: SFS procedure

Calculation

Figure 2 displays the main results. With no environmental constraints, the SDP strategy appears effective, yielding little spill and high income. When implementing environmental constraints, the SFS model performs better.

	Model	Correlation	Income [M€]	Production [GWh]	Spill [GWh]	End reservoir [GWh]	FF*
	SDP	No	22.9	374.0	15.2	90.1	1.188
Base	**SDP**	Yes	23.8	378.8	10.2	95.7	1.188
Case	**SFS**	No	22.4	360.7	21.3	95.0	1.163
	SFS	Yes	23.3	370.1	13.0	99.1	1.209
	SDP	No	18.2	319.9	29.4	126.4	1.108
Env.	**SDP**	Yes	19.1	329.1	25.6	125.2	1.145
const.	**SFS**	No	19.7	319.9	25.4	117.6	1.145
	SFS	Yes	20.8	343.4	18.0	119.1	1.183

Figure 2: Main results

With Environmental constraints, the SFS method performs better than SDP, producing and earning more and spilling less. Nevertheless, the SFS model is remarkably slower than the SDP model. A 20 times longer computational time makes the SFS model less convenient to use. The "Correlation" column in Figure 2, specifies if the model is accounting for autocorrelation in prices or not. As shown from the results, this has a positive effect when implemented in both models. Lundesokna has 3 reservoirs and only one of the reservoirs has a minimum summer reservoir constraint. This causes problems for the SDP aggregation strategy which is not able to make accurate strategies for reservoir management. The ability to specify which reservoir the summer restriction is present in the second stage of SFS is beneficial. The SDP model only knows it must save water, but not in which reservoir. Figure 3 shows the reservoir filling in Håen, a reservoir without summer restriction. While the SDP model saves too much water in Håen before summer and ends up spilling, the SFS model is better able to utilize the water.

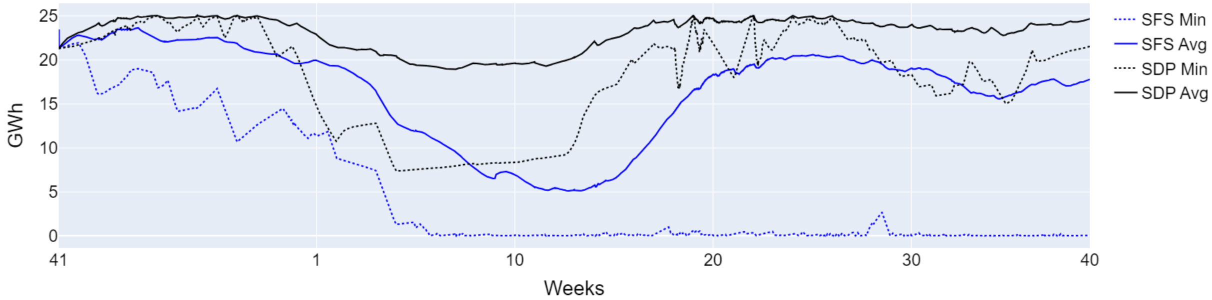


Figure 3: Håen reservoir level

Conclusion

In the case without any environmental constraints, the SDP model on average generated slightly better results in terms of income, production, and spill. Nevertheless, the results of the models changed when environmental constraints were implemented. In this case, the SFS model seems to outperform the SDP model on all levels except the computational time, which was 20 times as long. With less spill, higher income, more production, and higher flexibility factor, the SFS model can make better strategies for production. The SFS methodology allows for a more detailed description of the system, enabling it to handle the environmental constraints more precisely. Conversely, the aggregation of the SDP model makes it impossible to specify where the constraint is appended in the creation of the water values, which results in a model that is more restrictive in water usage.

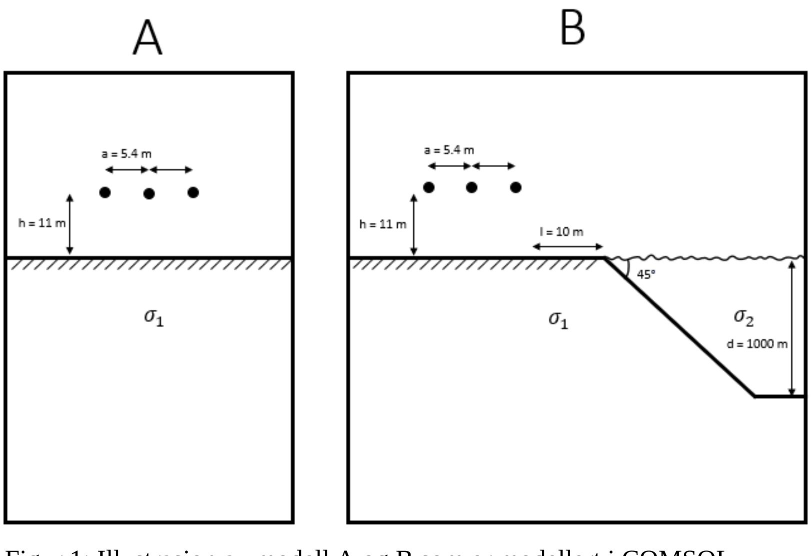
Luftledningers serieimpedans ved parallellføring med sjø

Student: **Elin Aune Forbord**
Veileder: **Bjørn Gustavsen**
Medveileder: **Ragnar Mangelrød**

Problemstilling
Det elektriske kraftsystemet spiller en kritisk rolle i å opprettholde en pålitelig strømforsyning, og beskyttelse mot feil er avgjørende for å unngå alvorlige konsekvenser.
I dagens høyspente regionalnett er spolejording en mye brukt jordingsmetode i Norge. Med et kraftnett som stadig øker i omfang og kompleksitet, vil spolejordete nett få noen utfordringer når det kommer til blant annet spolekompenseringen og feillokalisering av stående jordfeil. Spolejordete nett har sjelden gjennomgående jordliner, mens direktejordete nett er normalt utstyrt med jordliner langs hele luftledningens lengde.
Jordliner gir en sikker og rask utkobling av jordfeil. I et direktejordet nett kan jordfeil uten gjennomgående jordliner detekteres ved hjelp av den resulterende 3I0-strømmen i de tilkoblede nettstasjonene. Feilstrømmen kan imidlertid være lav, og den er sterkt avhengig av jordresistivitet og lokale forhold på feilstedet.

Oppgaven
Hensikten med denne oppgaven har vært å undersøke hvordan variasjoner i jordsmonnet påvirker impedansene, for å kunne estimere feilstrømmen ved en jordfeil. Oppgaven er avgrenset til modellering av serieimpedanser for ulike jordsmonn ved 2D-modellering.

Modell/målinger
Oppgaven bruker COMSOL Multiphysics for å modellere ulike jordmodeller for tre faseledere i en 2D-modell. To hovedmodeller (kalt A og B) er modellert for å studere hvordan impedansen påvirkes av faktorer som jordkonduktivitet og innvirkningen av toppliner. Modell A modelleres med en uniform jordmodell, mens modell B inkluderer en parallellført sjø. To ulike toppliner, med forskjellig ledningsevne, er også modellert. Beregninger av serieimpedanser for luftledninger i en uniform jordmodell er utført med analyseprogrammet ATP for å verifisere modellen i COMSOL.



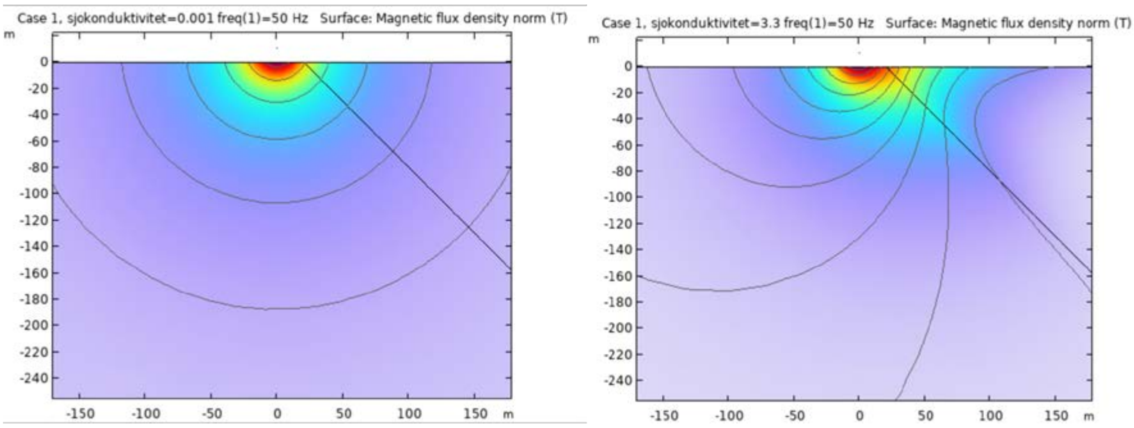
Figur 1: Illustrasjon av modell A og B som er modellert i COMSOL

Beregninger

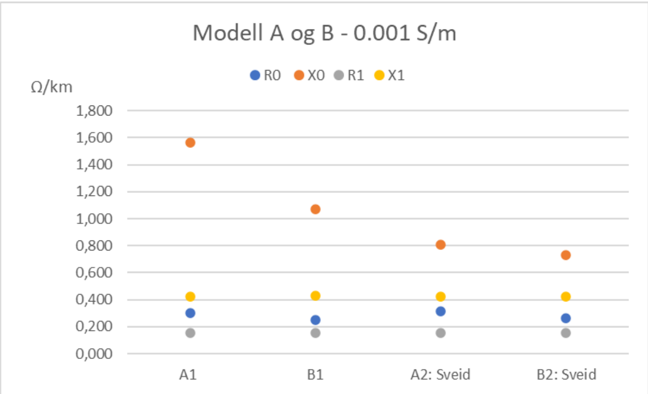
Resultatene viser at det er en betydelig endring i serieimpedansen når vi endrer på både jordkonduktiviteten og inkluderer en sjø parallelt med luftledningene. Tabell 1 viser hvordan serieimpedansen varierer for to ulike avstander på den parallellførte sjøen, hhv. 10 og 100 meter. Med toppliner blir endringene i R0 og X0, betraktelig lavere.

Tabell 1: Forskjeller i serieimpedansen når avstanden på den parallellførte sjøen er på 10 og 100 meter. Uten og med toppliner (hhv. B1 og B2)

	B1	B2 (Fe70)	B2 (Sveid)
R0	-19,62 %	1,37 %	1,53 %
X0	17,72 %	14,22 %	5,52 %
R1	-0,03 %	-0.04 %	-0,06 %
X1	-0,09 %	0,01 %	-0.05 %



Figur 2: Sammenligning av modell A1 og B1. Jordmodellene har en jordkonduktivitet på 0.001 S/m, mens på figuren til høyre er en sjø med jordkonduktivitet lik 3.3 S/m inkludert.



Figur 3: Serieimpedansene for modell A og B med og uten toppliner, med en jordkonduktivitet på 0.001 S/m. Modell B har den parallellførte sjøen på 10 meter avstand

Tabell 2: Serieimpedansene for modell A og B med og uten toppliner, med en jordkonduktivitet på 0.001 S/m. Modell B har den parallellførte sjøen på 10 meter avstand

	A1 til B1	A2 til B2 (Sveid)
R0	-15,79 %	-15,32 %
X0	-31,57 %	-9,69 %
R1	-0,04 %	0,07 %
X1	-0,40 %	-0,03 %

Konklusjon

Resultatene viser at serieimpedansene påvirkes betydelig av jordmodellen når toppliner ikke er inkludert. Nullimpedansen endres både ved variasjoner i jordkonduktivitet og ved inkludering av en sjø, mens den positive komponenten i serieimpedansen forblir uendret. Dette er forventet da det er nullsystemet som blir påvirket av de ulike jordmodellene.

Oppgaven konkluderer med at COMSOL er et nyttig verktøy for analyse av ulike jordmodeller i kraftnettet, og at 2D-modelleringen gir troverdige resultater som kan gi økt innsikt i feilstrømanalyse og kan brukes i videre undersøkelser.

Spenningsregulering i distribusjonsnett med økt integrasjon av solcelleanlegg og endret forbruksmønster

Student: **Furuhaug, Ola**
Faglærer: **Uhlen, Kjetil**
Veileder: **Sand, Kjell**

Oppgaven skal ikke publiseres, og sammendrag er ikke tilgjengelig.

GaN-based, High-frequency Converter for Use in Auxiliary Power Supplies for MVDC Converters

Student: **Gagnat, Lars**
Supervisor: **Weiss, Beatrix Veronika**

Abstract

In recent years, gallium nitride (GaN) technology has advanced significantly, establishing itself as a key material in the development of high-frequency converters. GaN's superior electron mobility and high breakdown voltage capability enable more efficient and compact power systems. These properties make GaN particularly advantageous for high-frequency applications, offering reduced energy losses and improved thermal management.

This master thesis investigates the design of an auxiliary power supply for MVDC converters, building on previous work. MVDC converters using SiC MOSFETs typically require 10 W at 20 to 25 V and must be supplied through a galvanically isolated source for safety. This work presents a new inverter design using discrete GaN HEMTs and an optimized layout. Additionally, the isolation transformer design was realized by using ceramic carriers instead of FR4, serving as both the PCB and insulation material. Prototypes of the inverter and transformer were designed, built, and tested before being implemented and tested in the full converter setup. For this purpose, an adaptable test stand was created.

The ceramic transformer demonstrated good thermal dissipation, improving the system's thermal performance by lowering the coil resistance and increasing the thermal conductivity compared to previous transformer designs. This while maintaining strong magnetic coupling. However, parasitic capacitance coupling between the transformer coils emerged as a potential challenge with this design. The impact of different insulation thicknesses and shield placement was therefore also tested.

The inverter prototype operated as expected under lower loads. However, a shoot-through problem arose at higher loads due to challenging tuning of the system resonance tank, resulting in an unstable output. Despite this, the converter showed promising results at lower loads, achieving a peak efficiency of 88%, indicating potential for an efficient system.

It is demonstrated through this work changing to the ceramic substrate for the transformer and discrete devices can mitigate previously observed thermal issues. However, a tuning of the resonant tank needs to be conducted to investigate the full potential of the optimized converter.

Electrical Fault Analysis for a Modular HVDC Generator

Student: **Uxue Garciandia Irisarri**
Supervisor: **Pål Keim Olsen**
Co-Supervisors: **Lorrana Faria da Rocha, Wei Wang**
Contact: **uxuegarziandia2000@gmail.com**

Problem description

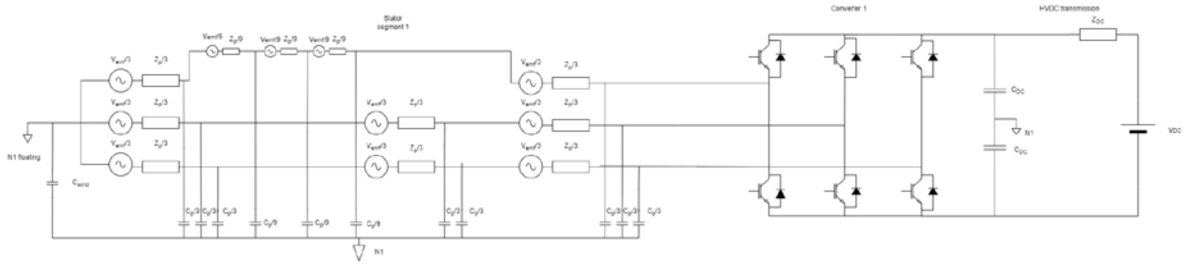
Electrical faults that can happen in a Modular HVDC generator module can affect the normal operation of the system and based on the fault behaviour of the system, the possibility of operation through the healthy modules can be analysed. This is an initial research to ultimately design a system that can handle and protect the system from faults and continue operating after a fault event to improve the reliability of the system.

The task

Build an electrical model of the system for one module in Matlab Simulink for nominal power production of the module. Analyse possible fault events and simulate them to understand the system's behaviour. Add a protection logic to the system control to protect the generator windings and converter and simulate the fault events once again. Scale the number of modules of the system to the 16 of the original design. Implement the fault analysis in the lab setup.

Model/ measurements

The electrical model consists of a segment of the three-phase PMSG generator connected to an AC/DC converter. The current through the converter is then smoothed by two DC link capacitors and is then transmitted by a HVDC power line.



Results

The following table shows the summary of the protection used in the analysed internal module faults for the simulations on one module:

Fault type	Protection
Inter-turn short circuit fault	Cannot be detected with used method
Open phase fault	Six Switch Open
Phase-to-phase short circuit fault	Active Short Circuit
Phase to module neutral short circuit fault	Active Short Circuit
Single switch short circuit fault	Active Short Circuit
Single switch open circuit fault	Six Switch Open
DC pole-to-pole short circuit fault	Active Short Circuit
DC capacitor overvoltage fault	Active Short Circuit

The following table shows the summary of the protection used in the analysed internal module faults and inter-module faults for eight modules and whether it is possible to continue operating after the fault is detected and the protection is activated:

Fault type	Protection	Operation post-fault
Phase to module neutral short circuit fault on a module	Module 1: Active Short Circuit Rest: Six Switch Open	Bypass switch and n-1 operation
DC pole-to-pole short circuit fault on a module	Active Short Circuit	Bypass switch and n-1 operation
Module neutral-to-neutral short circuit fault	Active Short Circuit	Switch on module neutral and n-1 operation
Module neutral to ground short circuit fault	Active Short Circuit	Cannot operate
Module-to-module open circuit fault	Six Switch Open	Cannot operate

Conclusion

The faults were detected through a logic circuit that measured over/undercurrents and over/undervoltages. This detection was used to activate the converter protection schemes. Active Short Circuit protection was implemented by allowing switching on the power converter just on one level of the switch bridge. The purpose of this protection was to discharge the high currents in the winding when a short circuit fault occurred due to the fault current being fed in the generator phases and safely and effectively shut down the generator while the module disconnected from the grid. On the other hand, Six Switch Open protection acted on open circuit faults and overvoltages on the DC side by opening all the switches in the power converter bridge. This protection method also effectively shuts down the generator for the fault events without high currents in the generator phases.

Through analysis it can be concluded upon further research that in some fault cases the system can continue operating by disconnecting the faulty module, if protection elements like bypass switches were to be added to the system to disconnect the faulty modules, and operating the system with n-1 operation control on the remaining healthy modules. This would result on proof of a fault resilient generator that improves offshore wind turbines' availability.

Lifetime Estimation of Extruded HVDC Cable Insulation

Student: **Silas Merlin Gerhard**
Supervisor: **Frank Mauseth**
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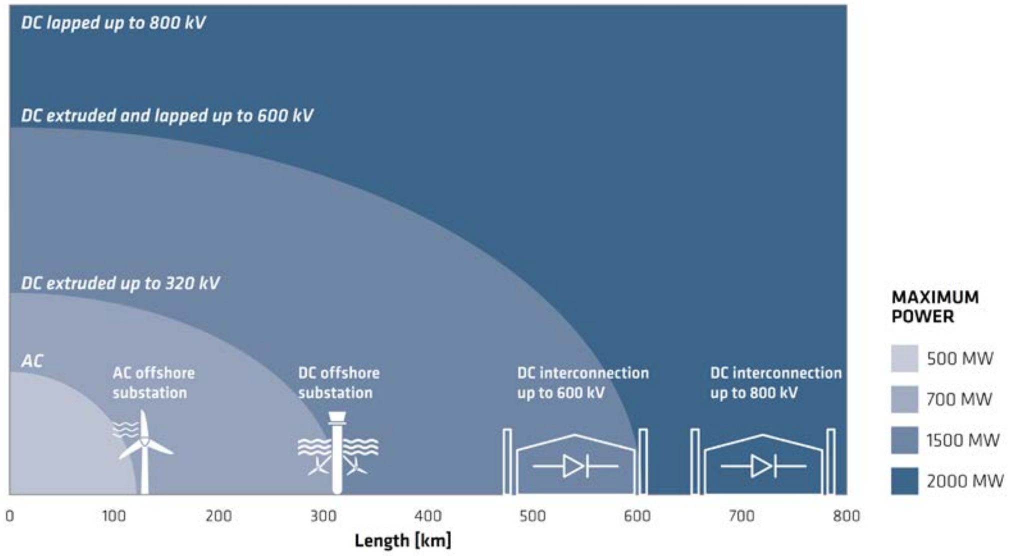
Collaboration with: **Nexans Norway AS, SINTEF Energy AS**

Problem description

Extruded high voltage direct current (HVDC) cables are essential for the green shift and for the electrification of the world. Subsea cables for offshore wind parks are especially relevant. Sales of extruded HVDC cables show a quasi-exponential rise since approx. 2009 and they are displacing mass impregnated cables increasingly. The DC-XLPE insulation of the cables is aged (mainly) by the electrical and thermal stress they are exposed to and, therefore, they will fail at some point. Hence, extruded HVDC cables have a limited lifetime due to aging by electrical field stress. Extruded HVDC are in operation for just a few decades and, thus, their operation lifetime is unknown.



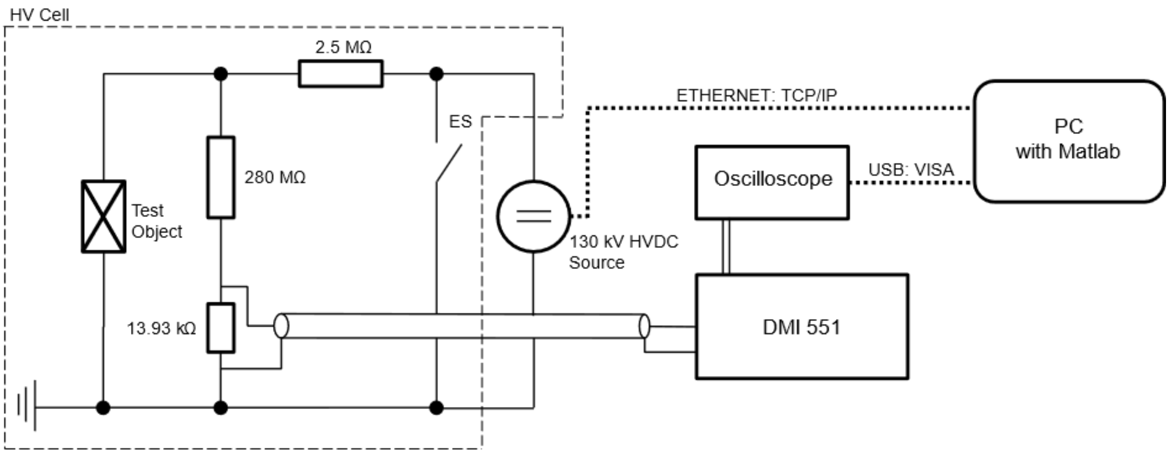
Source: Prysmian Group, 2018

The task

The objective of the master thesis is to estimate the lifetime of extruded HVDC cable insulation by tests (accelerated life tests) and measurements on DC-XLPE cable peelings peeled from a 525 kV cable from Nexans. Additionally, the ageing behavior shall be evaluated. The insulation is investigated at two regions, near the inner semiconductive screen and near the outer semiconductive screen. Furthermore, fresh and prequalification (PQ) test aged cable peelings are available to examine the PQ-test aging. The findings are compared to studies from literature.

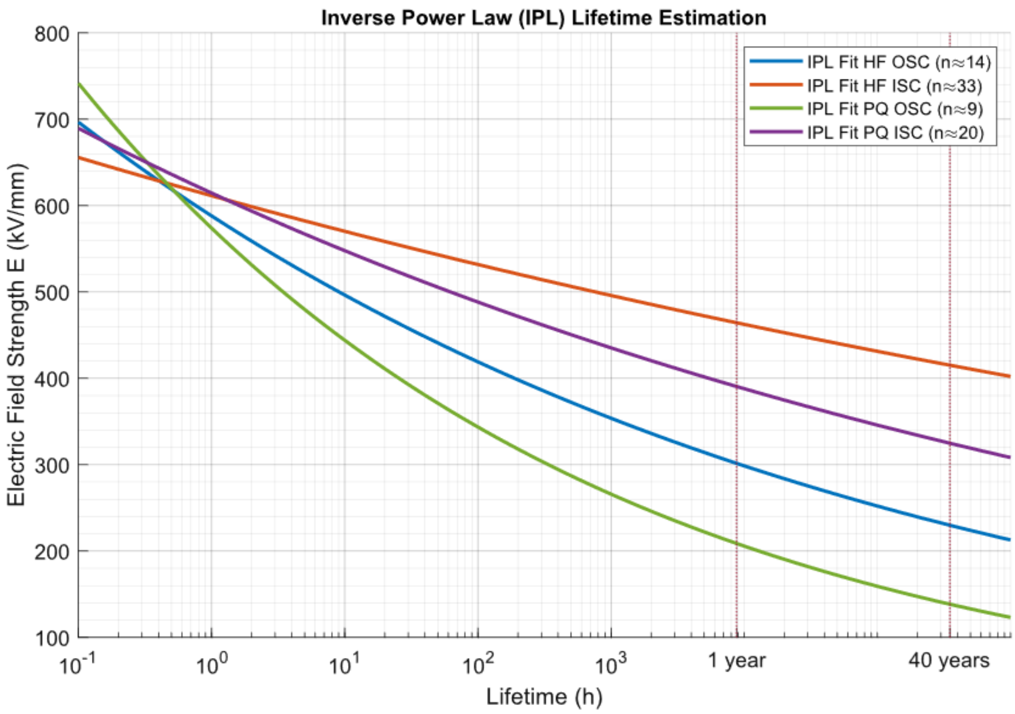
Experimental Setup

HVDC breakdown strength tests are carried out on the insulation by progressive stress tests with different ramp rates. An automated test setup is designed and programmed with Matlab. The cable peelings are degassed before testing to remove cross-linking byproducts. Additionally, differential scanning calorimetry (DSC) and dielectric response measurements are carried out.



Results

The results of the lifetime estimations are shown in the figure below. The lifetime for all investigated peelings and peeling area is shown depending on the field stress. The evaluations are based on the inverse power model (IPM).



Conclusion

The insulation near the inner semiconductive screen performs significantly better than the insulation near the outer semiconductive screen. In contrast, no significant differences can be found for the fresh and PQ-aged insulation. However, it is still presumable that the aging mechanism changes. The performance of the insulation and their lifetime are generally much better than assumed by standards. The differences in the findings are attributed to the manufacturing process and aging processes during the PQ-test. The changes must be of morphological nature since the crystallinity of the insulation is analyzed to be approximately constant at 40% by DSC. In conclusion, the master thesis shows differences among the insulation of the same cable that have not been discovered before, but also that the lifetime of DC-XLPE insulation is very high as the literature confirms.

Operation of an EV parking lot subject to capacity-based grid tariffs offering grid services through demand response

Student: **Andreas Fosse Hansen and Jonas Henrik Pinderud**
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Collaboration with: **SINTEF Energy Research, FME CINELDI and Lede AS**

Problem description
This thesis aims to evaluate the costs and potential benefits of having a flexible Electrical Vehicle Parking Lot (EVPL) when participating in an Incentive-Based Demand Response Program (IBDRP). These programs provide incentives for altering consumption patterns, and this thesis focuses on optimizing EV charging and associated costs, examining how the IBDRP impacts operational performance and costs. Additionally, the thesis explores Vehicle-to-Grid (V2G) technology to analyze how the technology affects operational performance, with and without IBDR-participation. The IBDRP allows participation with varying notice times before activation, impacting operational decisions due to the uncertain activation notification

The task
A Receding Horizon (RH)-framework combined with Stochastic Dual Dynamic Programming (SDDP) is developed on an optimization model that minimizes the cost of operation for an office building with a flexible EVPL, subject to hourly spot prices and monthly demand charge. The framework is investigated for IBDR-participation, where load reduction is requested by the local DSO. With a variation in notice times before activation and different quantities of throttled power, the EVPL scheduling is analyzed to provide insights on consequence of IBDR for the office building. By including V2G, the EVPL scheduling is analyzed to provide insights on the consequence of IBDR when the DSO requires a throttling bigger than the capacity of the EVPL. Lastly, the consequence of an IBDRP when economic incentives reduce the cost of the demand charge cost based on the notice time of the IBDR-signal are investigated.

Model
Figure 1 shows a overview of the model used in this master thesis. The Input Data block organizes and puts into action the data used in the model. The Model Setup block includes the general optimization problem for the SDDP- and RH-framework. The SDDP-framework produces marginal cost curves in each iteration, which are then passed to Model Setup. With the information from the Model Setup including the future cost curves, the RH-framework can generate real-time results for the output.

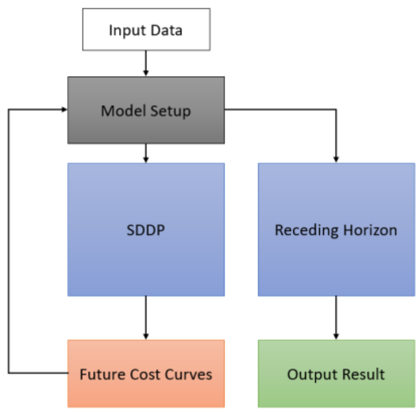


Figure 1: Block-diagram of model

The scheduling structure of the RH-framework is presented in Figure 2, where the Scheduling Horizon (SH) considers the overall operational period of one month. The Control Horizon (CH) is the hour of operation that is to be determined, considering a jump of 1 hour for every step. The Prediction Horizon (PH) is the period the optimization problem has detailed information in regards to spot-prices, office demand, and EV demand. Information beyond the PH is described by the linear cuts derived from the SDDP-framework, enabling a simplified representation of the entire SH and the monthly demand charge. This methodology has a receding PH for each time step, only considering the horizon of the operating day. At 1 PM, when the spot-prices for the next day are revealed, the PH is expanded from 12 to 36 hours, revealing information of the next day of operation. The linear cuts are replaced to consider the cuts from the next day of operation.

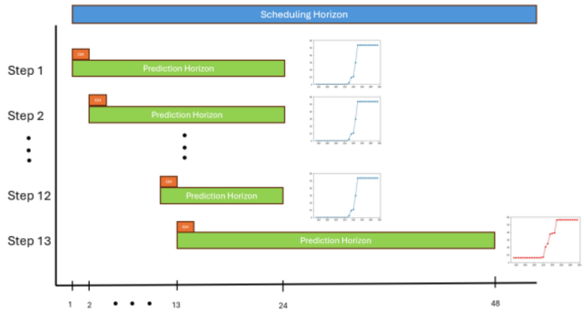


Figure 2: Receding horizon framework with extended PH at 1 PM each day

Calculation

In Figure 3 the marginal cost of increasing the peak power from the future cost cuts is presented. Between 215 and 245 kWh/h, the marginal cost increases rapidly for higher peak value, implying a higher peak leads to higher cost of operation. The figure showcases that later in the month and the closer the model is to realizing the demand charge cost, the higher the marginal cost is for increasing the peak value. Figure 4 shows the daily operational performance when an IBDRP includes economic incentives by offering demand charge cost reduction based on the notice time. In the figure, a 12 hour notice time is given, where the full lines represent the planned EV charging for normal operation before the notice time of the IBDR-signal is given. The dashed lines represent the planned charging after the signal is revealed to the RH-framework. The yellow bar represents the notice time, and the red bar represents the throttling activation hour. The figure shows how the system reacts proactive and reactive to a IBDR-signal, where the energy shifted before activation is distributed over several hours where the spot price is low due to the peak increase. Using a 12 hour notice time and a demand charge cost reduction as an economic incentive for participating in the IBDRP, a 1.8% reduction in total operational costs is achieved.

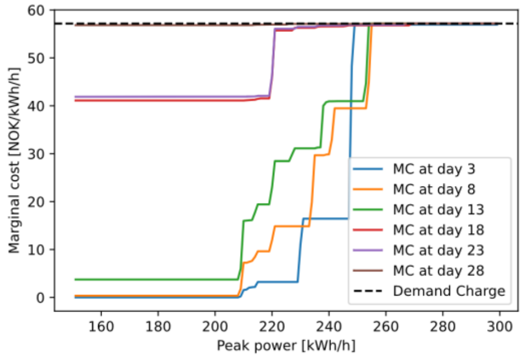


Figure 3: Marginal cost from increasing peak

Conclusion

This thesis investigates how an EVPL can reduce office building operational costs and provide grid services through an IBDRP. Using a SDDP and RH framework, the model optimizes EVPL operations and while handling unexpected IBDRP signals. This thesis finds that the model performs best with a 12-hour notice, while shorter notice times lead to not being able to supply the energy requested. The study also explores a V2G implementation, finding it effective only with a 12 hour notice time. Lastly, an existing IBDRP with demand charge cost reduction shows cost savings for the 12-hour notice scenario, indicating that the EVPL can provide value and flexibility to the office building owner and to the DSO.

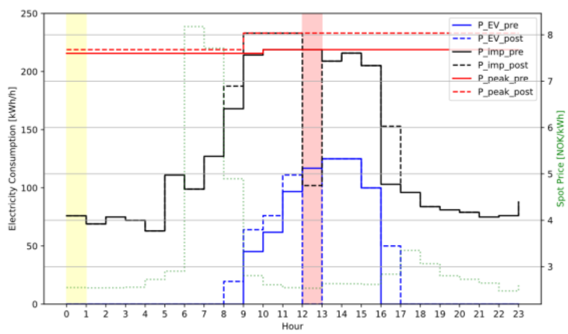


Figure 4: Changes in operation before and after IBDR-signal

Resonance Management in Salient Pole Synchronous Machines

Student: **Haugen, Haakon Magnussen**
Supervisor: **Nysveen, Arne**

This thesis will not be published, and abstract is not available.

Hydrogen in the Distribution Grid for Capacity Planning and Flexibility

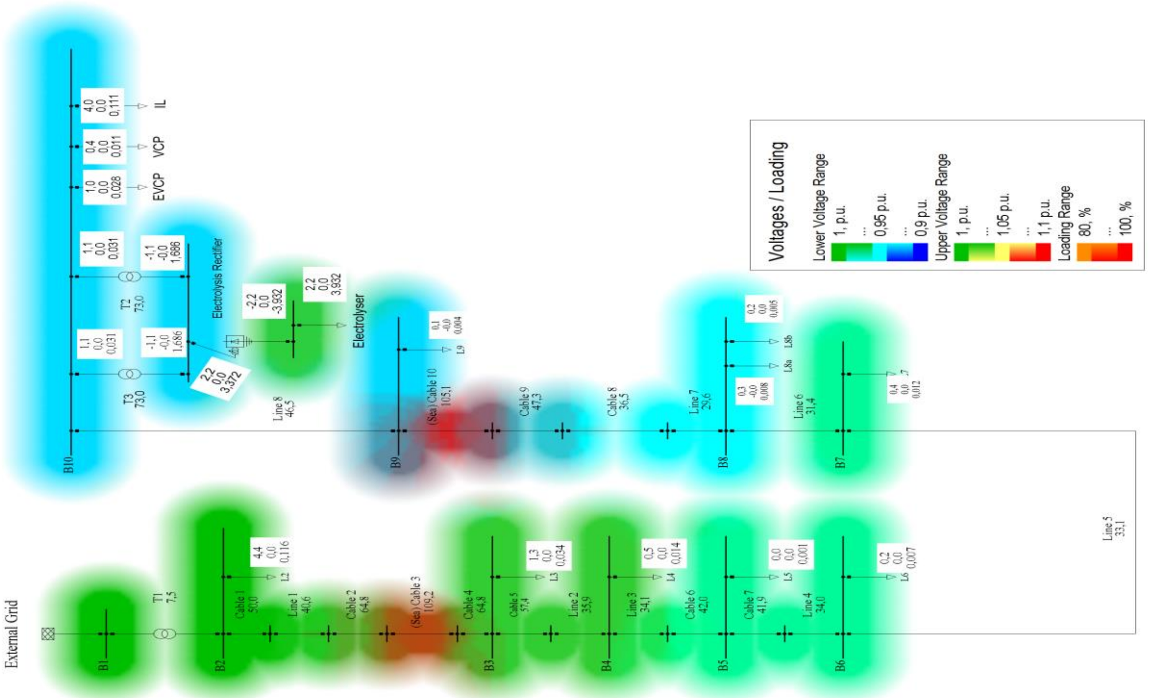
Student: **Torgeir G. Hauso**
Supervisor: **Irina Oleinikova**
Contact: **NN** --------- ” -------------
Collaboration with: **ZeroKyst**

Problem description
The local DSO in Lofoten, Elmea, are planning to install new loads capable of drawing a substantial amount of capacity from the existing grid. These new loads causes problems on sea cables in the distribution grid along with voltage problems during high-demand periods.

The task
The task is to investigate capacity planning problem by scheduling hydrogen production and storage over a system lifetime and, if possible, using the hydrogen storage for flexibility purposes in the distribution system. The scope of the project encompasses

1. Literature review on the relevant project in NO.
2. Hydrogen modelling in PSS.
3. Model different scenarios with focus on capacity planning and grid integration aspects implementing flexibility.
4. Flexibility potential. Technology vs grid operational logic.
5. Summary (indicate that/how electrolysers and hydrogen storage can contribute to flexibility and power supply).

Model/ measurements



Figur 1: Heat map visualization of simulated network model.

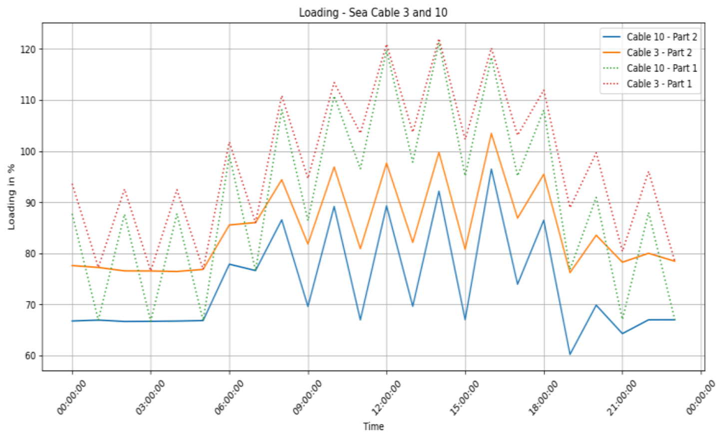
A model is built in the simulation tool Powerfactory and based on an earlier master thesis. The model implements the expansions of loads which are planned by DSO. The new expansions are installed at the end of the radial (Bus 10). Furthermore, the model implements a simplified hydrogen solution with storage capabilities at the end of the grid radial, having the possibility to operate as a flexible source.

Calculation

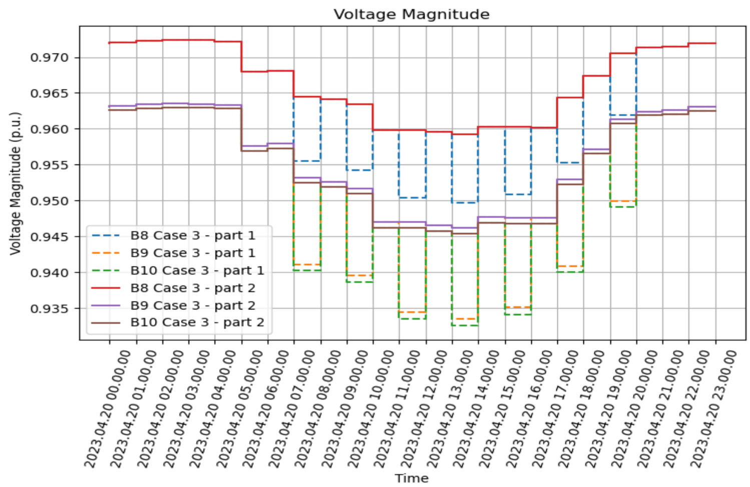
In the simulated study-case represented by figure 1 and figure 2, the loads operate according to a realistic consumption pattern. Further there is installed a ferry charging point at the end ot the radial, which draw 1,5 MW every second hour.

Calculations show that the introduction of a flexible electrolyser could help to decrease the loading of vulnerable cables/lines and other equipment in periods where the demand is high.

The condition in the network also improves by the flexible operation of the electrolyser. By curtailing the production of hydrogen and thereby operating the electrolyser as a flexible load, it is possible to deliver support to the network during high-demand periods.



Figur 2: Loading of sea cables without flexible electrolyser (part 1) and with flexible electrolyser (Part 2).



Figur 3: Voltage magnitude for the last three buses in the network without flexible electrolyser (part 1) and with flexible elctrolyser (part 2).

Conclusion

Results affirm that hydrogen energy technology, through the flexible operation of electrolysers, offers a promising solution for capacity planning and grid flexibility. The observed trends suggest a positive impact on grid stability and operational efficiency, reinforcing the value of integrating hydrogen technology into the distribution grid. The introduction of planned loads will affect the distribution grid, necessitating flexibility from surrounding sources in the grid for mitigation and load shifting under high-demand periods. Expensive grid upgrades that would be necessay without the use of flexible hydrogen solution in combination with storage, could be postponed saving the DSO for expenses.

Optimizing Production Scheduling of Hybrid Wind-Hydro Systems with Environmental Considerations

Student:	**Sunniva Rosland Hebnes**
Supervisor:	**Ümit Cali**
Co-Supervisors:	**Kristian Astad Dupont and Spyridon Chapaloglou**
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Collaboration with:	**SINTEF Energy**

Problem description

The share of variable renewable energy sources is significantly rising with the global pursuit towards sustainable power production. Given the limited operational flexibility and vulnerability of renewable sources, this presents challenges for regulators, grid operators, and energy producers. Coordinating electricity generation, developing sophisticated storage solutions, and strengthening control mechanisms are all aspects supporting the development of reliable grid operation.

The task

In general, this study aims at investigating how various dynamics affect the flexibility and performance of a hybrid power system. To achieve this, various limitations are incorporated into an optimization model to analyze possible consequences on system efficiency and model objectives. The premise of this research is built upon a co-simulation framework consisting of a multi-objective optimization model solving the operation of a hybrid wind and hydropower system, along with a simulation tool that integrates diverse control techniques for the wind farm. The wind farm control framework, *RegFarm,* is developed by Spyridon Chapaloglou at SINTEF Energy. Further, the optimization model incorporates a hydro pump to enhance system flexibility as the power system is connected to a local grid with limited transmission capacity. This study revolves around a case study set in an appropriate location in Northern Norway, chosen to assess how the hybrid operation of wind and hydropower influences the objectives of revenue generation and turbine damage accumulation.

Furthermore, the extensions include studies of how various environmental considerations impact model outputs. This broadens the study to address the increasing awareness of the effects of renewable production on local ecosystems and wildlife.

Model/ measurements

Figure 1 shows a flowchart of the current co-simulation framework, including all attributes and input variables. The multi-objective optimization process is solved using lexicographic optimization and the augmented epsilon-constraints method (AUGMECON) through an implemented Python framework. Furthermore, the concept of fuzzy-logic decision-making is used to quantify and discuss the different solutions.

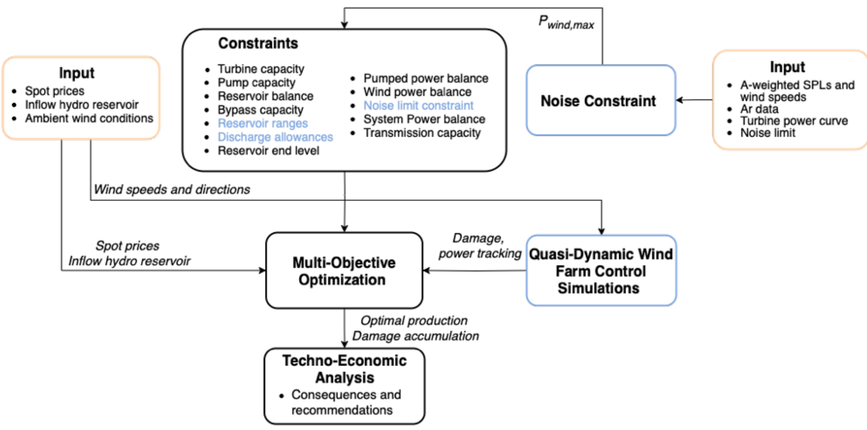


Figure 1: Flowchart of the co-simulation framework.

All boxes and constraints marked in blue represent the extensions performed throughout this study. Including the additional environmental constraints on both power plants and the wind control framework, *RegFarm*.

Calculations
Figure 2 shows a system simulation for the base case, granting the revenue objective highest priority. Similarly, Figure 3 shows the same simulation but with the inclusion of environmental constraints. Comparing the two figures highlights the impact of incorporating additional constraints, necessitating the hydropower plant to reduce peak production and distribute production more evenly throughout the year. Additionally, wind power generally decreases under the restrictions compared to the base case. Consequently, this shift results in a decline in overall revenue, as certain segments of hydropower production are compelled to occur during time steps of lower power prices and wind power curtailment increases.

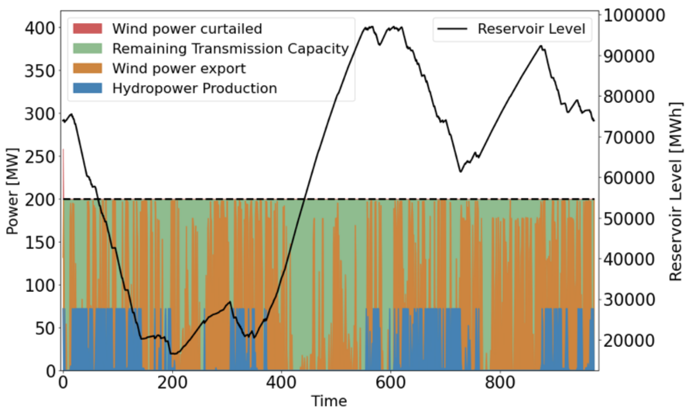


Figure 2: Base case system simulation, solution 49.

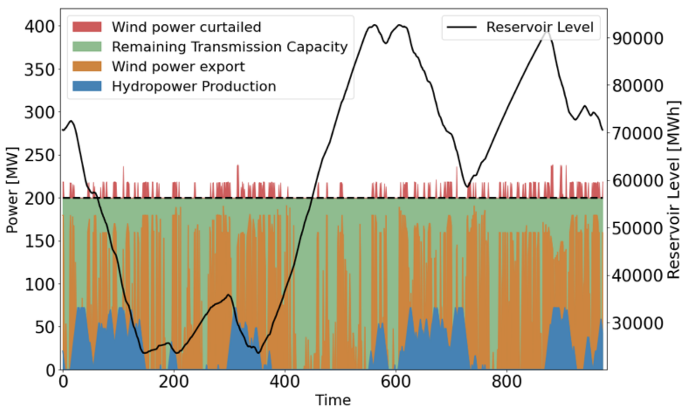


Figure 3: System simulation with env. constraints (5% ramping).

Table 1 present a comparative analysis of the two objectives, examining the environmental outcomes relative to the base scenario. Looking into the changes when incorporating the environmental constraints shows a general decline in revenue, resulting in a more noticeable reduction of accumulated damage levels. For weight 5, the damage is optimized, and reductions of this objective is therefore zero in all scenarios. Substantial reductions occur in weight 4 as the solution space has shifted one step closer to optimizing the damage objective.

Table 1: Relative revenue and damage for the env. case with 5% ramping.

	Weight 1	Weight 2	Weight 3	Weight 4	Weight 5
Revenue [M€]	-5.47%	-5.05%	-6.84%	-22.90%	-9.75%
Damage [-]	-13.41%	-11.13%	-13.41%	-56.70%	-0%

Conclusion
In summary, hybrid systems connected through storage solutions have been shown to improve overall system efficiency and provide critical attributes towards stable power provision. The results from this project display how hybrid coordination through a PHS system improves system flexibility and reduces wind curtailment when hydropower production covers an increasing share of the limited transmission capacity. Also, the additional wind farm control attributes improve wind power output by simulating various influencing factors and dynamics. Furthermore, the imposed constraints present possible reductions in accumulated damage and revenue generation by considering environmental effects. The simulated results can be beneficial for decision-makers when developing new projects and improving existing facilities per upcoming environmental tariffs and regulations.

Verification of Magnetic Field Harmonics in the Air Gap of Double Layer Fractional Slot Concentrated Winding PMSMs

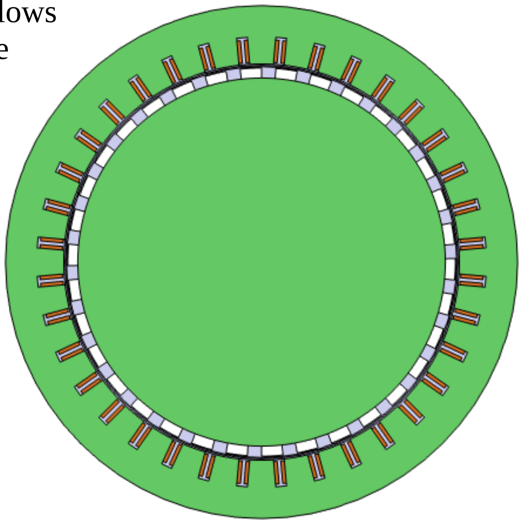
Student: **Thomas Hepsøe**
Supervisor: **Robert Nilssen**

Problem description

European renewable energy production capacity has approximately doubled from 2004 to 2019, with the majority of this expansion being due to wind and solar energy. This creates challenges for the electric grid operators as the amount of unregulated energy production increases while the amount of regulated energy production from fossil fuel sources decreases. Norway has about 50 % of Europe's hydroelectric storage capacity. A report from 2011 found that 1080 MW of hydroelectric power plant capacity has great potential for Pumped Hydroelectric Storage(PHS). A cost-efficient method of installing PHS is by installing booster pumps to pump water up the existing waterway. Contra-rotating propellers have a hydrodynamic advantage over single propellers that reduce losses and wear. A single stator dual contra-rotating rotor electric machine is suggested to build a cost-effective dual-rotating electric booster pump.

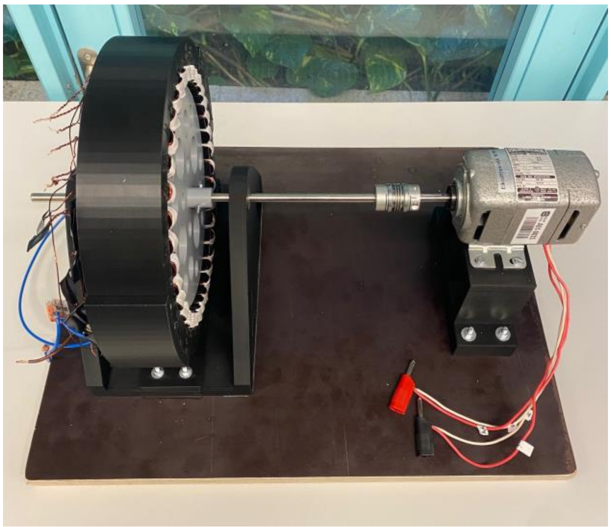
The task

The thesis aims to investigate and verify the magnetic field harmonics in the air gap of a double-layer fractional slot concentrated winding PMSM that allows for two contra-rotating rotors inside the same stator. This is done by measurements and testing of a 3D printed prototype machine as well as 2D FEM simulations in COMSOL.

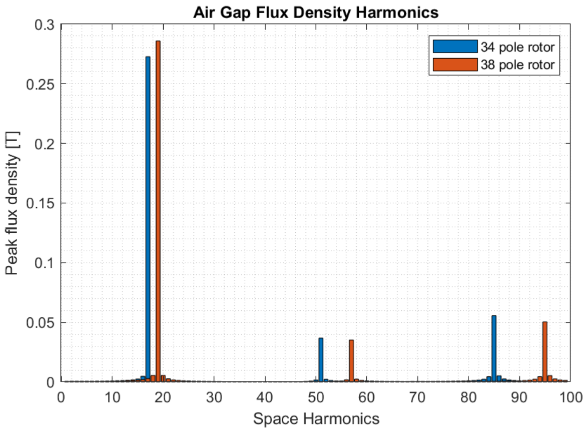


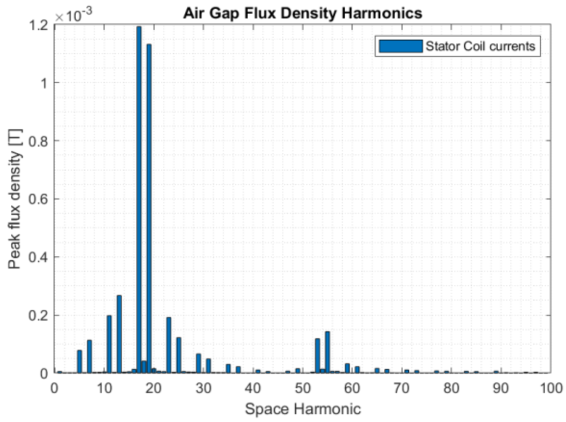
Model/ measurements

Both the simulation models and the physical prototype were simplified to only test one rotor at a time. The 3D printed machine was made with interchangeable rotors, and separate simulation models for each rotor were made. Only no-load tests were measured for the physical model where a DC-motor was used to drive made prototype.



Results
Simulations and measurements show that rotating the different rotors in opposite directions induces the same sequence of three-phase voltages in the stator, indicating that they could operate simultaneously. There are some amplitude differences between measurements and simulations that are though caused by slight differences of the models and the measuring circuit used. Simulations and measurements of single coil and single conductor voltages show that the shape of the induced voltages is very similar, indicating that the underlying magnetic field shapes also are similar. Harmonic analyses of the simulated air gap magnetic field distribution in the air gap show the present harmonics created by each rotor and by applying a balanced three-phase current through the stator windings in the figures below.





Conclusion
The differences in voltage amplitudes shown in the measurements and the simulation models are thought to be caused by inaccuracies in the produced machine and disturbances of the measuring circuit. The equal voltage shapes, however, indicate equal magnetic field shapes. This is thought to validate magnetic field harmonics in the air gap.
The harmonic analysis of the simulated magnetic field in the air gap shows that the stator coils create two oppositely rotating ”fundamental” twin harmonics. These correspond to the fundamental harmonic created by each rotor, which are the pole pair numbers of 17 and 19. This indicates that each rotor will have its strongest flux linkage with different oppositely rotating stator harmonics. This is the working principle of the single stator dual contra-rotating rotor PMSM.

Impact of Enhanced Spatial Resolution in Energy System Modeling: Investigating the Impact of Bidding Zone Disaggregation and Cost-Effective Grid Expansion in the North Sea

Student: **Hestvik, Birk & Kvannli, Aleksander**
Supervisor: **Farahmand, Hossein**

Abstract

Urgent actions are needed in order to combat the effects of climate change. Transforming the fossil-based energy system over to a renewable energy source-based system is integral to lowering emissions. The European Union has set a target for their member countries to reduce greenhouse gas emissions by 55% compared to 1990 levels by the year 2030 [1]. To achieve this they need a lot of new and renewable energy sources, like the planned 60 GW offshore wind power in the North Sea. Norway on their part aims to allocate areas with a combined offshore wind capacity of 30 GW by 2040 [2].

Energy system models can be utilized in order to explore the outcomes of lowcarbon energy system scenarios. In this thesis, five different scenarios were created for the open-source energy system model, GENeSYS-MOD. These were all based on the gradual development openENTRANCE scenario. A base case, Denmark disaggregated, offshore node connected to NO2, offshore node connected to NO2 and DK1, offshore node connected to NO2, DK1, and UK. These scenarios were studied in order to answer the following research questions:
Research question 1: To investigate whether the disaggregation of Denmark into bidding zones has a meaningful impact on the energy system or if it is negligible.
Research question 2: What is the cost-effective grid expansion strategy from the Norwegian offshore wind area to the neighboring countries around the North Sea?

Results regarding research question 1 highlighted the significance of disaggregation, as it uncovered a bottleneck in the Danish energy system, resulting in a 21.9% difference in installed capacities in Denmark between the two scenarios. The disaggregated scenario had the least total capacity of 63.2 GW in 2050. Results regarding research question 2 showed a clear trend that favored a meshed grid structure in the North Sea. The grid expansion, which connected to NO2, DK1, and UK, resulted in the most cost-effective solution and produced the most significant capacity expansion of offshore wind in the North Sea.

Optimization of a renewable energy system for use in offshore sea-based fish farms with a focus on wave energy

Student: Erlend Gjetrang Holmane
Supervisor: Steve Völler
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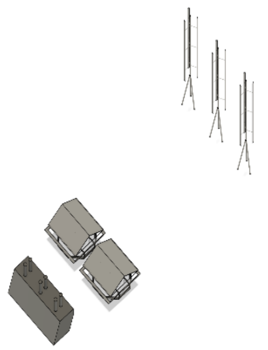
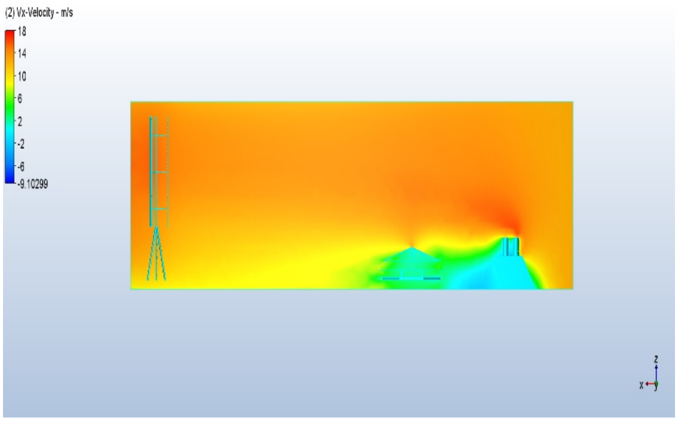
Problem description

As of today, about 60% of fish farming facilities are run through sea cables connecting them to the Norwegian power grid with the remaining running on diesel generators. With the fish farming sector trying to align itself with climate goals, a shift towards renewable energy is being investigated. As some fish farming locations are located too far from the mainland grid to economically justify a connection to the Norwegian mainland grid, a hybrid renewable energy system has been proposed. As both solar and wind power are variable, inclusion of wave power plant was analyzed. This thesis investigates the feasibility of a 100% renewable energy system supplying the load from an off-grid fish farm. To account for variation in production battery storage was included to minimize oversize of the renewable energy installations. To achieve this, an optimization model, minimizing the total cost, was developed to find the optimal size for the installation. Autodesk CFD was used to simulate the effect each physical element had on the wind speed. The wind speed simulation model created can be seen below, as well as one picture of the simulated wind speed result.





Conclusion

The results clearly show how all location simulated in this project can be technically operated completely off-grid, with only use of renewable energy, though not at a competitive cost. At current prices a battery-renewable floating system is not able to compete in diesel generation in terms of costs. A hybrid system consisting of floating PV, floating WTs, OWC, diesel generation and a battery system is a better solution to power an off-grid system. Extra redundancy from both the diesel generation and battery system, as well as reduced costs stemming from synergies between energy sources yields a safer and cheaper system compared to a fully renewable system.

Based on the current costs of wave power, and the locations simulated, an OWC struggles to compete with solar and wind power, though some location show that OWC could compete if the wave conditions are correct. The OWC has an extreme dependence on the location, with most location simulated not being suited. A combined FPV, OWC and floating WT system will ultimately depend mostly on solar wind generation to cover most of the demand, as OWC production can at best be described as very sporadic. At current prices a full diesel system would be cheaper than a floating system, but with large future reductions in prices as well as increased carbon taxes expected, such a system might compete in the future. Wind speed simulations show little interference from the OWC and FPV in terms of wind speeds. As such, a combined movable system could be see use in the future, if sufficient reduction in renewable technology costs are seen.

Modeling and Control of an Active Power Filter using Conservative Power Theory

Student: **Islam, Md Rabiul**
Supervisor: **Tedeschi, Elisabetta**

Abstract

This thesis investigates a three-phase system that utilizes a shunt active power filter (SAPF) using Conservative Power Theory (CPT) to improve power quality. CPT is an effective method for generating reference currents for harmonic rejection, offering a robust framework for analyzing and compensating power quality disturbances. Non-linear loads generate harmonic currents that degrade power quality, causing high losses, equipment overheating, and malfunction of sensitive devices. The proposed system model mitigates these issues by providing effective harmonic rejection. The system is implemented in MATLAB Simulink, a powerful tool for simulating and analyzing dynamic systems. The literature review covers various control algorithms for SAPFs, focusing on the advantages of CPT over other power theories. CPT decomposes source currents into orthogonal components, allowing for precise identification and compensation of harmonic disturbances. Passive and hybrid filters are compared with active power filters, highlighting the superior performance and adaptability of SAPFs in real-time harmonic compensation. The system model utilizes a pulse-width Modulation (PWM) scheme controlled by a hysteresis current controller to generate the necessary compensating currents. The performance of the system was compared with and without SAPF for various load conditions. The SAPF effectively reduces the total harmonic distortion (THD) in both secondary voltage and current, improving overall power quality. Overall, this thesis contributes valuable insights into the application of digital power theories for harmonic mitigation in power systems. The findings indicate the potential of SAPF, controlled by CPT, to significantly improve the quality of power in power grids for more reliable and efficient systems.

Control and Dynamic Assessment of Rotary Transformers as Inertia Providers in Solar PV Applications

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Supervisor: **Olimpo Anaya-Lara**
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Problem description

Traditionally, power systems have relied on large synchronous generators to ensure power system stability, reliability and security of supply. These generators possess natural inertia due to the kinetic energy stored in their rotating masses, allowing them to resist and counteract changes in system frequency. Wind and solar photovoltaic (PV) systems do not inherently have the same stabilising characteristics. Due to their weather-dependency and consequent power output variability, RES are connected to the grid through a converter interface, which decouples any potentially stored energy, and prevents them from naturally contributing with inertia.

This master's thesis investigates the possibility of natural inertia provision from a solar PV system based on a rotary transformer (RT). Operating similarly to an induction machine, the RT will function as the interconnection component between a solar PV system and the main grid, enabling the potential advantages of its inherent frequency support capabilities, while also ensuring that the active power produced by the solar PV, at any time, is transferred to the grid. The RT is commonly used in variable frequency transformers (VFTs) to enable power transfer between asynchronous power grids. The innovative flexible short-term Frequency Response PROvider (FR-PRO) introduced in this thesis is based on the mechanical design and capabilities of the VFT. The key distinction between the two devices is that the FR-PRO utilises a voltage source converter to ensure flexible control over the mechanical rotor speed of the RT, thereby regulating the available inertia. The connection scheme of the FR-PRO with the solar PV system is illustrated in Figure 1.

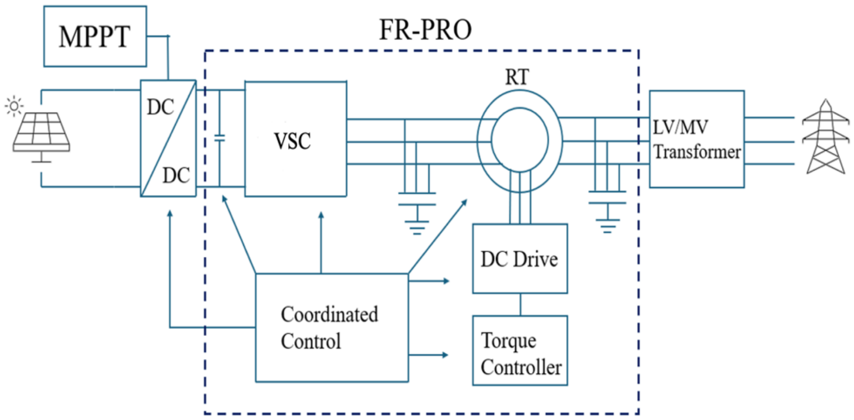


Figure 1: The FR-PRO in a low-voltage solar PV application.

The task

A thorough literature review and theoretical study is conducted to understand the characteristics, operating principles, and control requirements of the FR-PRO. The device is modelled in Matlab/Simulink for a high-voltage grid application, in addition to integrating the FR-PRO with a low-voltage solar PV system. The main components of the FR-PRO, including the RT, DC drive system and voltage source converter are integrated into the models. Coordinated control of all components of the device and solar PV system is implemented, providing a detailed representation of how the FR-PRO would function in a real-world application. Lastly, the thesis provides insight into the potential economic benefits/advantages that the FR-PRO can enable in the provision of power system inertia. A cost discussion of the FR-PRO in a low-voltage solar PV application is carried out.

Model/ measurements
Initially, Matlab/Simulink models were developed for two DC drive system configurations to understand the dynamic performance and behaviour of the DC drive system. These configurations aimed to investigate how the system behaved when the DC motor was mechanically coupled with the RT or functioning as an external unit, as well as whether it was connected to the stator or the rotor side of the RT. Further, two Matlab/Simulink models of the FR-PRO in a low-voltage solar PV application were developed and compared against a conventional solar PV system with grid-following control. In the first FR-PRO model, the solar PV representation was simplified using a controlled-current source. Whereas, the second model represented a more realistic implementation of a solar PV array, by integrating the PV panel, MPPT algorithm and DC-DC converter. This also includes additional control measures to maintain a stable DC-link voltage while operating the voltage source converter.

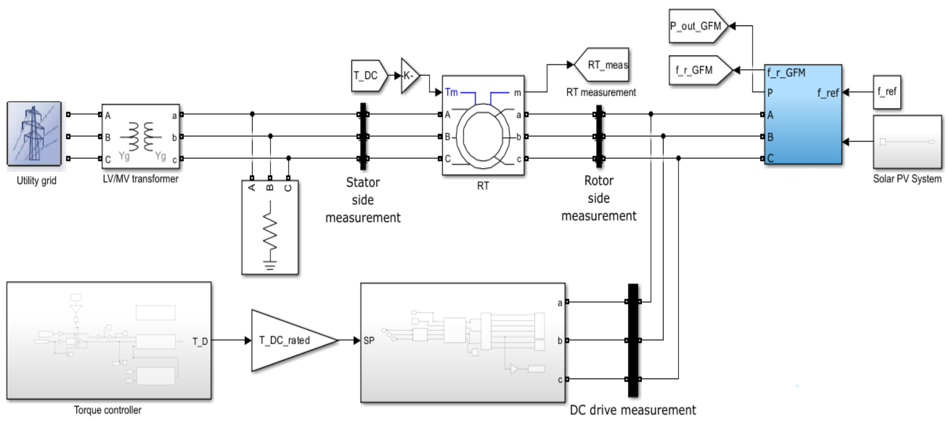


Figure 2: Overview of the Simulink implementation of the FR-PRO in a low-voltage solar PV application.

Calculation
The simulation results of the embedded and external DC drive, whether connected to the rotor or stator side of the RT in a high-voltage grid application, show minimal differences in the system's overall performance. Further, the simulation results confirm the capabilities of the voltage source converter to track a given rotor frequency set point, ensuring that the RT rotates at a specified speed while the power transfer through the RT remains unaffected. The simulation results of the FR-PRO within a low-voltage solar PV setup show that the FR-PRO has a greater impact on grid frequency than when discharging the DC-link capacitor in the grid-following based solar PV model in response to a contingency. It is observed that the FR-PRO provides a more pronounced influence when the rotor frequency is adjusted in a step-manner, rather than being smoothed out by a second-order low-pass filter, which is attributed to the small size of the RT, limiting its contribution.

Conclusion
Overall, the theory, model implementations and simulation findings of this thesis demonstrate that the FR-PRO can assist in grid stabilisation by providing natural inertia to power grids. By modelling the device in both a high-voltage/power system scenario and in a low-voltage solar PV setup, it is demonstrated that the FR-PRO is adaptable, and the potential applications where the device can provide frequency support in future RES-heavy power systems are extensive and diverse.

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

Student: **Jenssen, Thomas Bjørn Olivier**
Supervisor: **Mauseth, Frank**

Abstract
Over recent decades, global dependency on electrical energy has significantly increased, making a stable and consistent connection to the electrical grid crucial for both personal and professional activities. Reliable grid infrastructure is essential to meet today's energy demands, and equipment malfunctions can cause significant financial losses and widespread energy shortages. Consequently, assessing and monitoring the condition of grid equipment to prevent failures has become increasingly important. Implementing a system to track equipment degradation, particularly for critical components like transformers and circuit breakers, is beneficial for reliability and maintenance costs.

The SmartACT project, which this master thesis contributes to, aims to implement sensors on 420kV cable terminations to predict their condition. This research specifically examines the impact of humidity in silicone oil (SO) on partial discharge (PD) characteristics, a key factor in termination failures.

To simulate various environmental conditions, a climate control cabinet was employed to precisely regulate temperature and humidity. Within this controlled environment, custom electrode housing was designed to hold the SO, featuring adjustable spacing for spherical electrodes. These electrodes were connected to
a 15kV 50Hz AC voltage source and ground respectively, to evaluate the oil's PD activity. Omicron hardware and software were used for comprehensive data acquisition and analysis, ensuring accurate and reliable measurements.

In the climate control cabinet, the SO was initially heated to 65°C and humidified to various levels of relative humidity (RH). The PD repetition rate and charge values were analyzed over a 20-hour period, during which the temperature was reduced to 5 °C after the initial two hours. This controlled cooling process allowed for a comprehensive examination of the oil's insulating properties and the effects of temperature and humidity variations on PD characteristics.

The results indicated that the PD magnitude was approximately 1-2pC during the initial two hours. As the temperature decreased, there was a clear reduction in PD activity. However, a small resurgence in PD activity was observed later, with the intensity, initiation time, and duration of this resurgence depending on the initial RH of the oil.

The decrease in PD activity when the temperature is reduced, is believed to be attributed from the increased oil viscosity limiting the movement of condensed water droplets. However, at lower temperatures, sufficient water condensation created larger droplets that counteracted this effect, causing the resurgence in the
activity. This effect continued until the electrodes attracted enough humidity from the oil, reducing it enough to diminish the PD activity.

New Environmentally-friendly Insulation Gases - Positive and Negative Streamer Propagation Along Micro-Profiled Dielectric Surfaces

Student: **Kari Sværen Klævold**
Supervisor: **Frank Mauseth**
Collaboration with: **ABB**

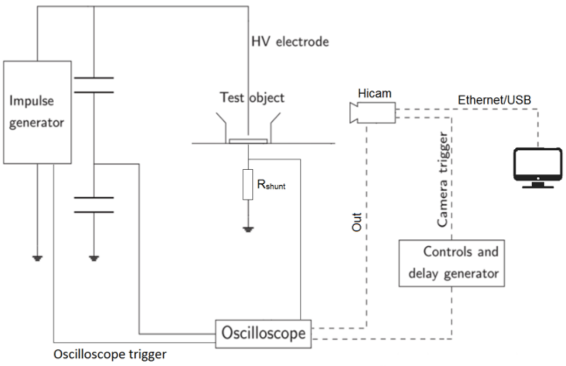
Problem description

The gas sulfur hexafluoride (SF_6) is a preferred insulation medium in encapsulated high voltage systems due to its excellent dielectric, thermal, and electronegative properties. However, the gas has a substantial Global Warming Potential, making it necessary to phase out its use while maintaining a compact design for high voltage systems.

The task

The objective of this thesis is to investigate how dielectric surfaces with micro-profiles influence the propagation length and path of streamers under the application of positive and negative lightning impulses (LIs) in a non-uniform gap. The focus is particular on the regions where the streamers may locally be forced to propagate in the reverse direction to their actual background electric field propagation direction. The investigation includes laboratory work with a disk-plane gap in the air and capturing the streamer activity with a fast ICCD camera. Additionally, COMSOL and fluid simulations are conducted for comparative purposes.

Model/ measurements



The test objects consisted of four dielectric plates with different designs. A foot-shaped micro-profile and a peninsula-shaped micro-profile were made to study the streamers in the regions where they may locally be forced to propagate in the reverse direction to their actual background electric field propagation direction. Additionally, a flat surface and a rectangular-shaped micro-profile were produced for comparison purposes. The plates were 3D printed with resin for accurate fabrication. The permittivity of the test objects was measured to be ε_r = 3.3.

Results

The results from the laboratory work and the simulations indicate that micro-profiles significantly reduce the streamer propagation length along the surface compared to a flat surface. Furthermore, the results show that positive streamers propagate longer than negative streamers. The propagation mechanism for the streamers along the micro-profiles differs from that for streamers along the flat surface. Regarding the interest in studying whether streamer behavior is affected by the regions where they may locally be forced to propagate in the reverse direction to their actual background electric field propagation direction, the streamers tend to avoid propagating closely along the surface into these regions. Instead, they either propagate through the air with the correct field orientation into these regions or stop before reaching them. It was also observed in the laboratory work that overly rounded corners increase the streamer propagation length, as the streamers along the peninsula-shaped micro-profile showed a longer propagation length in the simulations and partially in the laboratory work.

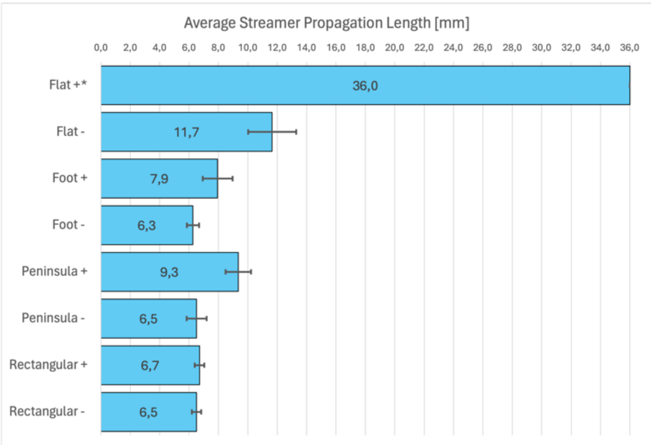


Figure 5: Average streamer propagation length

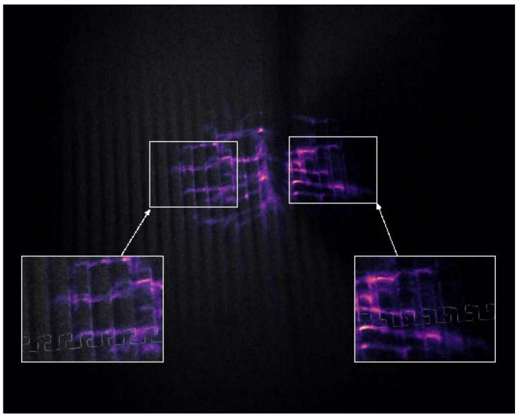


Figure 4: Streamer propagation along the foot-shaped micro-profile in the laboratory work

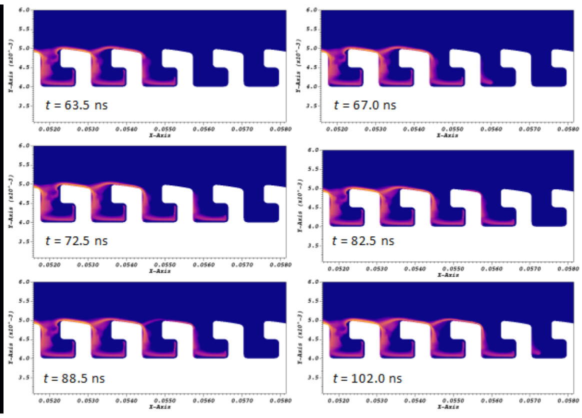


Figure 3: Streamer propagation along the foot-shaped micro-profile in the fluid simulations

Conclusion

Implementing dielectric micro-profiles can effectively reduce the streamer propagation length and consequently increase the withstand voltage. Therefore, it will be beneficial to implement micro-profiles in high voltage equipment when trying to maintain system efficiency and avoid increasing the size of the equipment, all while phasing out SF_6.

Aging of alternative gases to SF6 for use in GIS by PD: CO2 and Technical air in HV

Student: Jonas Kragset
Supervisor: Frank Mauseth, Nina Sasaki Støa-Aanensen, Arik Subhana
Contact: Nina Sasaki Støa-Aanensen
Collaboration with: SINTEF Energy Research

Problem description

Most gas insulated switchgear (GIS) systems today utilize SF_6 as insulation gas. This is one of the most potent greenhouse gases known, with a global warming potential between 23,000 and 25,000 times that of CO_2. Many alternative gases have been found and studied, but the long-term performance of these gases has yet to be studied. In this master, the withstand strength of CO_2 and technical air is studied before, during, and after aging to find out if accelerated aging by using PD affects the gases' dielectric properties.

The task

The task is to determine if accelerated aging by using PD changes the dielectric properties of CO2 and technical air. The tests performed are lightning impulse (LI), AC breakdown, partial discharge inception voltage (PDIV), and partial discharge extinction voltage (PDEV). In addition, gas samples were collected.

Model/ measurements

The tests were performed inside a vacuum-sealed tank. Figure 1 shows the different circuits used for tests, while Figure 2 shows the circuit used for aging.

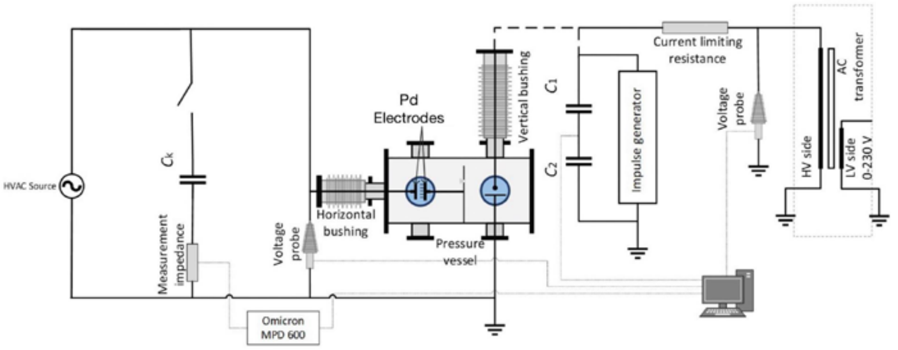


Figure 1 Circuit showing the three different circuits used during this experiment. The circuit for PDIV/PDEV, LI, and AC breakdown tests is from left to right. C_k is a coupling capacitor, while C_1 and C_2 are capacitive dividers.

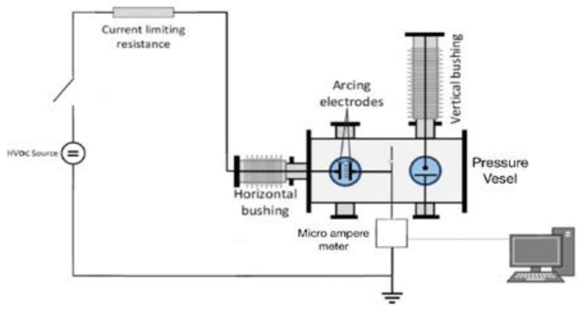


Figure 2 Circuit used for aging the gas during the experiment. The resistance used was a water resistor with a value of approximately 220 kΩ

Calculation

The results from the different test results obtained can be seen in Table 1.

Table 1 The results from the different tests performed during the work with the master thesis. The results for the AC breakdown test are the median, while the results from the two LI tests performed are the average breakdown voltage.

	CO_2			Technical air		
Voltage stress	Before aging [kV]	After aging [kV]	Percentage difference [%]	Before aging [kV]	After aging [kV]	Percentage difference [%]
AC	47.16	49.63	5.2	50.00	53.91	7.8
LI+	88.63	82.46	-7.0	60.06	57.13	-4.9
LI-	74.55	84.42	13.2	63.88	64.10	0.3

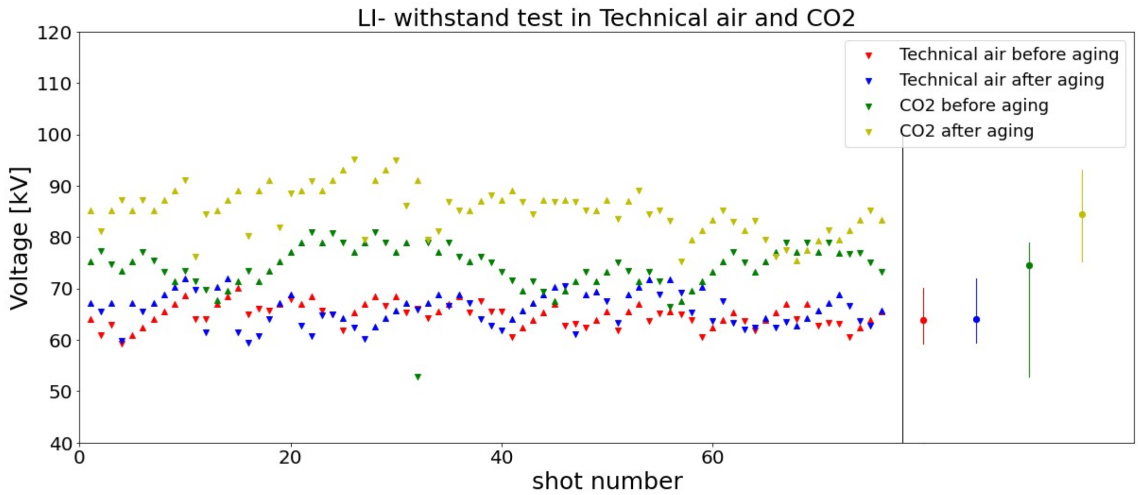


Figure 3 The results of the negative LI test. The point indicates the average breakdown voltage while the whiskers at the side stretch from highest hold to lowest breakdown.

Conclusion

The results show that accelerated aging affects the dielectric properties of CO_2 and technical air. However, whether the change in dielectric strength is permanent is hard to determine because the gas analysis performed was not accurate enough. The results show that both gases improve at the AC breakdown test. Both get lower dielectric strength at the positive LI test, and at the negative LI, both get improved, but the change for technical air is so small it can be deemed negligible.

The results also show that both gases have similar breakdown results for the AC breakdown test, but during the LI test, CO_2 exhibits a much higher average breakdown voltage. CO_2 does, however, also display more variability in breakdown values for most tests performed.

Unlocking the Potential of Value Stacking in the Norwegian Distribution Systems

Student: **Jacob Fredrik von Krogh**

Supervisor: **Olimpo Anaya-Lara**

Co-supervisor: **Raymundo E. Torres-Olguin**

Contact: Jacob.vonkrogh@gmail.com

Problem Description

This master's thesis investigates the optimal operation of a Battery Energy Storage System (BESS) providing stacked services within a distribution system mode. The primary aim is to enhance the integration and profitability of BESS in modern energy grids. The model used for testing includes typical elements such as photovoltaic systems, batteries, and fluctuating loads.

The task

The task of the thesis is to explore the feasibility and profitability of employing BESS for value stacking within the Norwegian distribution grid. This involves investigating multiple scenarios to determine how BESS can be optimally integrated into the energy landscape to provide various grid services simultaneously, such as voltage regulation and energy arbitrage. The thesis aims to develop and test algorithms for these services, analyze their performance both individually and when stacked together, and quantify the economic benefits and technical challenges of service stacking.

Model

The algorithms used to perform energy arbitrage were inspired by relevant literature and then altered to suit the problems faced in this thesis. Several methods were developed to allow comparison between methods, both in terms of performance and computational requirements. The model which the different grid services were implemented was built in Simulink and Matlab and implemented in the model in Figure 1.

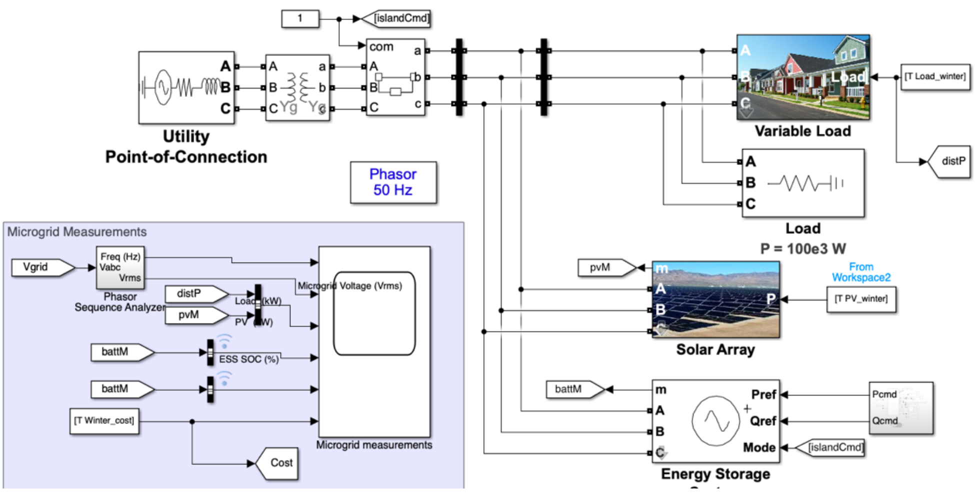
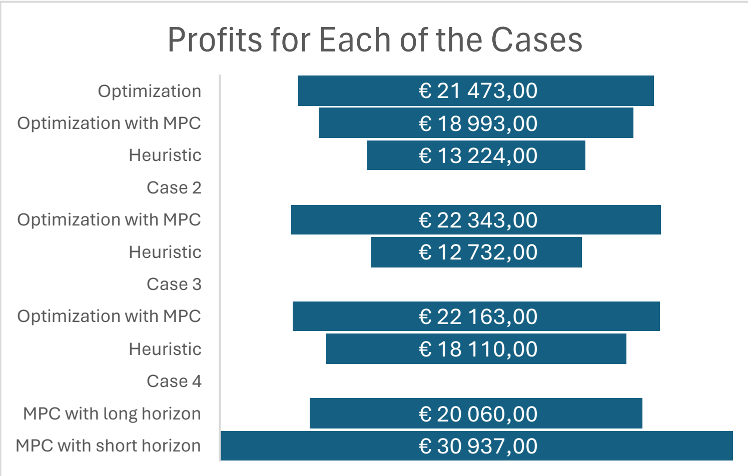


Figure 1: Grid Model in Simulink

Calculation

The main results for thesis came in total power transfer for the battery, the revenue it managed to make and the net present value of the entire investments. Four different cases were tested. These cases varied what services they included and how they were stacked. The goal of the different cases was to highlight the performance of the different methods when they were subjugated to new constraints.



Cases	Net Present Value
Case 1	
Optimization	€ 71 906,00)
Optimization with MPC	€ (107 015,00)
Heuristic	€ (99 125,00)
Case 2	
Optimization with MPC	€ (36 865,00)
Heuristic	€ (88 150,00)
Case 3	
Optimization with MPC	€ (21 077,00)
Heuristic	€ (6 366,00)
Case 4	
MPC with long horizon	€ (41 569,00)
MPC with short horizon	€ 64 417,00

Conclusion

In conclusion, All the methods succeeded in making a profit from arbitrage. When combining services the optimization method using forecasted values had the best performance. Both methods increased their revenue by providing voltage support, displaying the potential service stacking has. It was even enough to make one of the cases profitable. Furthermore, based on the simulation cases a more regulated voltage provision market will improve profit quantification, leading to more accurate economic assessments.

Modeling of Saturation and Cross-coupling in a 6-phase IPMSM

Student: **Norunn Krokeide**
Supervisor: **Roy Nilsen**

Problem description

Accurate modeling of the relation between stator currents and flux linkages in Permanent Magnet Synchronous Motors is essential to achieve the best possible control systems. Precise motor models and parameters are especially valuable in the context of sensorless control, where certain algorithms rely on model equations to estimate rotor position. Here, the nonlinearity caused by saturation and cross-coupling phenomena inside the motor must be included. Although saturation and cross-coupling have been studied in literature previously, the effect of the different phenomena depend on the type of motor and design.

The task
This project aims to analyze and model the saturation and cross-coupling in a 6-phase IPMSM. Another objective is to further develop nonlinear models of the flux linkages as function of stator currents, by studying a paper with results from comparable tests.

Model/measurements
Constant-speed tests of a 6-phase IPMSM are done, applying d- and q-axis current references manually, and this way mapping flux linkages to a range of stator currents in the dq-reference frame. The setup includes an Induction Motor (IM) working as a load, with a separate control system with speed control. The range of tests is limited by inverter voltage limitations, along with the maximum torque of the IM, which result in a decreased range of d- and q-axis currents. The lab results are curve fitted to several nonlinear polynomial models deduced in previous thesises.

A study is done of the data of a previously conducted paper, analyzing saturation phenomena and developing new more detailed nonlinear flux linkage models that capture the differential inductances. These new models are fitted to the lab results.

$$\text{Curve Fit: } \psi_{dm} = 0.329\, i_d + 0.233\, i_d\, i_q\, -0.519\, i_d\, i_q^2\, -0.151\, i_d^2\, 0.068\, i_d\, i_q^3$$

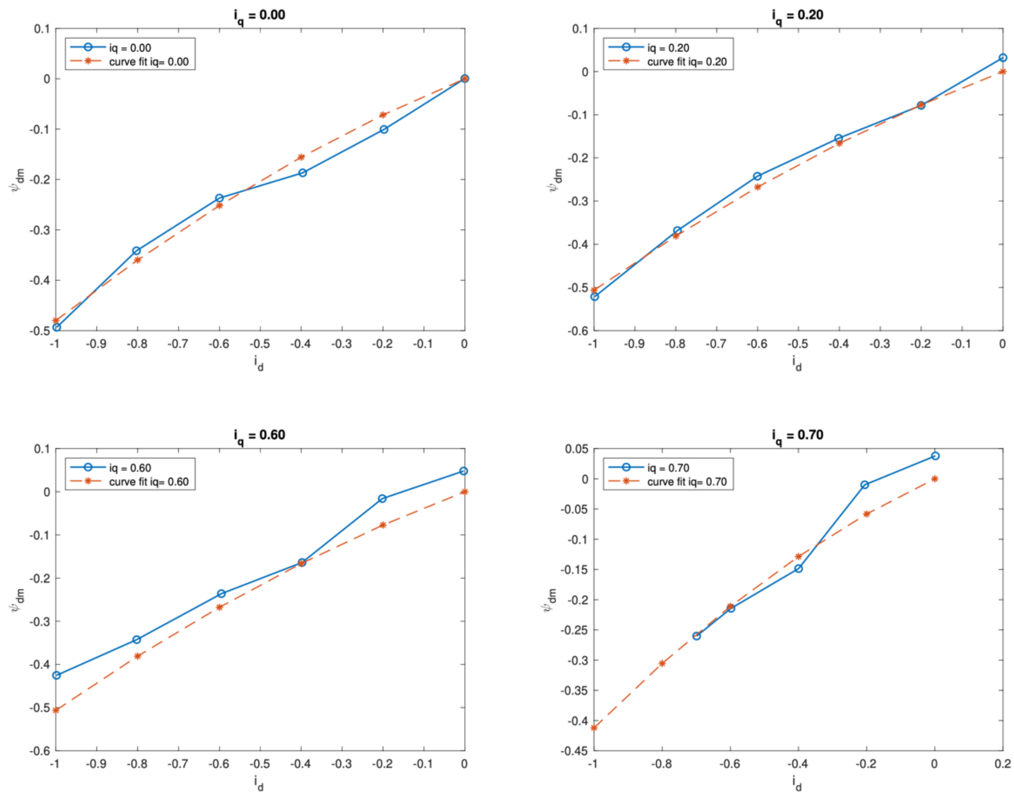


Figure: Lab results of flux linkage on the d-axis where a constant PM flux linkage value is subtracted, fitted to the new developed polynomial model where the d- and q-axis currents are state variables

Results

There is not much visible saturation in the lab results, but there is some cross-coupling on the d-axis flux, though it is difficult to discern any trends here. There is also some cross-coupling on the q-axis, but very small.

The new developed models are fitted to the conducted lab data, which results in a good fit, and it is found that basing the models on curve fits to differential inductances could be a promising approach for future work. Generally, the functions model the flux linkage on the q-axis more precisely than the d-axis. It is discussed that there possibly has been variations on the PM flux on the d-axis, because of saturation and cross-coupling effect, affecting the results. It is recommended that the PM flux variation should be modeled in further work.

Conclusion

There is little saturation in the tested 6-phase motor within the current range that was tested. Several propositions on how the saturation phenomena look were put forward, as well as propositions on further work. It is also clear that different polynomial models can capture the form of the flux linkages, and that basing models on the differential inductances could be an interesting approach forward on.

Automatic Testing of Interlockings in Digital Substations

Student: **Jens Kruse-Hansen**
Supervisors: **Hans Kristian Høidalen (NTNU), Marjan Popov (TU Delft)**
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Collaboration with: **TU Delft & OMICRON**

Abstract

This thesis proposes an automated method for generating, executing, and assessing an interlocking test in a digital substation using a Python script designed for that specific purpose.

The goal is to expedite the process of performing the factory acceptance test (FAT) and the site acceptance test (SAT) of a substation automation system (SAS). This work requires a good understanding of the IEC 61850 standard, which is the international standard applicable to protection, automation and control systems (PACS). An account of the relevant parts from this series is therefore given, in addition to an overview of the benefits of digital substations in general.

The workflow for automatically generating a test case is based on previous work that made it possible to execute and assess an interlocking test automatically but not to generate a test case automatically for this purpose. Therefore, that is the main intention of the thesis.

It is done by having knowledge of the underlying interlocking logic of the system subject to test. From this logic, a test sequence can be created, where the position of the various switchgear is changed sequentially. This and the signal addresses for these devices are needed to generate a test case.

For additional robustness, the script can cross-check the signal addresses provided with the signal addresses in the substation configuration description (SCD) file and validate the final test case generated using a suitable schema. It is furthermore capable of generating a test case irrespective of the number of test steps, switching devices, and bays present in the substation.

A test file generated using this script is further validated by executing the test it describes in the SAS laboratory at the Norwegian University of Science and Technology (NTNU). This test was carried out remotely to showcase the possibilities of IEC 61850, which can be valuable for distant or offshore substations. Another benefit of this workflow is that it allows for the simulation of all devices of the test except for the device under test (DUT). This is particularly useful during commissioning if all devices have not yet been delivered or installed. In this case, the missing equipment can be compensated for by simulating the signals expected from these devices.

The final assessment of a test case relies upon the presence of the IEC 61850 LN (Logical Node) CILO (Control Interlocking). The output of this LN controls the interlock status of the DUT. If the DUT is allowed to operate, it sends a release signal or, alternatively, a blocking signal. In addition to this, information is gained based on the position of the switchgear under test to check that the CILO signal is consistent with the actual switchgear control command. This control command is known as the AddCause in IEC 61850 and will provide additional information on whether or not the DUT is interlocked.

Finally, the thesis will describe ongoing work in the IEC 61850 that could lead to a more streamlined approach and touch on the utilities' attitude towards SAS.

Study of acoustic emissions in power electronics used in offshore wind power applications

Student: **Kvannli, Kristoffer**
Supervisor: **Anaya-Lara, Olimpo**

Abstract
The need for clean renewable energy is greater than ever, with the year 2023 having the highest greenhouse gas emissions and warmest temperatures recorded in human history [1]. This incentivizes a global push for offshore wind power production. By 2032, a 590% increase in offshore wind power capacity, from 64.3 GW to 447 GW, is expected [2]. Earlier untouched areas of the ocean will soon be occupied by offshore Fully Rated Converter Wind Turbine (FRC WT). This brings new acoustic noise pollution from the continuous operation of the FRC WTs to a vulnerable marine ecosystem.

This master's thesis focused on the high-frequency acoustic noise produced by offshore FRC WTs. The major contributor to this noise is the switching operation done by Insulated Gate Bipolar Transistors (IGBTs) in the WT's converter systems. A laboratory experiment was set up to gather the necessary data for a digital model of IGBT acoustic noise emissions. The experiment brought forth interesting data and trends explaining the relationship between the IGBT's acoustic noise, EMI, and the parameters of the circuit. This empirical data is a contribution of this thesis and may be used for future research. However, the task of making a digital model of an IGBT's acoustic noise emissions proved to be too complex for the time frame of this thesis and will need more work going forward.

The laboratory experiment's findings conclude that there is a strong relationship between the IGBT's turn-off current and the strength of the noise produced. This relationship looks quadratic, where the rate of increase of the noise decreases at higher current values. This quadratic relationship may be explained by the microphone picking up both acoustic and electronic noise, but more research is needed to confirm this.

While the turn-off current seems to have the biggest impact on the strength of the noise, the results also indicate that the magnitude of voltage and load may impact the noise profile of the IGBT circuit without changing the turn-off current. This knowledge may be used to better adapt noise emissions to cause less harm to local wildlife.

With switching speed between 1-21 kHz, the highest noise peaks were normally between 60-100 kHz, with smaller peaks extending to 140 kHz. This highlights the possibility of noise emissions that may be unnoticeable to humans but may cause a negative impact on marine mammals because of their extensive hearing range of up to 200 kHz [3].

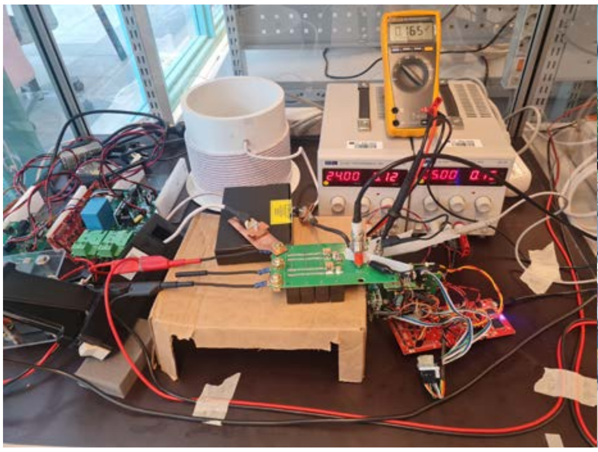
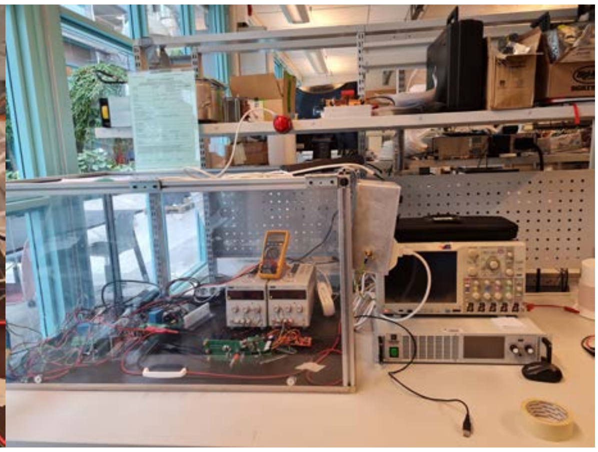
Control of a Four Level Active Gate Driver for SiC MOSFET

Student: **Eli Laupsa**
Supervisor: **Dimosthenis Peftitsis**
Contact:
Collaboration with:

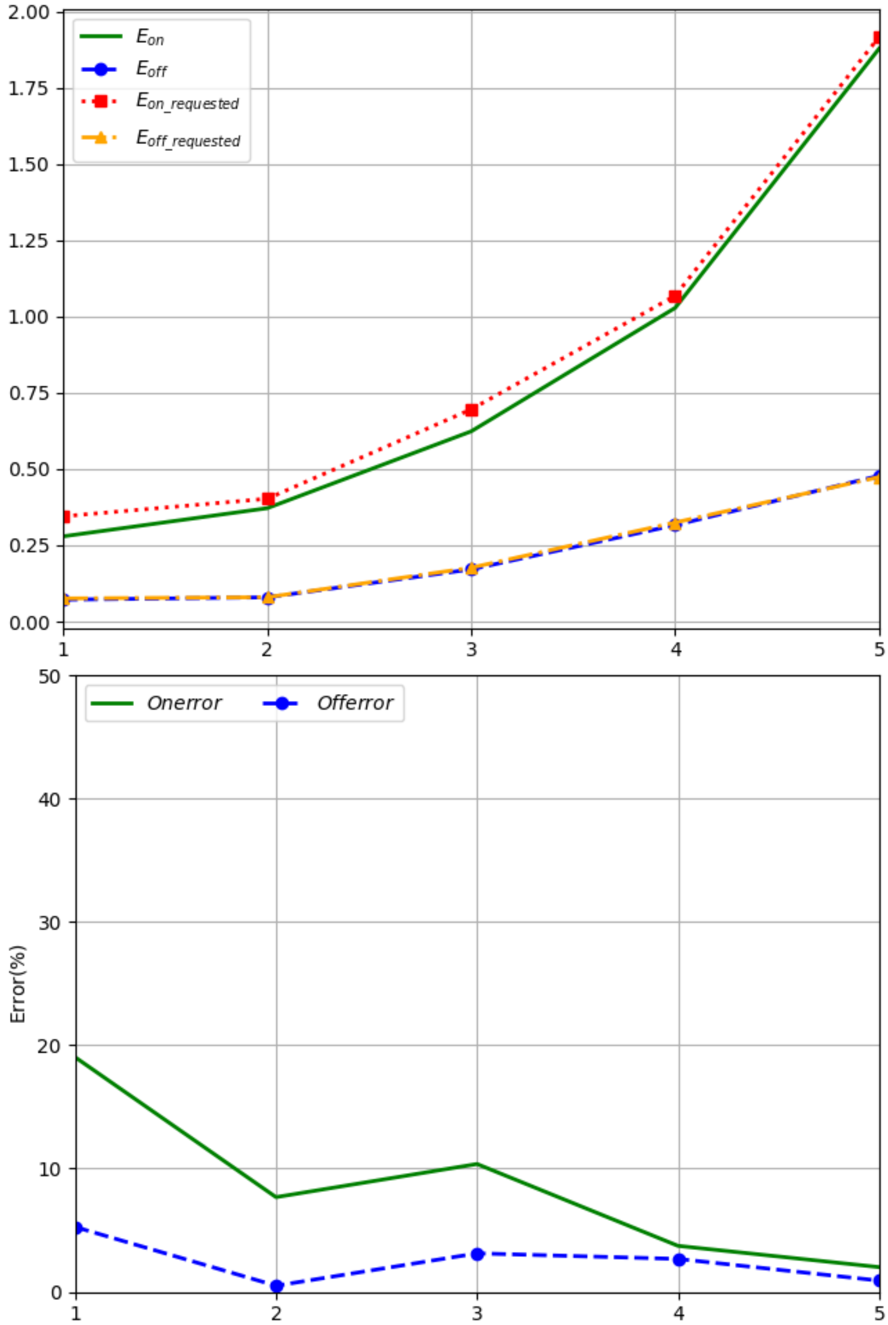
Problem description
A four level active gate driver for SiC MOSFET has been developed. Test data from driving a MOSFET with this gate driver is available. This gate driver's brain was required to decide the performance of the SiC MOSFET by utilizing the gate driver and the test data.

The task
The task was to develop this "brain" in a real-time program to a DSP. This to make the active gate driver produce the gate driving signal that will provide the desired performance of the SiC MOSFET. The gate driver produces a driving pattern with intermediate intervals. Simulations were first conducted to understand and look at the influence these intermediate levels had on the MOSFET. Results from these showed that the gate driver manage to influence and manipulate the required parameters, such as dv/dt, di/dt, conduction and switching loss and overshoots in voltage and current.

Model/ measurements
Experimental double pulse tests were conducted in the power electronics lab. The active gate driver was tested with the program developed in this thesis. With a DC bus voltage of 600V and load current of 15A. Actual switching losses of the SiC MOSFET under testing were measured with the oscilloscope. Then these results were compared to the requested from the program.

Calculation
These results show the requested and the measured switching loss of the SiC MOSFET. In addition, the error is calculated.



Conclusion

The AGD is able to influence the SiC MOSFET’s required parameters. The DSP program is also able to control the AGD to produce the required driving pattern. The program manages to find the best possible combination on intermediate voltage amplitude and time duration, bu utilizing the characterization data of the MOSFET. The tests clearly shows that the desired losses are close to the actual measured losses.

Analysis of Dynamic Eccentricity faults in a Permanent Magnet Synchronous Machine using stray flux

Student: **Laurhammer, Oscar**
Supervisor: **Nilssen, Robert**

This thesis will not be published, and abstract is not available.

Local stability Problems in Hydro-Dominated Power Systems

A Root-Cause Analysis of the Østerdalen Case

Student: **Oddmund Bratseth Leite**
Supervisor: **Kjetil Obstfelder Uhlen**
Collaboration with: **Hafslund ECO Vannkraft AS**

Problem description

The Tolga hydropower plant in Østerdalen, Norway, has been experiencing unexplained oscillations in its active power output. These oscillations, if poorly damped, can grow in amplitude, leading to system instability, increased wear on equipment, and potentially causing widespread power outages. This issue is particularly critical in the Norwegian power grid, where 90% of the power comes from hydropower, making it essential to understand and mitigate low-frequency oscillations (LFOs) in such systems.

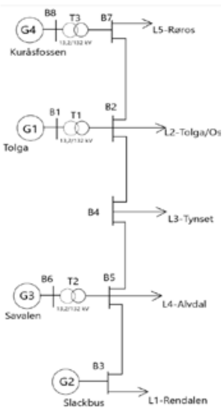
The task

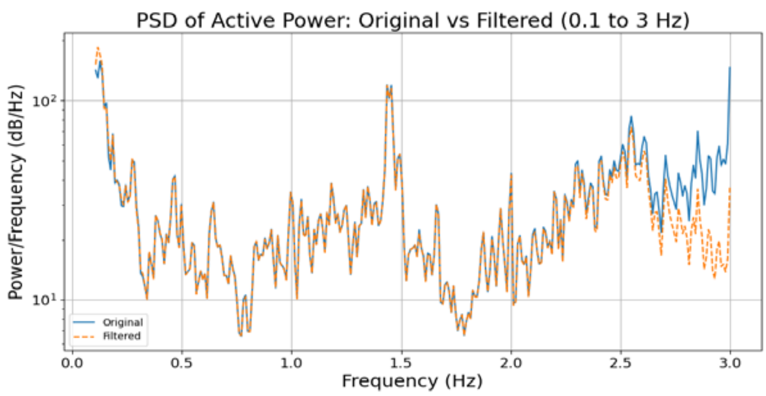
The primary task of this thesis is to investigate the characteristics and underlying causes of the oscillations observed in the active power output at the Tolga power plant. This involves:

1. Analyzing high-resolution measurements from Tolga using Power Spectral Density (PSD) analysis to identify natural frequencies of oscillation.
2. Conducting transient and small-signal stability simulations to understand the system's dynamic behavior and identify corresponding modes of oscillation.
3. Evaluating the impact of different load and production scenarios on the damping of these modes.
4. Assessing the effectiveness of Power System Stabilizers (PSS) in improving the damping of identified modes.

Model/ measurements

Measuremets were acquired through Tolga’s protection devices. A model of Østerdalen was created in DYNPSSympy for transient and small-signal stability analysis. PSD analysis was conducted in Python.





Conclusion

In conclusion, the combined use of PSD analysis and simulations proved effective for investigating LFOs. The identification of a natural frequency of 1.4 Hz at Tolga and its corresponding mode in simulations underscores the capability of these methods. Future research should focus on obtaining additional high-resolution measurements as described in the discussion. These efforts would help determine the cause of the oscillations.

Environmental impact of electric vehicles

Student: **Amund Lilleås**
Supervisor: **Korpås, Magnus**
Co-supervisor: **Dimanchev, Emil**

Problem description

To reduce the high emissions of the transport sector, transitioning from fossil-fuel vehicles to electric vehicles is essential. This change can significantly reduce emissions, depending on how the electricity consumed by the vehicles is produced. As energy systems are complex and electricity is constantly traded between regions, determining the exact origin of specific electricity amounts is almost impossible. Consequently, the indirect emissions of electric vehicles need to be allocated based on the energy mix. Today, this allocation is mainly performed using three different emission factors, which are the average, short-run marginal, and long-run marginal emission factors. However, no consensus exists on which method should be utilized in similar cases.

Future energy systems will contain flexibility on both the demand side and production side. A large fleet of electric vehicles represents a massive potential for demand side flexibility, such that the demand of electric vehicles can be distributed in an optimal way. Which charging strategy is deployed can have a big impact on the emissions.

The task

In this thesis a case study of the German power system of 2040 is performed. This system is modelled in an optimization tool, that obtains the optimal energy mix and dispatch to cover the predicted German demand of 2040. Based on this energy production, the different emission factors are computed.

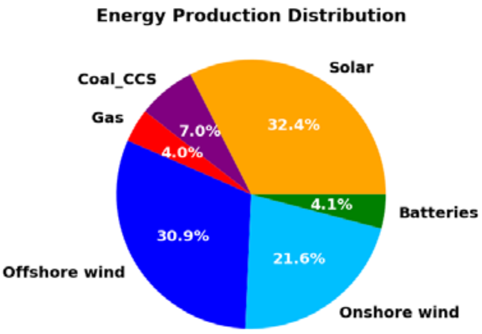
Additionally, the thesis aims to find the optimal EV charging strategy from an environmental point of view. To include a substantial demand side flexibility, the entire German vehicle fleet, consisting of 46 million vehicles, is considered electric. The demand of electric vehicles is distributed through the day in different ways based on different charging strategies. The different EV demand profiles are added to the remaining German demand and simulated to observe the environmental impact of each charging strategy.

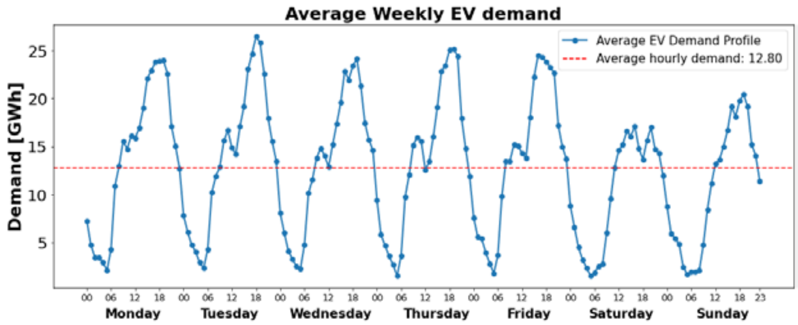
Model/ measurements

The utilized model was the optimization tool GenX. The objective of GenX is to find the optimal energy mix and production each hour in the most cost-efficient way. To obtain realistic results, the model requires input data about the demand and weather conditions of each hour, as well as all the costs associated with investment and operation of the different energy sources.

Calculation

The optimal energy mix (top left) is dominated by renewable energy sources, resulting in generally low values for all emission factors computed. The default EV demand profile (top right) led to the lowest values for all emission factors, which could be observed in the comparison of emission factors (bottom).





Emission factors [g CO_2-eq/kWh]			
Scenarios	Average EF	Short-run EF	Long-run EF
EV_1 - Default demand	17.97	23.07	7.48
EV_2 - Flat demand	23.66	24.87	19.79
EV_3 - Night charging	25.88	26.09	19.82
EV_4 - Seasonal variance	22.87	23.44	21.02
EV_5 - Linear increase	23.28	24.87	23.28

Conclusion

Generally low values were obtained for all emission factors as the study is based on a futuristic energy system dominated by renewable energy sources. The values for long-run marginal emission factors were lower than those for the short-run for all scenarios analyzed. The impact of the charging strategy is crucial, as distinct differences in emissions are observed across the various EV profiles. The optimal charging strategy from an environmental standpoint was to charge at full power after plug in, resulting in a peak around 6 PM every day. However, the best charging strategy will vary a lot based on the energy system of the analyzed region, meaning that this charging strategy can be far from optimal in other energy systems. Additionally, this strategy may have drawbacks from other perspectives. For instance, it can be counterproductive to the power grid, which prefers a stable load with minimal peaks.

Techno-Economic Analysis of Green Hydrogen Production from PV Plants

Student: **Mira Elise Litleskare**
Supervisor: **Basanta Raj Pokhrel, Irina Oleinikova, Thomas Alan Adams II**

Problem description

The urgent need to combat climate change necessitates a global reduction in emissions, with the Paris Agreement aiming to keep global temperature rise well below 2°C. While increasing renewable energy sources is crucial, fossil fuels remain essential for certain applications like plastic and fertiliser production. Hydrogen, particularly green hydrogen, presents a promising solution due to its high energy density and adaptability for zero-emission applications. Integrating solar photovoltaic (PV) technology with green hydrogen production, especially in climate-sensitive regions like Nepal, offers a viable strategy to decarbonise critical sectors such as transportation and industry, aligning with global sustainability goals.

The task

This thesis aims to determine a practical and economical method for producing green hydrogen from a hybrid plant with PV as the primary energy source. It involves investigating various water electrolysis techniques, different hydrogen storage methods, and choosing the best grid connection plan. The thesis will include a case study in Nepal, using an existing PV plant operated by the Golyan Group. The goal is to offer a techno-economic analysis that describes best practices and suggestions for installing a solar PV-powered green hydrogen generation system, helping stakeholders make well-informed decisions that balance economic viability and technical feasibility.

Model/ measurements

The case study evaluates the practical and economic feasibility of producing green hydrogen at the chosen project site using HOMER Pro. The research collects key data from the company, such as PV specifications, plant efficiency, and local grid characteristics, in addition to data needed for the additional components required. Various scenarios are considered, including different types of electrolysers (ALK and PEM), grid connection strategies, and battery energy storage options. To model and simulate these scenarios, HOMER Pro software is employed, allowing for optimisation of system configurations based on technical and economic criteria. The study involves sensitivity analysis to understand the impact of varying parameters on the system's performance and cost-effectiveness.

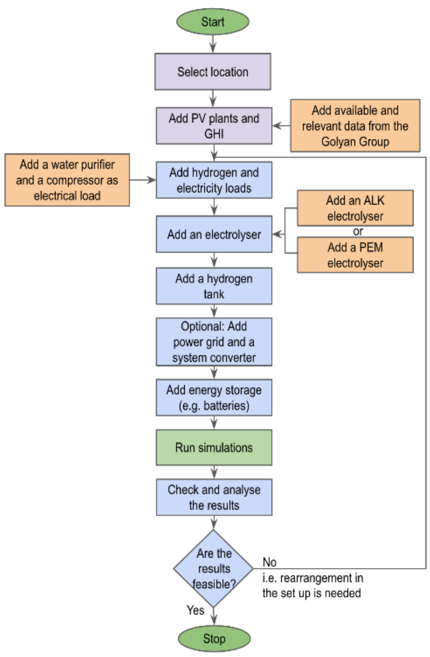


Figure 1: HOMER simulations for a green hydrogen production powered by solar power

Calculation

Case 1: One PV plant, no grid-connection
Case 2: Both PV plants, no grid-connection
Case 3: One PV plant, grid-connections
Case 4: Both PV plants, grid-connections

The assumed average annual hydrogen load for the system is originally 208.5 kg of hydrogen a day and is used to find the NPC of all the cases in Figure 2. Later, a grid-connected system using an ALK electrolyser was simulated for an increasing hydrogen demand of up to 1200 kg of hydrogen a day. Here, different grid electricity intensities have also been used: 83.42 gCO2/kWh for Nepal, 390 gCO2/kWh for the US, and 730 gCO2/kWh for India. The emissions for the grid-connected cases with increasing loads can be seen in Figure 3.

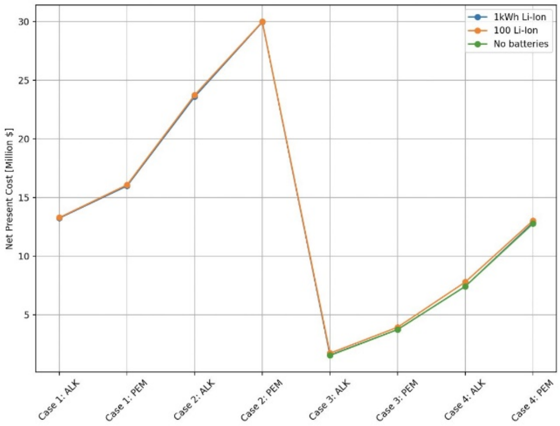


Figure 2: *The total net present cost*

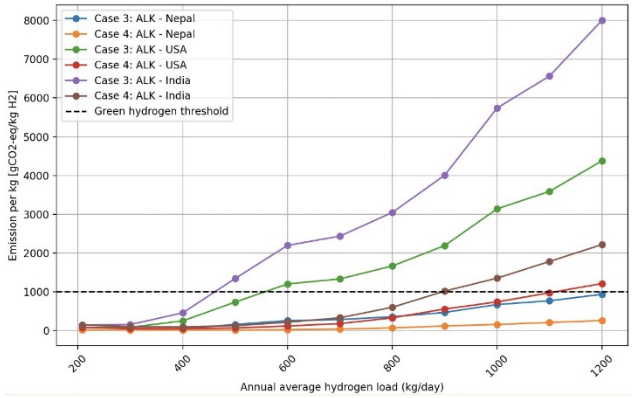


Figure 3: The emissions per kg of hydrogen produced

This demonstrates that the most economical system for the Golyan Group is a grid-connected system on a single PV plant site that uses an ALK electrolyser. Nonetheless, for grid-connected systems, the electricity mix of the grid determines the system's emissions. Thus, the only scenario that will guarantee that the hydrogen remains green if the system is designed to produce more than 1200 kg of hydrogen daily is Case 4. A grid-connected system can fulfil a substantially lower hydrogen demand without generating emissions beyond the green hydrogen classification threshold in countries with higher emission intensities, like India.

Conclusion

The case study identifies that using ALK electrolysers is currently the most cost-effective option, despite the higher hydrogen production potential of PEM electrolysers. Compressed gas is highlighted as the most viable hydrogen storage method due to its efficiency and cost, though the grid-connected systems offer significant cost savings and flexibility benefits. The findings underscore that a grid-connected system using a single PV plant with an ALK electrolyser is the most economical solution for this case study, whereas systems producing higher hydrogen quantities require dual PV plants to maintain green hydrogen classification. Future work should focus on conducting further sensitivity analyses, exploring hydrogen transportation methods specific to Nepal, and evaluating the market potential and applications for the produced hydrogen to ensure sustainable and economically viable green hydrogen production.

Assessing different balancing strategies in the Norwegian power market with high wind penetration

Student: **Knut Ivar Røraas & Øystein Lydersen**
Supervisor: **Gro Klæboe**
Contact: **gro.kleboe@ntnu.no**

Problem description

The Norwegian government are planning to allocate areas for 30 GW of offshore wind power before 2030. Energy production from wind turbines is highly dependent on weather conditions, making electricity generation sensitive to weather changes. The scheduling of electricity production is based on consumption and weather forecasts, making the forecasts an important component of the production schedule. Disparities between forecasted and real-time values necessitate regulations of electricity production to balance these forecasting errors. The installed generation capacity from wind farms impacts the amount of balancing capacity necessary, as larger production capacities can potentially create more significant production deviations due to forecasting errors compared to smaller capacities.

The task

This thesis aims to investigate the Norwegian power system's ability to balance disparities between forecasted and real-time wind production. It examines this by developing a power scheduling model specifically to analyse the expansion of wind power. It has been examined how the balancing market will behave with and without reserving power. Where it have been looked at balancing market without and with capacity reservation.

Model/ measurements

A model for power scheduling of the day-ahead market and balancing market is made to investigate this. The model for power scheduling clears the day-ahead market and the balancing market sequentially. The balancing model acts on the decisions from the day-ahead model to balance the difference between the forecasted and real-time electricity production from wind turbines.
The model schedules the day-ahead and balancing markets sequentially. The day-ahead market is scheduled hourly for one year. Subsequently, the balancing market is scheduled hour-by-hour for the same duration. The balancing market operates to balance the disparities between forecasted and real-time wind production in each hour independently.
Consequently, the decisions made in one hour do not influence the decisions in the following hours. The operation of the model is illustrated in figure 1.

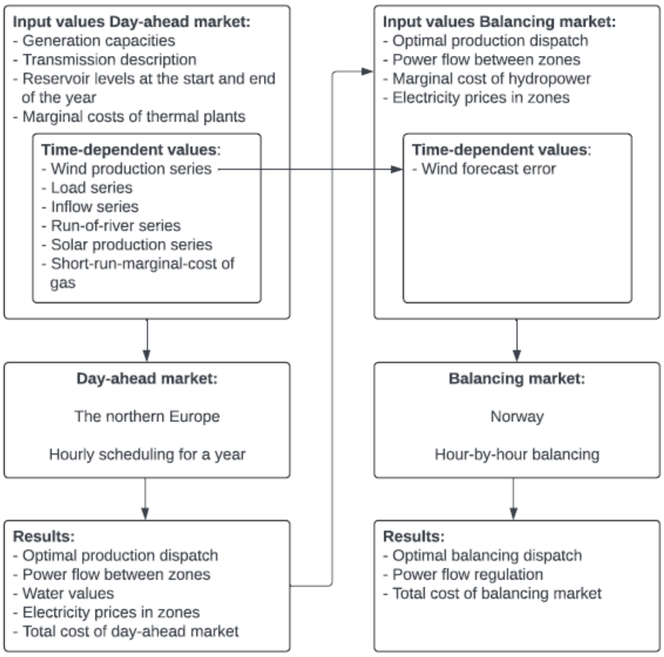


Figure 1: Model decription

Results

Reserving capacity from the day-ahead model provides the balancing market with an initial foundation of balancing capacity. The initial foundation allows the power system to balance the majority of forecasting errors from an early stage. Consequently, the power system is not dependent on reaching the threshold where wind power covers significant parts of the electricity demand in the day-ahead market to liberate balancing capacity, as observed when excluding capacity reservations. As a result, load rationing increases at a lower rate in line with increased wind power. Additionally implementing capacity reserves on interconnectors provides significant balancing properties even in the current power system, as seen in figure 2. As a result, the power system can balance all the forecasting errors in the current power system. However, the forecasting errors increase with the increasing wind power. With the power system able to balance the baseline of forecasting errors, the peak forecasting errors connected to increasing wind power cause the rate of load rationing to increase in line with increasing wind power.

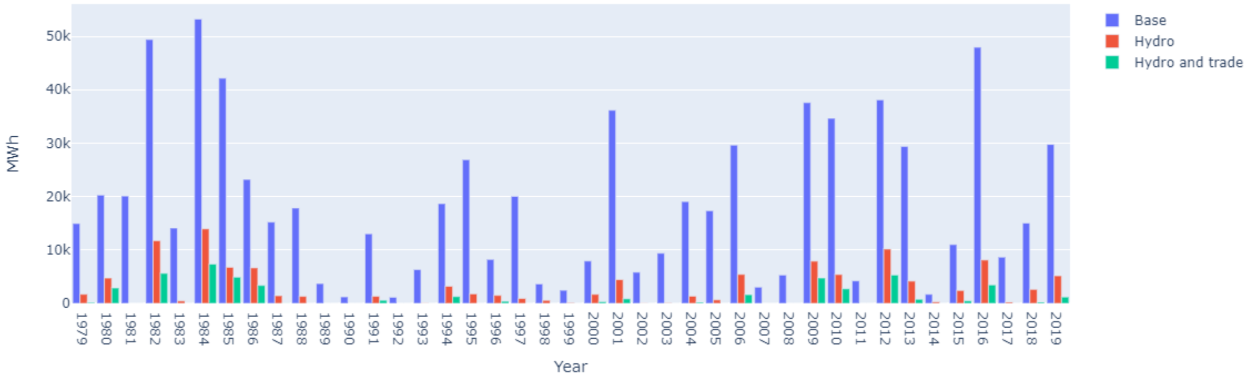


Figure 2: Rationing in Norway's balance market with reserve strategy in 30 GW scenario

Conclusion

The study found that the limitations set on the day-ahead market to reserve production capacity did not deteriorate the power system's ability to clear the day-ahead scheduling. The implementation of capacity reservations had a negligible impact on the total cost of the Northern European day- ahead market. Additionally, Norwegian electricity prices received a marginal change in electricity prices compared to a day-ahead market without capacity reservations. The difference in electricity prices increased with increasing wind power. As a result, the power system can implement capacity reservations in the day-ahead market without a noteworthy impact on the day-ahead market.

Implementing capacity reservations in the day-ahead model resulted in a significant reduction in load rationing in all wind scenarios compared to a day-ahead model without capacity reservations. The capacity reservations resulted in a significantly improved system adequacy, with a LOLE within limits set by TSO's across Western countries. Capacity reservations on interconnectors provided balancing properties, making the integration of an additional 30 GW of wind power feasible. Further, the improved system adequacy and reduced load rationing resulted in a substantially decreased cost of clearing the balancing market. This resulted in an overall lower cost of the day- ahead and balancing market combined. As a result, the Norwegian power system can implement 30 GW additional wind power in the current power system while ensuring sufficient system adequacy.

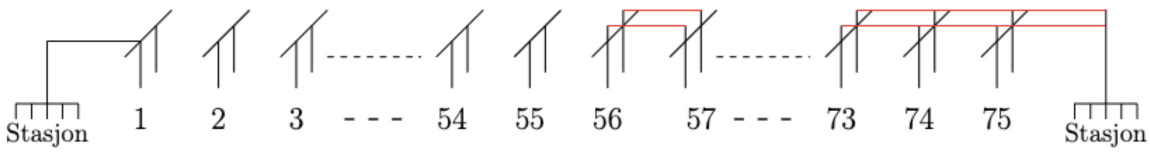
Håndtering av farespenninger ved jordfeil i direktejordede 132 kV regionalnett uten gjennomgående jording

Student: **Jenny Lyng**
Faglærer: **Bjørn Gustavsen**
Veileder: **Anders Dall´osso Teigset**

Problemstilling
Bakgrunnen for oppgaven var at Tensio og Statnett har vurdert en overgang fra spolejording til direktejording i Trøndelagsnettet. Den største frykten med direktejording er at frakobling av høyohmige feil blir problematisk uten gjennomgående jord. Det ble derfor utført nettprøver for å studere dette, og resultatene viste at overgangsmotstanden mot jord ble brutt ned av feilstrømmen. Oppgaven studerer feil i/ved kritiske mastepunkt slik at feilstrømmen forplanter seg mot jord gjennom mastens jordelektrode. Kritiske mastepunkt kan oppstå i ofte okkuperte områder, og hvor nedført jording er nødvendig. Dette kan medføre økt fare i forbindelse med forhøyede skritt- og berøringsspenninger i områdene rundt masten. Oppgaven skulle studere om gjennomgående jord er nødvendig for å oppnå tilfredsstillende nivåer av skritt- og berøringsspenninger.

Oppgaven
Oppgaven har vært å studere hvordan en overgang fra et spolejordet til et direktejordet 132 kV nett kan gjøres for tremastledninger, uten at mulige forhøyede skritt- og berøringsspenninger medfører en større farerisiko. Feilstrømsnivået for et spolejordet og et direktejordet nett ble sammenlignet ved hjelp av manuelle beregninger og programmet Tower Pole Earthing (TPE), i tillegg til at det ble studert om ionisering av jordsmonnet ville ha innvirkning på resultatene. TPE ble også brukt til å bygge opp en virkelighetsnær modell basert på en eksisterende ledning. Deretter ble basismodellen i TPE benyttet til å se på innvirkningen av å innføre tiltak i form av en lokal, gjennomgående jordline langs deler av ledningen. Tre fremgangsmåter for innføring av jordlinen ble studert, og fremgangsmåtene omhandler hvordan antall sammenkoblede mastepunkter kan optimaliseres, og hvordan en endring av jordelektrode kan ha innvirkning på resultatet. Siste fremgangsmåte ser på hvordan gunstige jordforhold som myrområder, sammen med en kort jordline, kan utnyttes for å oppnå en potensialutjevning.

Modell/målinger
I TPE ble en radiell 132 kV ledning modellert som vist nedenfor. De tre faselinene er ikke tegnet inn, men strekker seg fra stasjon til stasjon. Den ene enden av ledningen har innføringsvern som vist i rødt i figuren. Det studeres en feil ved mast 25 gjennom hele oppgaven, først for basismodellen uten en gjennomgående jordline, og deretter for de tre ulike fremgangsmåtene med underhengende jordline. For basismodellen blir resultatet som vist under *Direktejording* i tabellen nedenfor.

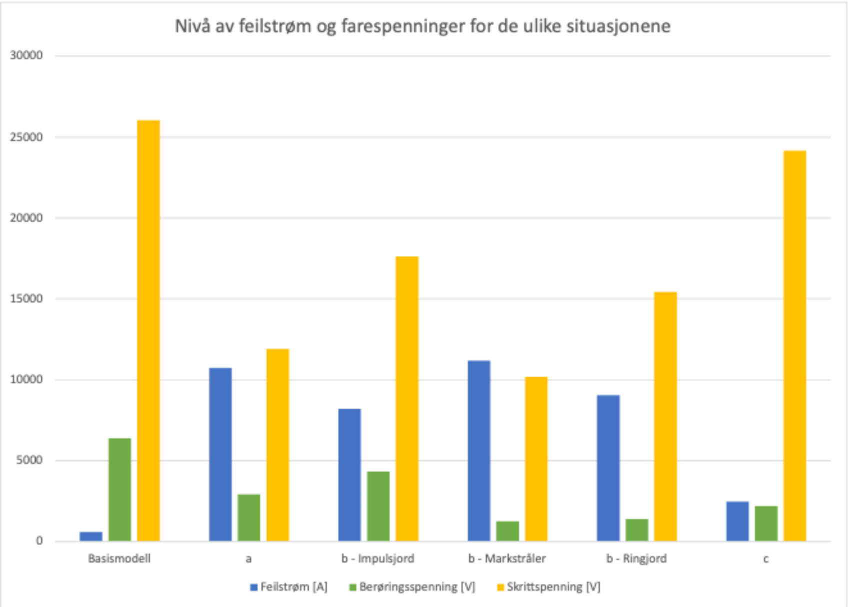


Beregninger

Gjennom manuelle beregninger og programvaren TPE ble nivå av feilstrøm beregnet for en spolejordet og en direktejordet 132 kV radiell ledning. Resultatene fra det studerte tilfellet er presentert i tabellen nedenfor, og viser store ulikheter i størrelse på feilstrøm. Dette påvirker videre nivået av skritt- og berøringsspenningene. Ionisering av jordsmonn ble funnet til å ha liten innvirkning på beregninger med disse feilstrømsnivåene.

	Spolejording	Direktejording
Feilstrøm I_g, RMS [A]	27	587
Skrittspenning [V]	851	26037
Berøringsspenning [V]	789	6392

Siden berøringsspenningen for den aktuelle modellen er høyere enn tillatte verdier, studeres tiltak. Ved å innføre en underhengende jordline, tilpasse jordingsarrangementet og utnytte gode jordsmonn, ble resultatet en berøringsspenning nede på 1400 V. Denne verdien er lavere enn terskelverdien for den aktuelle modellen. I figuren nedenfor representerer *Basismodell* ledningen før gjennomgående jordline ble inkludert, mens for *a* er en lang, underhengende jordline innført. For situasjonene *b* er ulike jordelektroder benyttet sammen med en middels lang jordline. I situasjon *c* er jordlinen svært kort, men gode jordingsforhold i form av myr er utnyttet.



Konklusjon

De gjennomførte studiene og tilhørende resultater viser at det er mulig å gå fra en spolejordet ledning til en direktejordet ledning uten å måtte innføre gjennomgående jord for den totale ledningen. Det vil dog kreve en god del tilpasning og prosjekteringsarbeid, men ved hjelp av gode og tilpassede tiltak er det i oppgaven vist at man kan oppnå tilfredsstillende farespenninger ved kritiske mastepunkter etter en overgang til direktejording.

Experimental Characterization of Short Commutating Arcs in Fast Mechanical DC Circuit Breakers

Student: **Simon Løvdal**
Supervisor: **Kaveh Niayesh**

Problem description

Integration of renewable energy sources has led to the need to further develop and expand the power grid. This challenge has increased the interest in developing Multi-terminal Direct Current (MTDC) systems. Future MTDC systems are expected to be constructed using Voltage Source Converter (VSC) technology. A problem with VSCs is that they are susceptible to damage if exposed to large currents. Development of reliable DC Circuit Breakers (CB) with short fault clearing time is crucial in order to establish MTDC systems.

The task

The objective of this Master's thesis is to investigate current commutation to a capacitor using a fast mechanical switch. The primary focus is on studying the impact of varying system parameters on the current commutation process. This will be done using an experimental setup. The visual development of the arc will also be investigated.

Measurements

The experimental setup consists of a battery bank (U_s) connected in series with a Thomson Coil Actuated switch (TC) and a variable load (R_{var}). A capacitor bank (C) is connected in parallel with the switch. The circuit diagram of the experimental setup is shown in Figure 1. TC is opened by injecting a current impulse into the coil of the Thomson Coil Actuator. This induces magnetic force in the switch, which opens TC. The current impulse is injected using a pre-charged capacitor C_{coil} in an auxiliary circuit. The charge of C_{coil} regulates the opening velocity of the switch. Tests are performed with an initial current of 100 A or 200 A, system voltage of 50 V or 100 V, charge of C_{coil} of 400 V (6.5 m/s) or 600 V (12.7 m/s), and capacitance of 198 µF or 495 µF on the capacitor bank. Five tests are performed for each combination of system parameters. During the tests, the initial current (i), current into the capacitor bank (i_c), and voltage over the switch (u_{sw}) are measured. A high-speed camera is used to capture the visual development of the switching arc.

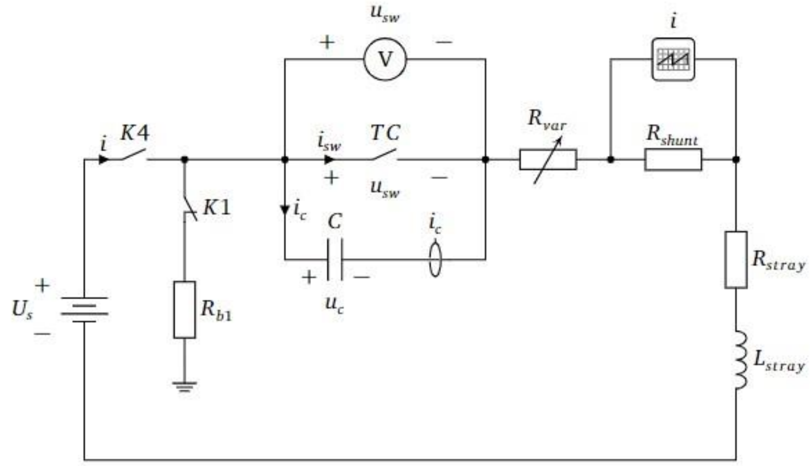


Figure 1: Circuit diagram of experimental setup

Results

The observed trends in the current and voltage measurements show that the current commutation is dependent on the system parameters. The capacitance of the capacitor bank is observed to have little impact on current commutation in tests with an initial current of 100 A. In tests with an initial current of 200 A, the commutation time is reduced when the capacitance is increased. Increased initial current is observed to increase the commutation time. Increased system voltage is observed to increase the commutation time. Increased opening velocity is observed to reduce the commutation time and increase the consistency of the measurements within the test series. The impact of increased opening velocity is more significant in tests with an initial current of 200 A and system voltage of 100 V. The capacitor bank is able to successfully commutate the current within 10 µs in tests with an initial current of 100 A, as shown in Figure 2. When the current and voltage is increased, the 198 µF capacitor bank struggles to commutate the current, as shown in Figure 3. In these cases, commutation times greater than 1 ms are measured in several tests. The commutation time is influenced by the development of the arc voltage. Fluctuations in the arc voltage or re-strikes are observed in some tests. These phenomena increase the commutation time compared to tests where the current is commutated directly to the capacitor bank. No relation is observed between the rate of re-strikes and system voltage or opening velocity.

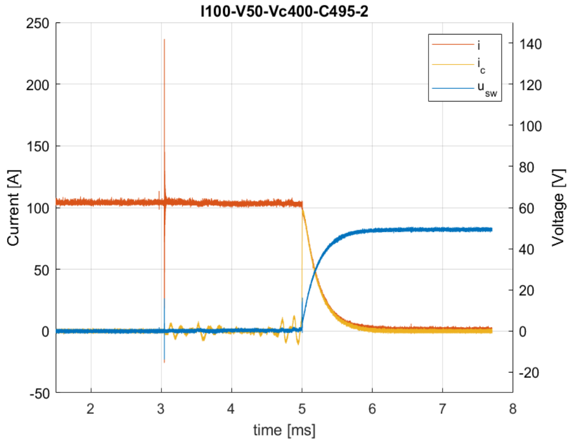


Figure 2: Measurement with system parameters: initial current: 100 A, system voltage: 50 V, charge of C_{coil}: 400 V, capacitance of capacitor bank: 495 µF

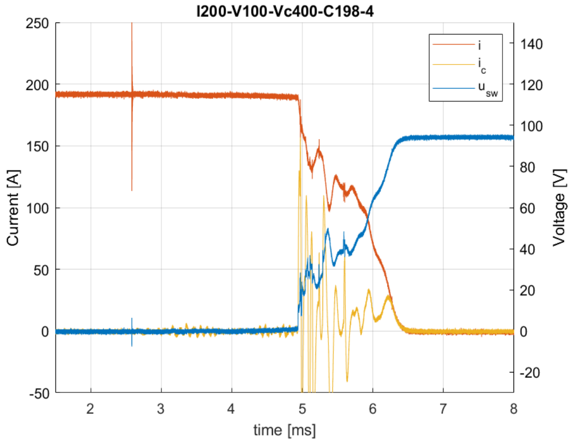


Figure 3: Measurement with system parameters: initial current: 200 A, system voltage: 100 V, charge of C_{coil}: 400 V, capacitance of capacitor bank: 198 µF

Conclusion

- Increased capacitance reduces the commutation time and allows larger currents to be commutated
- Increased initial current increases the commutation time
- Increased system voltage increases the commutation time
- Increased opening velocity reduces the commutation time and increases the consistency of the measurements
- The impact of changing one of the system parameters is dependent on the other system parameters

Low-carbon energy solutions for Longyearbyen, Svalbard

Student: **Kristian Midtbø-Salvesen**
Supervisors: **Magnus Korpås, Martin N. Hjelmeland and Jonas K. Nøland**
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Problem description

Longyearbyen aims to reduce carbon emissions from energy production by 80% by 2030 compared to 2018 levels. Low-carbon energy sources must then be integrated into the isolated energy system. The solution must also be reliable, as energy security is paramount in the cold and Arctic climate. Currently, the energy system in Longyearbyen consists of an interim diesel solution. The Norwegian government and Longyearbyen Lokalstyret (LL) have outsourced several studies to propose possible energy system alternatives combining variable renewable energy sources (VRESs), energy storage systems (ESSs), and fossil fuels. However, nuclear power is not included in any of these studies.

The task

This thesis aims to explore alternative low-carbon energy solutions for Longyearbyen based on an energy mix of VRES, ESS, small-scale nuclear, and diesel. It also showcases the risk of optimizing isolated energy systems with VRES and how it affects optimization results.

Model/ measurements

A least-cost capacity investment optimization model constructed by Multiconsult AS, based on the PyPSA (Python for power system analysis) framework, is used to conduct scenario-based robust optimization with 38 weather scenarios, accounting for the uncertainty of VRES. The average weekly capacity factor for the weather scenarios is shown in Figure 1. This is performed for three main investment cases: 1) Renewable & Nuclear (RN), 2) Renewable & Diesel (RD), and 3) Renewable, Nuclear & Diesel (RND). The worst-case solution and other selected investment solutions for all investment cases are tested with in-sample testing by removing investment opportunities in the model and simulating least-cost optimal generator dispatch with the solutions as existing capacity. The aim of robust optimization is to provide a feasible solution under all conditions of the uncertainty set. Load shedding is added to the model at a high penalty cost (30 000 NOK/MWh) to ensure feasible simulations. Optimization with current and 2030 load profiles is also performed to see the effects of increasing energy efficiency in Longyearbyen

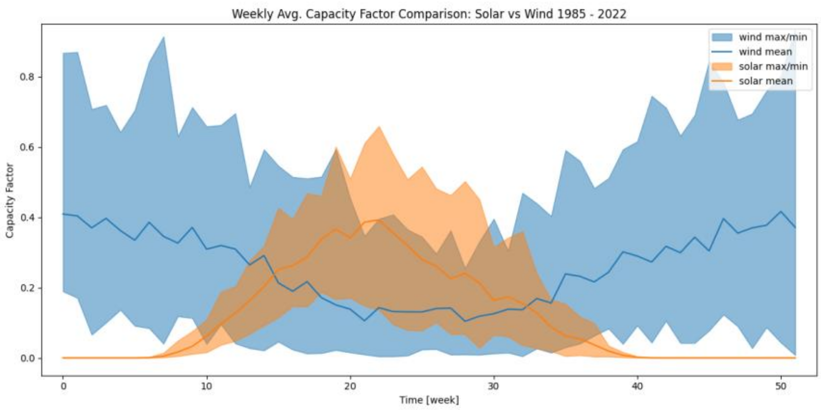

Figure 1. Average weekly capacity factor for solar and wind in the scenario-based uncertainty set.

Calculation

The variation in renewable resources resulted in high variation in operational cost due to load shedding and increased diesel consumption. The total system cost for each tested solution is presented in Table 1. The high standard deviation indicates high uncertainty in operational costs. RN-2, RN-3, RN-4, RD-1, RD-2, and RND-2 all required load-shedding measures and performed inefficiently when subjected to different weather scenarios. The solution testing revealed two robust solutions: RN-1 and RND-1. The installed capacities are shown in Table 2. The battery installation is the existing battery in Longyearbyen.

Table 1. Total system cost for each tested

Case	Fixed investment cost [MNOK]	Operational cost [MNOK]		Expected total cost [MNOK]
		Median	Std. Dev.	
RN-1	65.4	18.20	0.122	83.60 ± 0.12
RN-2	73.1	24.05	6.661	97.15 ± 6.66
RN-3	67.4	20.10	5.351	87.50 ± 5.35
RN-4	70.5	50.60	21.339	121.10 ± 21.34
RD-1	59.6	24.10	7.542	83.70 ± 7.54
RD-2	47.7	40.80	10.800	89.50 ± 10.80
RND-1	52.7	18.90	1.417	71.60 ± 1.42
RND-2	46.5	27.05	3.967	73.15 ± 3.97

Table 2 Capacity installations for the two robust solutions

	Electric boiler [MWth]	Hydrogen electrolyser [MW]	Hydrogen fuel cell [MW]	Hydrogen tank [MWh]	Battery [MWh]	Solar PV [MW]	Wind [MW]	NPP [MWth]	Diesel generator [MW]	Diesel boiler [MW]
RN-1	4.29	0.02	2.5	180.85	7	0	2.63	26.34	-	-
RND-1	7.15	0	0	0	7	9.12	11.79	17.68	0.96	6.47

Conclusion

Improving energy efficiency in Longyearbyen can significantly reduce overall energy consumption and investment needs. Reducing heat demand by 30% by 2030 would result in an average annual system cost reduction of 23.8 MNOK.

Robust optimization of various investment cases revealed a range of hybrid energy systems. Most of the solutions with high investments in VRES and ESS performed inefficiently. This highlights the risks of optimizing energy systems with VRES, as the shift in renewable resources greatly impacts simulation results, resulting in uncertain operational costs driven by high load-shedding costs when the weather scenario is less than ideal.

The difference in total cost between the robust RN-1 and RND-1 solutions in Figure 2 represents a trade-off between a more costly alternative with zero local emissions in RN-1 compared to a more cost-effective solution with emissions in RND-1. The low standard divination of the operational costs indicates resilient and predictable solutions, where the variation in weather scenario had little effect on the operation uncertainty of the energy system

The real-life plausibility of installing the proposed RN-1 and RND-1 solutions is provided by suggesting installation sites with sufficient available land and infrastructure. Suggesting renewable installations on Platåberget and microreactor with interim spent fuel storage at Hotellneset.

Overall, given the preliminary estimates and assumptions in this thesis, a low-carbon energy system with incorporated small-scale nuclear energy has been proven cost-effective and provides energy security in Longyearbyen.

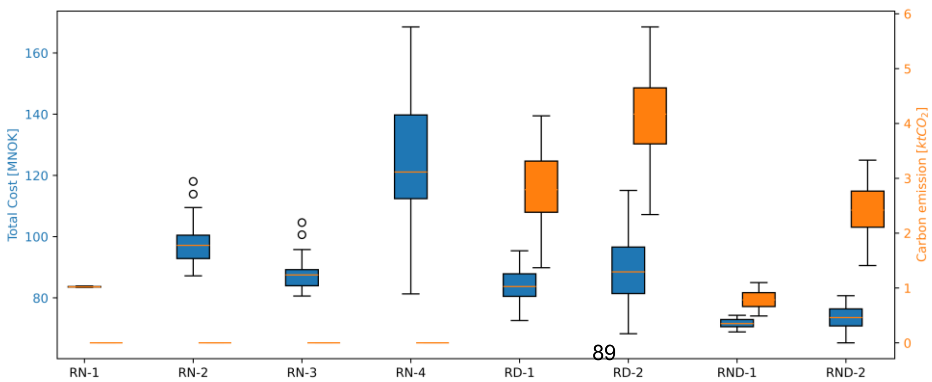

Figure 2. Total cost and emissions from solution testing

Developing an Early Warning Application for Detecting Low-Frequency Oscillations in Power Systems

Student: **Maurits Sørensen Molberg**
Supervisor: **Kjetil Obstfelder Uhlen**
Co-supervisor: **Aldrich Zeno**
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Problem description

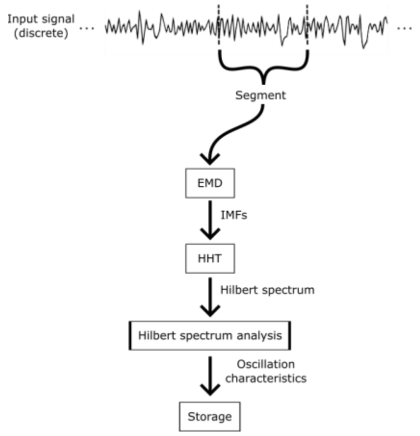
Large disturbances like faults and tripping of generators can introduce low-frequency, high-amplitude oscillations in the power system, which may disrupt the system's stability. They need to be damped quickly to prevent instability.

There is a great untapped potential of using advanced processing techniques on phasor measurement unit (PMU) data to give grid operators in the control room more interpretable insight into the state of the system. An application that gives grid operators early warnings for low-frequency oscillations would be a helpful tool for making good decisions quickly in critical situations.

The task

The objective of this thesis was to develop a Python application that can connect to PMUs and continuously analyze their data to detect and give early warnings for low-frequency oscillations in the power system. Functionality for analyzing a pre-given signal snapshot in the same way was also implemented, letting the application be tested on recorded simulated and real PMU data or any other type of signal. The developed application, OscilloWatch, is published with open source code on GitHub.

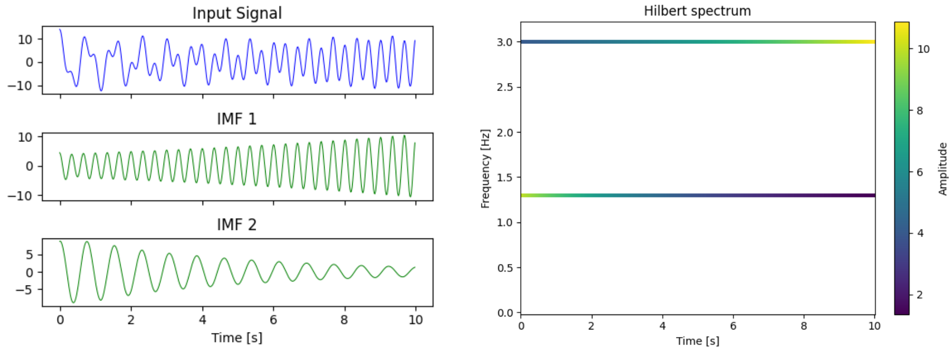
Methodology



The PMU data stream is divided into time segments of a certain length, each of which is processed individually, as illustrated in the block diagram on the right.

The analysis is based on the Hilbert-Huang transform (HHT). It produces a Hilbert spectrum, a time-frequency representation of a signal, where each oscillating mode should ideally be a straight, horizontal line with amplitude values that follow a decaying exponential curve.

The figure below shows how a signal with two frequency components is decomposed into intrinsic mode functions (IMFs) on the left, and its Hilbert spectrum is shown on the right.

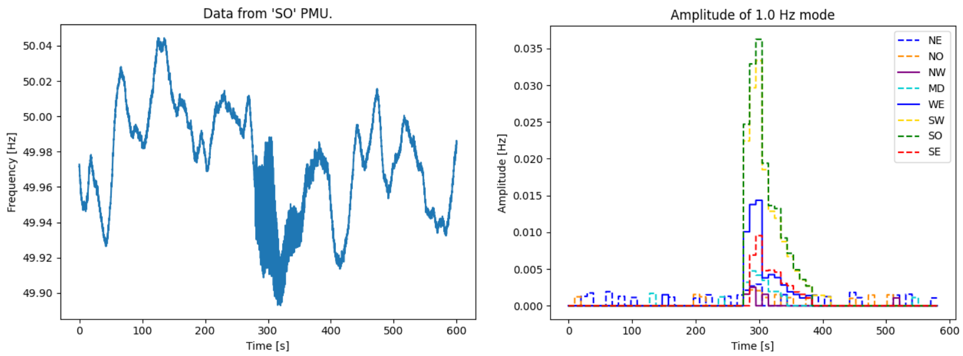


An algorithm was developed for identifying and characterizing modes from the Hilbert spectrum. Rows that contain points that are part of an approximately straight horizontal line of non-zero values are combined to identify a mode, and the damping of the mode is estimated by fitting a decaying exponential curve to the amplitude points in the combined row. If a sustained mode with low damping is detected, an alarm is raised. This is done for all detected modes in each segment, and the results are stored in a table in a CSV file.

Results

The application was tested on a synthetic sine wave signal, and on simulated and real PMU data.

One of the test cases was an oscillatory event in the Norwegian power grid in 2018. 10 minutes of PMU data from eight PMUs across the grid was analyzed. The time-series plot of the system frequency at the PMU with the largest oscillations is shown on the left in the figure below. The dominating mode's frequency is around 1 Hz. The evolution of OscilloWatch's measured median amplitude of this mode from segment to segment at all the PMUs is shown on the right.



The time when the application detected the spike in amplitude aligns well with the time-series plot. Alarms were raised for this mode between 290 seconds and 360 seconds. No false alarms were raised.

Conclusion

The results are promising and indicate that the application and the method it uses have great potential to be useful for grid operators. Modes and their frequencies are accurately detected, alarms are raised when and only when critical low-frequency oscillations are present, and the analysis is robust to noise in the signal.

There is room for improvement, such as taking further measures to ensure that no false alarms are raised, improving the accuracy of the damping estimates, and using better criteria for when alarms are raised.

The version of the application developed here is meant as a proof of concept that can be built upon. It is functional and extracts useful information from the data but has no proper user interface, which would be necessary for it to be useful in a real control room setting.

Investigation of Increased stresses on circuit breakers switching offshore AC cables

Student: **Johan Mykland**
Supervisor: **Kaveh Niayesh**

Summary
The growing demand for renewable energy has increased the use of long HVAC cables for power transmission. Shunt reactors are commonly used to manage the reactive power generated by these cables. However, this compensation can cause the zero-miss phenomenon, where the current in the circuit breaker does not cross zero for an extended period, complicating the circuit breakers operation. This phenomenon can lead to severe risks, especially if a fault occurs during cable energization, potentially leaving the system unprotected.

This thesis aims to understand the zero-miss phenomenon in shunt-compensated cable systems and to identify ways to solve it. Using PSCAD software, a model of a three-phase shunt-compensated cable system was developed, including a voltage source, circuit breaker, shunt reactor, and high voltage cable. The study investigates the impact of various parameters, including the degree of compensation, cable length, source impedance, and load on the occurrence and duration of the zero-miss phenomenon.

Key findings indicate that certain conditions significantly increase the duration of the zero-miss phenomenon. Several countermeasures such as synchronized switching, pre-insertion resistors, sequential switching, and the use of several shunt reactors were tested to address this. Simulations under different system conditions demonstrated the effectiveness of these countermeasures in reducing the zero-miss current and associated transients.

Availability Assessment of Offshore Electrical Networks in Wave Farms

Student: **Negro El Khatib, Thamer**
Supervisor: **Anaya-Lara, Olimpo**

Abstract
Offshore renewable energy, including wave energy, may play a key role for the energy transition in the next decades. One of the most significant drivers to the advancement of this technology is the reduction of the Levelized Cost of Energy (LCOE). To address this, it is necessary to minimize overall costs and increase total energy production throughout the project life cycle. Improving wave farm availability is part of the solution to this problem, since it can help both increase the Annual Energy Production (AEP) and reduce Operational Expenditures (OPEX). However, equipment reliability poses a unique challenge in such a harsh marine environment. This thesis investigates this issue by developing a reliability model for offshore electrical networks in wave farms. It is demonstrated that downtime and maintenance play a key role in offshore network availability. The study reveals that an electrical network for a nominal 10 MW wave farm with 2 strings presents an availability of 95.5% while the same farm with 4 strings shows an availability of 97.4%. Sensitivity analysis for a 10 MW, 2 strings network, with rocky seabeds and lower HUB (offshore substation) reliability, showed that network availability can drop to 95.2% and 94.0% respectively. Between 0.7% and 1.5% points of availability loss was attributed to failures in the HUB and export cable across all cases whereas subsea cables and junction boxes accounted for up to 2.5% points of network unavailability. The study also emphasizes that redundant topologies and subsea switchgear can potentially improve availability by up to 3.6% points. Final recommendations to increase availability are anchored in reducing downtime for specific subsystems with a design towards HUB maintainability and efficient recovery for subsea components. Moreover, it is recommended that engineering efforts adopt a proactive resilience approach by being prepared for the correction of failures. This research supports the global transition to renewable energy and contributes to the broader field of offshore renewable energy by highlighting the critical role of technological reliability, availability and operational maintenance strategies in marine environments.

Simulation and Experimental Validation of Losses in Permanent-Magnet Synchronous Machines

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Collaboration with: **Rolls-Royce Electrical Norway**

Problem description

The task

The Permanent Magnet Synchronous Machine (PMSM) has seen a surge in popularity, due to its high torque density, efficiency, power factor and its low need for control and maintenance. Since the first PMSMs were introduced, many material and technical advantages have been made, reducing the price and increasing the overall performance, making the PMSM a strong competitor in the electric machine market.

This thesis focuses on the efficiency and the losses of the PMSM. Studying the losses found through Finite Element Method (FEM) simulations, and validating them with two identical 3kW WEG W22 Interior PMSMs in a back-to-back setup, the losses are allocated and analysed. The laboratory facilities were prepared by the Department of Electric Energy (IEL) at NTNU before the Thesis work began, as the first in a chain of investments in experimental validation equipment for use by NTNU and their industrial partners.

Model/ measurements

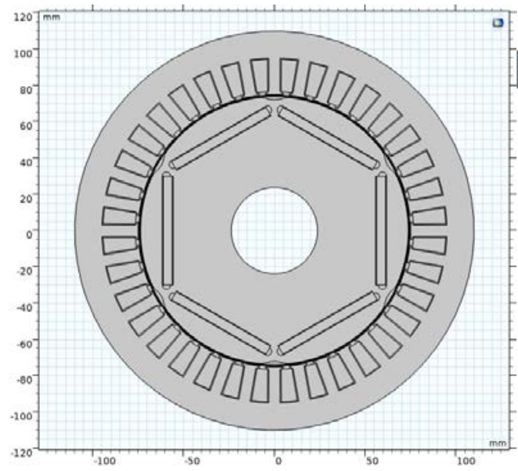


Figure 1 Cross-section geometry of IPMSM

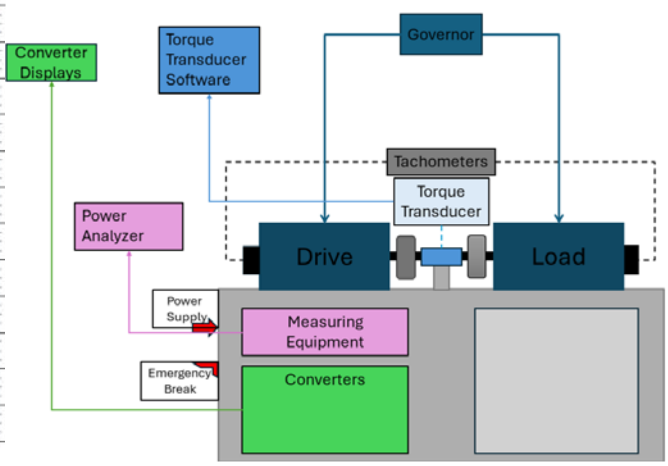


Figure 2 Laboratory setup scheme

The aim of the Thesis is to map the losses of an Interior Permanent-Magnet Synchronous Machine (IPMSM), focusing on the electromagnetic losses. The IPMSM is a WEG W22 MAGNET IE5 132S 3 kW, characterised by its high performance, efficiency in a wide range of operation, along with a high power density resulting from the Permanent-Magnets (PMs). In this Thesis, the machine was modelled in COMSOL Multiphysics 6.2 and simulated with its inbuilt Finite Element Method (FEM). The results of these simulations are compared with the losses measured in a laboratory setup, where two of these machines are operated back-to-back, one as a motor, and the other as a generator. Through these simulations and experiments, the performance of the machines is studied. The results are used to decide whether the tests in the Thesis are conclusive, and what other tests could be conducted.

Calculation

Using measure line current and DC resistance, a lower estimate of the Full-Load copper losses (185W) is simulated and measured, which is subtracted from the total losses, the difference between electrical and mechanical power. The remainder, ie. the rest losses in the machine, comprise mechanical losses, core losses, PM losses, PM plate losses and all of the copper losses not resulting from DC resistance. By measuring the No-Load losses at low speed, the mechanical loss (31W) and the core losses can be approximated.

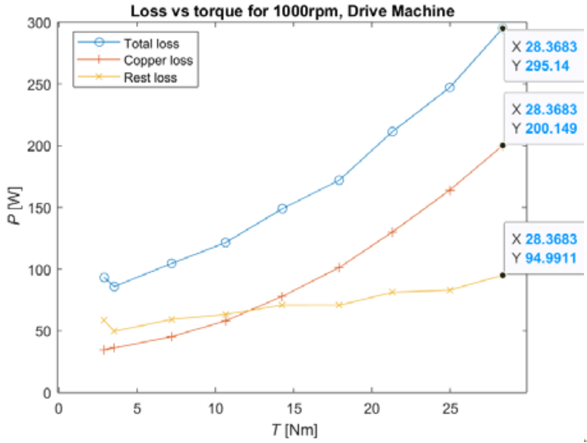


Figure 3 Measured losses at 1000rpm, Drive Machine

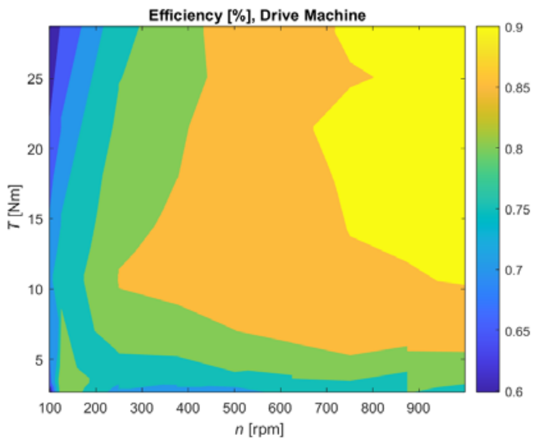


Figure 4 Efficiency Map for Drive Machine

The Full-Load core losses (18-41W) are also calculated through volumetric loss density simulation, using the Steinmetz Method, Jordan Method and the Bertotti Method. The methods are increasingly sophisticated and rely on the knowledge of material properties to be precise.

Though the simulated resistive PM losses are not of significance in the total loss picture, they are important for the performance of the machine, especially in an IPMSM, in part due to demagnetisation. They are simulated as resistive losses, and do not typically vary a lot with temperature. The resistive losses simulated in the PM plates are not large in the total losses aspect either, but carry the same importance as the PM losses, as they are hard to distribute, and will heat the PM if thermal management is not thought through. The intent and function of these plates should be further investigated, as their losses are greater than the losses in the PMs.

The residual copper losses are due to temperature rise, AC and proximity components, and circulating harmonic currents in the delta-configured winding. Of these, the greatest factor is estimated to be the temperature, which will increase the copper losses by 31.2%. The AC component is considered negligible for the the thin conductors, but the proximity component may not be. The circulating currents are not measurable at the terminals, and are therefore difficult to estimate, but they could be of significance to the machine design.

Conclusion

The measurement accuracy of the instruments in the laboratory setup is calculated and questioned, which brings the conclusion of needing more precise measurements in future experimental validation. This, along with a reconsideration of delta-connected machine, is the advice for IEL's continued laboratory investments.

Holistic Energy Systems Analysis for Norwegian Farms

Student: **Tobias Aas and Sveinung Berg Olsen**
Supervisor: **Steve Völler**
Co-supervisor: **Mulu Bayray Kahsay**

Problem description

Farms can play an important role in the current transition towards more renewable energy utilization. The ongoing development of energy production, storage, and consumption technologies can make farms more sustainable and profitable. This thesis aims to provide two case systems with practical, data-driven solutions to improve their energy systems, and ultimately expand the knowledge regarding sustainable energy utilization at Norwegian farms.

Both the electrical and thermal aspects of the energy systems are evaluated, and it is weighted that the recommendations are practically realizable given the available technology and market situation. A special emphasis is put on the implementation and utilization of storage technology.

The task

The two addressed case systems of this thesis are a farm and an agricultural high school. The farm, referred to as RIBI, is a dairy and pig farm that uses self-produced biogas to produce electric and thermal energy. The agricultural high school, referred to as Skjetlein, is a large school with several agricultural activities and a complex energy system containing, among others, a local heating plant connection, three PV systems, and a Vanadium Redox Flow Battery (VRFB) interacting with one of the three grid connection points.

A set approach is used to identify the recommendations for each system. First, the case system is mapped and understood before it is modeled and analyzed. The analysis aims to highlight the energy utilization today and point out room for improvement. Based on the results, the model is developed and new elements are added. Lastly, a holistic review of the results is used to suggest specific recommendations. To evaluate the model performance, three criteria are used:

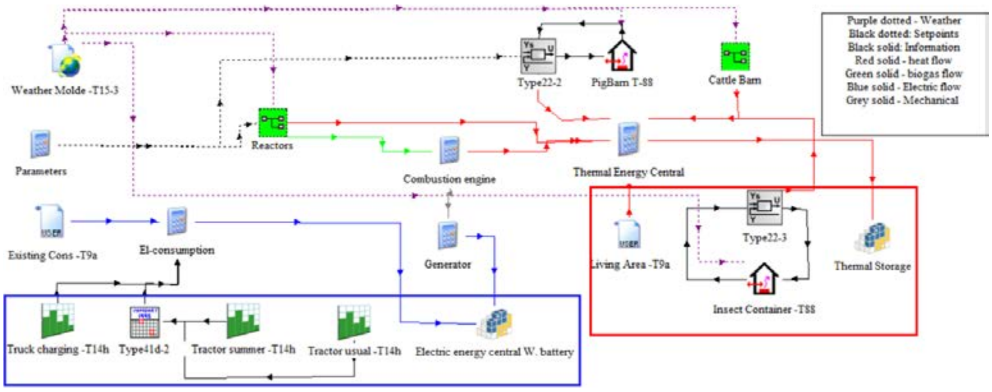
- Self-consumption rate, indicating how much of the locally produced energy is utilized in the system itself.
- Economic evaluation of costs, incomes, and savings directly affiliated with the energy system.
- The environmental footprint, measured in CO_2eq, directly affiliated with consumption of energy.

The case-system analysis is performed in such a manner that the same approach could easily be adapted to other similar systems. Correlations and general observations regarding the models and their proposed expansions are to be highlighted in order to give systems with similar characteristics a foundation for development.

Model

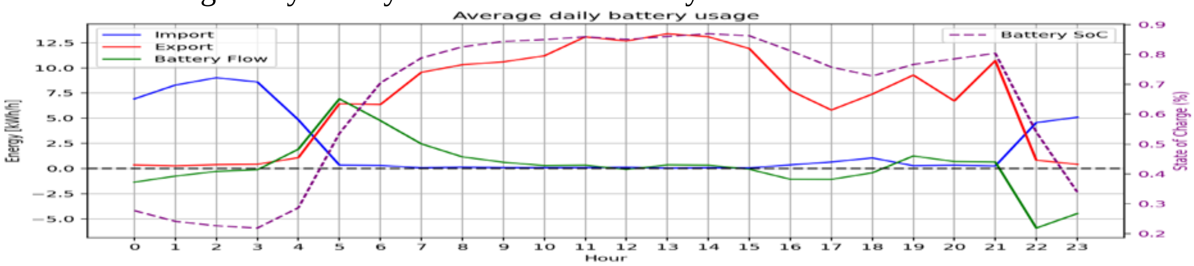
The case systems are modeled using TRNSYS and Python. Generally, TRNSYS is used to model most of the thermal elements in the system, while Python is used for electric elements. There is limited information available on the thermal system for both cases, requiring the collection of extensive data to construct a realistic model. For the electrical parts, data is mostly based on AMS measurements.

The figure shows an overview of the TRNSYS model of RIBI, where the proposed expansions are highlighted in red and blue.



Results

Results showed that the farm had 122 394 kWh of surplus electricity exported to the grid and 193 670 kWh of surplus thermal energy dumped to outside air annually. By implementing the charging of an electric tractor and an electric truck, as well as a load-shifting 10 kW/25 kWh Li-Ion battery, the annual self-consumption rate was lifted from 62.3% to 80.8%. The implemented Li-Ion battery proved to have a positive net present value. The figure below shows the average daily battery utilization over a full year.



For the thermal system at the farm, the model results show that there is enough surplus thermal energy the supply four shipping containers used for insect production. The yield from this production is enough to contribute to the production of 35 tonnes of salmon meat. More production can be enabled using a seasonal thermal storage.

For the school, results from the electric system show that a restructuring of the system can increase the total self-consumption rate from 80% to 98%, saving the school 35 831 NOK annually. Results from the thermal system show that the current operation of the system's sources is probably inefficient. Altering the dynamics within the system would lower its environmental footprint by over 5 tonnes of CO2eq.

Conclusion

Generally, this thesis highlights the importance of system modeling and how this can be especially useful for complex energy systems, such as Norwegian farms. The presented results show that both case systems considered in this thesis have room for improvement in their existing systems. The farm is recommended to charge electric vehicles during the night and start with insect production to use the excess thermal energy. The school is recommended to restructure the electrical system to form one common point and establish a better thermal system operation. On a general note, batteries are only found to be profitable for load-shifting purposes if they are utilized extensively throughout the year.

With new technology emerging, knowing the effects of implementation can help farmers make profitable and environmentally friendly decisions for their energy systems.

Differential Protection and Distance Pilot Protection in Transmission Grids with High Penetration of Inverter-Based Resources

Student: **Henrik Engum Pedersen**
Supervisor: **Hans Kristian Høidalen**
Collaboration with: **Statnett**

Problem description

Today protection relays are designed with the short circuit characteristics of synchronous generators (SGs). Renewable energy generation is mostly inverter-based, and inverter-based resources (IBRs) contributes different to the short circuit current compared to SGs. One problem is that IBRs have lower overload capabilities compared to SGs. Another is that the characteristics of the faults are complex and dependent on the control algorithm of the IBR. The amount of reactive current and negative sequence current injected during faults by the IBR are possible to control. There are indications that distance protection has a significant number of misoperations in grids with a high penetration of IBRs.

The task

This master thesis compares the performance of three different protection schemes in a transmission grid with high penetration of IBRs. The protection schemes are distance protection, distance protection with pilot protection and line differential protection. This will be studied by running electromagnetic transient simulations in PSCAD. The hypothesis is that both line differential and pilot protection will clear all faults correctly.

Model/ measurements

A part of the power grid is studied in this project, this is illustrated in Figure 1. This includes three substations, two transmission lines, transformers and a wind power park. In this project the wind power park is modelled by an inverter with a constant DC voltage. This makes the results also applicable for other inverter-based resources, for example large photovoltaic power plants. The connection to the rest of the power grid is modelled by a Thevenin equivalent. R32, R23, R21 and R12 is the relays studied in this project.

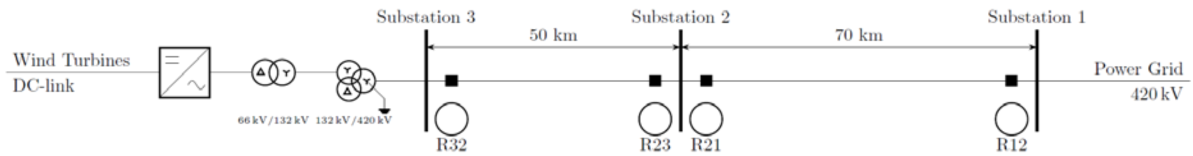


Figure 1: The part of the power grid modelled in this master thesis.

The PSCAD model built by L. T. Bremnes in 2022 for the master thesis *PSCAD Simulations of Distance Protection Performance in a Grid with high Wind Power Penetration* is used as basis for the modelling in this project. The wind park model used is developed by SINTEF.

The relay models were developed as a part of this project. The distance protection compares the measured fault impedance to the distance zones. The overreaching zone (zone 2) is time delayed by 300 ms. Pilot protection (POTT) utilizes communication between the relays at each end of the line. If both relays see the fault in zone 2, the relays trips the circuit breakers immediately. Line differential protection compares the fault current at both line ends. If the difference between the currents is above a threshold the relay sends a trip signal to both circuit breakers without delay.

The protection schemes are tested with different fault types, fault resistance, fault location, fault time and inverter control strategy, in total 1650 different test cases for each protection scheme. The main output from the simulation is the time from the fault to the relay sends a trip signal to the circuit breaker.

Calculation

To compare the protection schemes the trip times were categorized. Correct response if the protection relay complies with the main requirements of the Norwegian grid code: faults should be disconnected within 0.1 seconds and the relay should not trip for faults outside of the protected line. Longer trip time is when the relay trips after 0.1 s. No trip is relays that did not send a trip signal before the simulation ended. Unwanted trip is relays that tripped for faults outside of the protection zone. The results are presented in Figure 2.

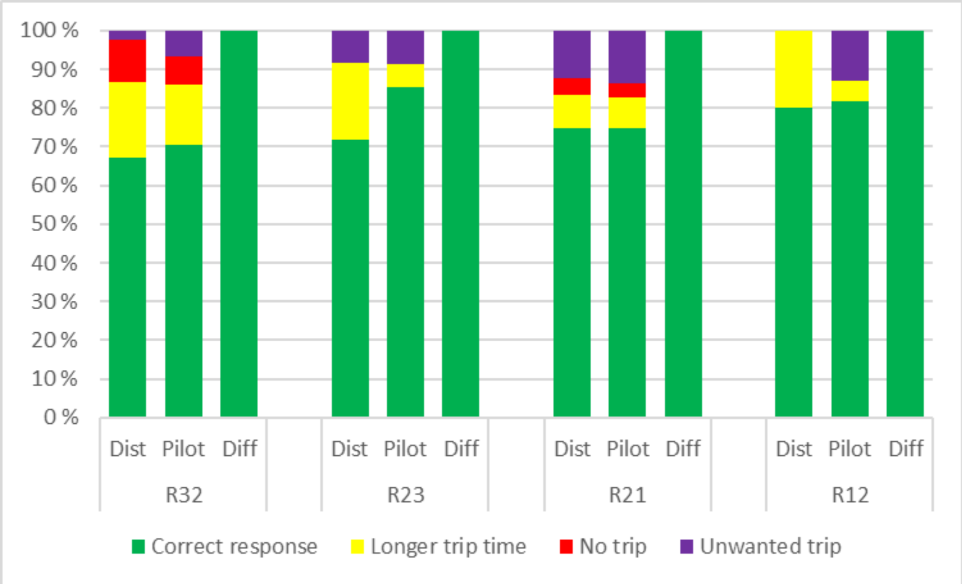


Figure 2: Results from the simulation

Conclusion

The hypothesis is partly correct. Line differential protection cleared all the faults correctly for the simulated cases. Distance protection with a pilot protection scheme is only slightly better than with the pilot protection for the simulated cases.

The SINTEF wind park model is not suited for symmetrical faults. When the inverter loses synchronism the frequency of the inverter voltage changes. This change causes the impedance measured by the distance to rotate making the results for three phase faults not reliable

In short circuit studies of power grid with high penetration of IBRs it may be necessary to model the loads. This project has proved that loads between the inverter and the fault have an impact on the results.

Development and Validation of the Nordic 45 Dynamic Simulation Model for Short-Term Frequency Stability Analysis

Student: **Eirik Stenshorne Sanden**
Supervisor: **Kjetil Obstfelder Uhlen**
Co-Supervisor: **Sigurd Hofsmo Jakobsen**
Collaboration with: **SINTEF Energy**

Problem description

Today's electrical power systems are experiencing rapid growth and escalating complexity, fueled by the global push for electrification and gradual phase-out of fossil fuels. This transition has led to a surge in electricity demand from households and industries alike. While transmission system operators maintain detailed models reflecting the responses of electrical power systems, these critical resources remain inaccessible to the public. This lack of transparency poses a barrier to scientific research aimed at enhancing grid infrastructure and efficiency.

The task

The aim of this thesis was to analyze and improve the ability of the Nordic 45, an aggregated electrical power system model of the Nordic synchronous area, to replicate the performance of the real electrical power system regarding power flows and frequency dynamics following a large disturbance.

Model/ measurements

This model was improved by comparing the response of the Nordic 45 model with frequency measurements from the real grid. Frequency data from three different cases were used for this comparison. The hydroelectric governors of the Nordic 45 were tuned to produce responses that closely matched those of the real grid cases. The tuning process was carried out using TOPS (Tiny Open Power System Simulator), and a script was developed to facilitate studies of the Nordic 45. This script integrates with the ENTSO-E Transparency Platform, allowing for easy changes of scenarios during studies.

Calculation

The water inertia time constant was increased from 1 second to 2.9 seconds. The Washout time constant was increased from 5 seconds to 5.6 seconds. The temporary droop was increased 0.5 p.u to 0.7 p.u.

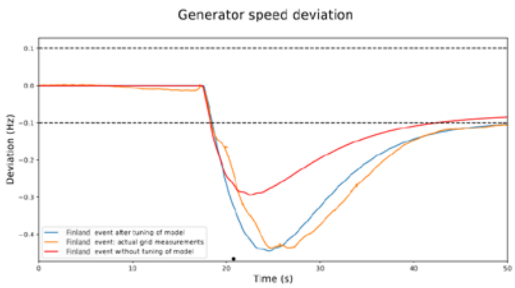


Figure 25: Comparison of simulation results prior to and after tuning. All plots represent the average generator speed of the system.

Conclusion

The model now gives significantly more accurate results when compared across all three cases. The water inertia time constant is unrealistically high, but it remains set at that value because the Nordic 45 lacks certain dynamics due to missing inertia time constants, which the water inertia compensates for.

Comparative analysis of the Swedish and Norwegian reserve markets:
Including a case study on the profitability of stationary batteries in business parks

Student: **Synne Aasvestad Sandvik**
Supervisor: **Steve Völler**
Co-supervisor: **Mette Kristine Kanestrøm**
Collaboration with: **Multiconsult**

Problem description

In Sweden, participation in some parts of the reserve market is better paid than in Norway. As a consequence of this, batteries have the potential to be a more profitable investment. The main objective of this master's is to investigate the differences between the Norwegian and Swedish reserve markets with the purpose of finding potential reasons for the price differences. The focus is mainly directed towards the primary reserves (FCR), but the remaining parts of the reserve market are investigated as well.

In addition to comparing the markets, a case study will be conducted to evaluate the difference in earning potential from participating with a battery in the FCR-N market with Swedish and Norwegian market prices. The case study is based on a battery placed in a business park which also has local energy production from PV panels. The potential that lies in utilizing business parks will also be investigated to some extent, with the main focus directed toward how they can contribute with flexibility services.

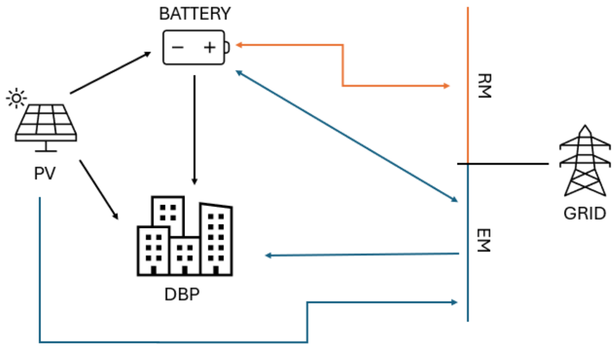
The task

Based on this, can the objective of the thesis be divided into three main parts:

1. Investigate the potential that lies in business parks, focusing on the possibility of implementing a battery and the services it can provide.
2. Map out the differences between the Norwegian and Swedish reserve markets and investigate potential causes for the observed price differences.
3. Conduct a case study investigating the difference in earning potential from partici pating in the FCR-N market with Norwegian and Swedish prices.

Model

To consider the economic potential of a battery in a BP, two different models are utilized.One model to optimize the battery size without considering participation in the reserve arkets, called Model 1, and another model to determine the earning potential of par ticipating in the FCR-N reserve market with a battery with a fixed size, called Model 2. These models will both be applied to the system presented in the figure below to conduct a case study.



Results
The two figures bellow show some of the most central results from the case study. Figure 6.8 shows the change in annual expences relative to a base case. Figure 6.10 shows the FCR-N procurement benefit for varius battery sizes, using both Swedish and Norwegian FCR-N prices.

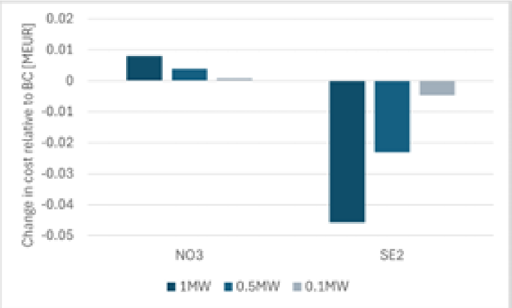


Figure 6.8: Expense reduction relative to the base case, including battery cost.

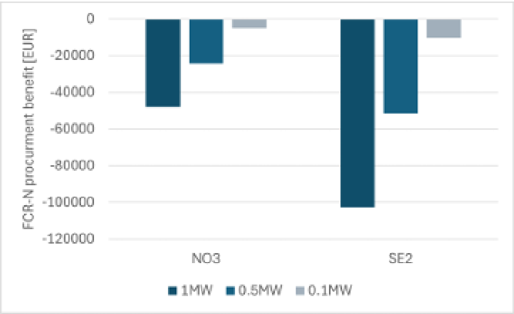


Figure 6.10: FCR-N procurement benefit.

Conclusion
There is an increasing need for flexibility in the Nordic synchronous area and it will therefore become more essential to better utilize the flexibility potential of the power system to ensure stability in the coming years. Business parks can be a central part of this, as there is a lot of unused potential in these areas.

Acomparative analysis has been conducted of the Norwegian and Swedish reserve markets to investigate potential causes for the higher prices of FFR and FCR in Sweden. The results showed that there are many factors that impact the reserve market prices and that there is no one clear reason for the price differences. Some key factors that impact the prices are the electricity price, reserve availability, reserve demand, the market structure and water level in the hydropower reservoirs.

The case study was split into two parts. In Case 1 a techno-economical analysis of the battery was conducted to determine the optimal size of the battery. The results showed that even with a significant reduction in battery prices, it would not be profitable to invest in a battery. Case 2 investigated the impact the difference in FCR-N prices has on the earning potential from reserve market participation. The results uncovered that based on the given input values, investing in a battery to participate in the FCR-N market would not be profitable based on the Norwegian price. However, with the Swedish FRN-N prices the battery was a profitable investment and a larger battery caused greater profit

Long-Term Hydropower Scheduling Using Scenario Reduction and Short-Term Inflow Prediction

Student: **Nicolay Sevang**
Supervisor: **Jayaprakash Rajasekharan**
Contact: **Jinghao Wang**

Problem description

The computation of water values, which is the marginal cost of water, in large hydro systems is a complex but necessary task. It is used to determine the optimal strategy of hydropower production with long horizons, called long-term hydropower scheduling (LTHS). LTHS is formulated as stochastic dynamic optimization problems (SDPs), typically with inflow as a stochastic parameter. Faster and more effective LTHS is necessary due to more variable renewable energy sources in the energy mix. However, including all technical details, such as a disaggregated representation of the hydro system, is computationally infeasible. Machine learning (ML) is therefore introduced to overcome the computational challenges of LTHS.

The task

This thesis involves expanding an existing model where ML was used as a framework for LTHS. SDPs struggle with "the curse of dimensionality", meaning that the complexity of the problem increases exponentially with the number of stochastic parameters. To deal with this, the model uses ML techniques to cluster inflow scenarios into groups, where scenarios within a group share the same features and characteristics. Instead of including all possible scenarios in LTHS, only the scenarios within a selected cluster are used, reducing computational complexity.

However, the existing model had some room for improvement. In this thesis, the model has been expanded to include an inflow prediction model using the ML technique of Long Short-Term Memory (LSTM). This expansion aims to make inflow predictions, and based on these predictions, select the most suited cluster of scenarios for LTHS. In addition, based on the predictions, the scenarios can be assigned individual probabilities, in contrast to previously assigned equal probabilities.

The research questions related to the thesis were oriented around the model performance when using the prediction model as a basis for cluster selection. In addition, the effect of assigning individual probabilities based on the predictions was investigated, and the model was tested against years with normal, low, and high inflow to evaluate the performance on years with abnormal inflow.

Model/ measurements

The entire model was implemented in Python, and a simplified model flowchart is presented in Figure 1.

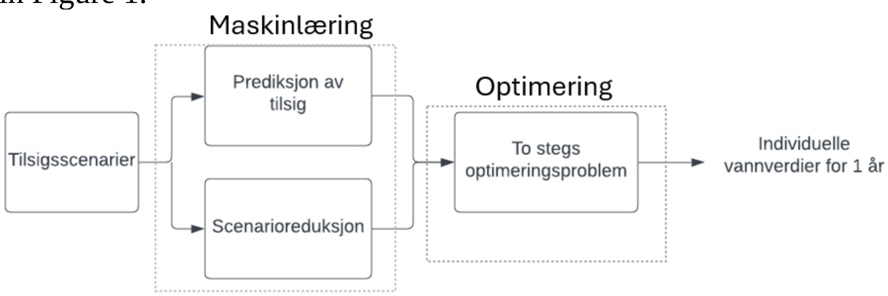


Figure 1: Model flowchart.

The model takes 20 weeks of inflow from a "true" inflow scenario, and then predicts the next 10 weeks. The cluster aligning best with the predictions is then selected as input for LTHS, and the scenarios are assigned individual probabilities. LTHS is done with a horizon of 52 weeks.
The scheduling results based on cluster selection were compared with those when only using the "true" scenario as input to LTHS, treating it as a deterministic problem. The evaluation was done by comparing water values and the optimal reservoir levels.

Calculation

The results showed that the computational time reduced significantly the computational time of LTHS, without worsening the scheduling accuracy.
The model performance was better for years with normal inflow than for years with abnormal inflow. Figure 2 shows the optimal reservoir levels when doing different predictions for a normal year, while Figure 3 shows the results for a year with low inflow.

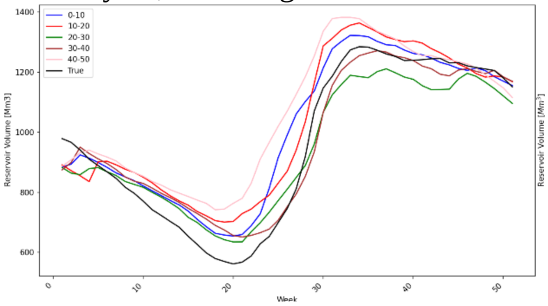


Figure 2: Normal inflow

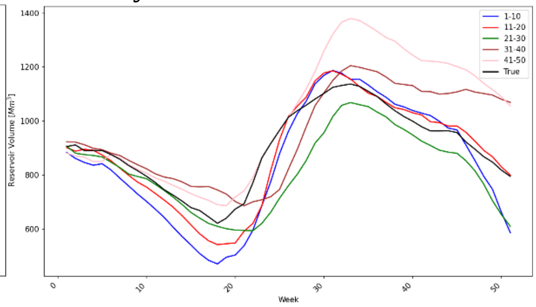


Figure 3: Low inflow

As the figures show, for the normal year there is a better alignment with the reservoir levels when only using the true inflow as input. The scheduling results are more variable for the low inflow case. The effect of assigning individual probabilities also varied. In some cases, the accuracy improved compared to assigning equal probabilities, and one of the cases is illustrated in Figure 4.

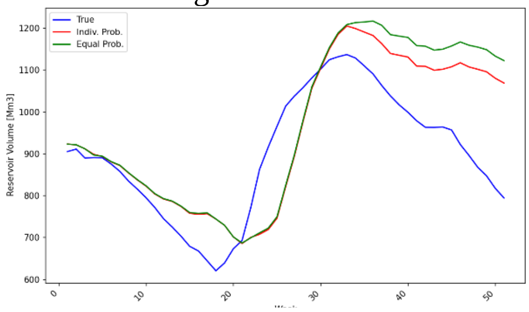


Figure 4: Comparison of individual and equal probabilities to the inflow scenarios.

Conclusion

It was concluded that the model shows the potential of combining a prediction model with the cluster model to create a framework for LTHS. However, due to some variations in the model accuracy, it was proposed that the prediction part should be investigated further for improvements and other methods for assigning individual probabilities.

Future Dutch Power System:
Synthetic Modeling and Stability Analysis

Student: **Sander Skogen**
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Collaboration with: **TU Delft (Dual Degree)**

Abstract
As the global shift towards renewable energy accelerates, it is crucial to address the inherent challenges and fully leverage its potential. Electric power systems have undergone significant transformations, transitioning from traditional generation methods to those incorporating renewable energy sources and power electronic interfaces (PEI). This transition necessitates extensive research to ensure future power system stability and reliability. This thesis work aimed to enhance a Root Mean Square (RMS) synthetic model of the future 380 kV Dutch power system and conducted comprehensive research using this model.

A scenario analysis was conducted to evaluate various future scenarios for the Dutch power system, highlighting deviations and uncertainties. The national scenario from the II3050-2 project was selected as the baseline for further work. This approach ensured a comprehensive understanding of potential future developments and their implications for policy and planning.

The synthetic model was developed by updating the existing model with new dynamic models and parameters as defined by IEEE and CIGRE standards and aligning it with future public projections and investment plans for the Dutch power system towards 2050, rooted in the scenario analysis. This included upgrading infrastructure such as transmission lines and substations and incorporating new generation and flexibility resources. The model was designed to enhance the dynamic characteristics and facilitate extensive research by integrating DigSilent PowerFactory, Python, and Excel.

Three different case studies were performed using the enhanced synthetic model to analyze the system's response to various perturbations. These studies evaluated the impact of varying levels of renewable generation and load, the role of grid-forming converters, and the effects of different kinetic energy and inertia constant levels on system stability with respect to frequency and rotor angle stability. The findings underscored the significant potential of grid-forming converters to enhance frequency stability and system damping, the influence of controller parameters on system performance, and the critical role of kinetic energy and inertia in maintaining system resilience.

By leveraging the capabilities of PowerFactory, Python, and Excel, the research demonstrated the utility of the enhanced synthetic model in facilitating a broad range of stability studies and other analyses. This work provides a valuable foundation for future research and regulatory planning, contributing to the ongoing efforts of Dr. J.L. Rueda Torres' team. The findings have been submitted to international journals and conferences, emphasizing the importance of continued technological adaptation and research to ensure stable and resilient power systems.

Future work should focus on developing smart control strategies, optimizing dynamic control settings, investigating the impacts of kinetic energy and inertia constants, enhancing the synthetic dynamic model with additional features, and assessing the role of flexibility resources in future scenarios. This research offers crucial insights into the evolving dynamics of power systems and sets the stage for further advancements to ensure their stability and resilience.

Assessing the Impact of Solar Power on Calculated Water Values in a Hybrid Hydro-Solar Power Plant

Student: **Benjamin Trondsen**
Student: **Oscar Martinius Steen**

Supervisor: **Gro Klæboe**
Co-supervisor: **Alexandra Jane Sheppard**

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Collaboration with: **NTNU**

Problem description

In Norway, hydropower is the main energy source and is used for flexible and renewable power production. With the growing electricity demand, an increasing amount of variable renewable energy sources (VRES), like wind- and solar power, are being incorporated into the energy mix. As such, the motivation for combining the hydropower plants with VRES into hybrid power plants arises. Efficient methods for combining these energy resources require solutions that optimize the allocation of resources. However, there is little research on how the inclusion of VRES impacts the value of stored water. In this thesis, a reference multi-reservoir hydropower plant located in Indre Fosen, Norway, was modeled as a hybrid power plant with floating photovoltaic (FPV) solar power added to the main reservoir. The impact of including or excluding FPV power from the valuation of the stored water in the reservoirs was then studied.

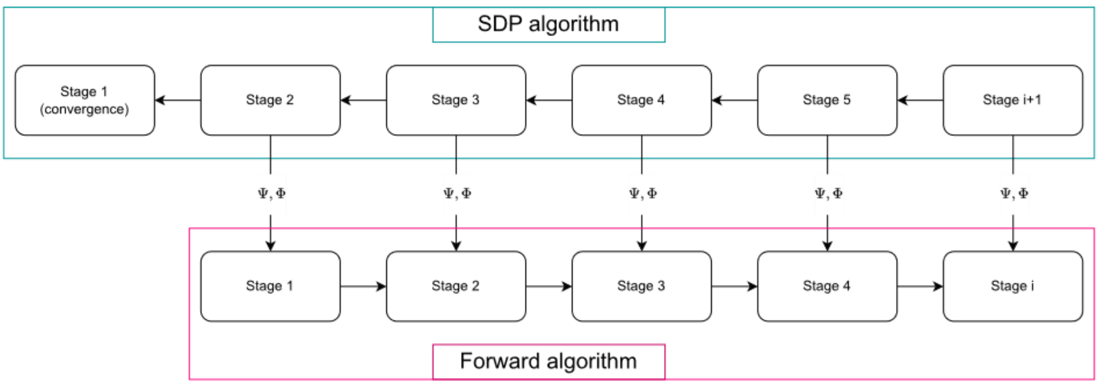
The task

The main research question of this thesis seeks to address the optimal scheduling of a hybrid FPV/hydro power plant and concerns the following:

- Should FPV generation be included when calculating water values for the medium-term scheduling of a hybrid FPV/hydro plant?

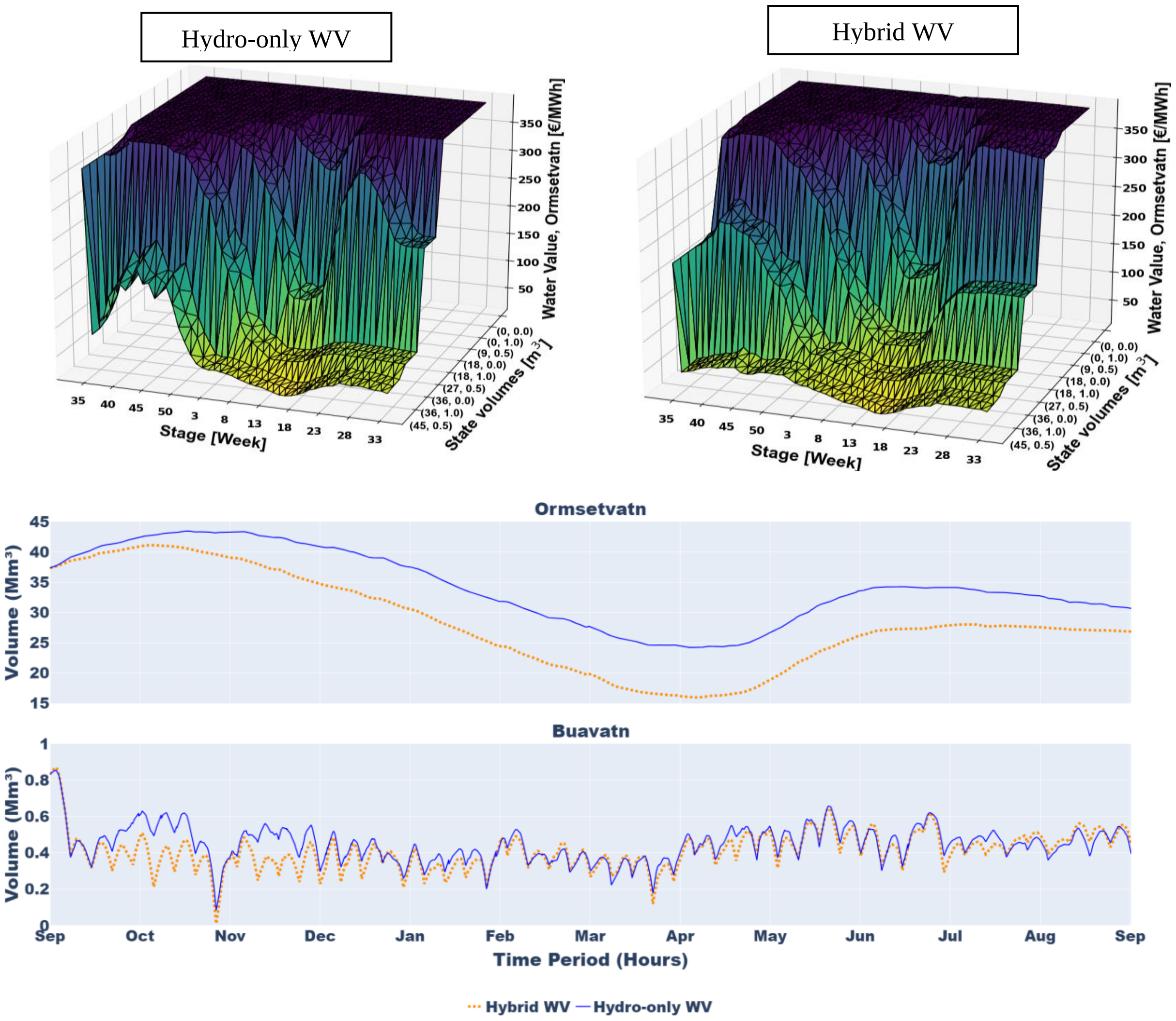
Model/ measurements

The stored water was evaluated using two medium-term Python models based on stochastic dynamic system. 30 years of weather data were obtained and included to represent stochasticity of inflow, solar power production, market prices, and load demand. The water values were fed as boundary conditions for a forward simulation to evaluate how production planning was affected by each water value calculation.



Calculation

Including FPV in water value calculation resulted in lower values for medium to high storage levels. The FPV inclusion was seen to have a cross-seasonal effect, where the water values were lowered even in seasons with no FPV generation. As a result, the production schedule could benefit from higher hydropower production, less rationing, and lower operational costs than when excluding the impact of FPV in the water values. The water values calculated without FPV power production caused a more conservative use of the stored water, which is more risk averse, but at the cost of higher rationing and a higher risk of spillage. The inclusion of FPV in calculated water values improved load coverage across all weather years analyzed, and the hybrid dispatch was most sensitive to water value calculations when it was reliant on resource or grid availability towards a load obligation. The results indicate that the inclusion of VRES should be carefully considered as it may affect price forecasting and production planning in hydropower-dominated systems.



Conclusion

In conclusion, FPV power should be included when calculating water values for medium-term scheduling of hybrid FPV/hydro plants while minimizing rationing costs and spillage. This conclusion specifically applies under the Nordic weather uncertainty, and for renewable hybrid systems that are relatively self-sufficient towards a load obligation. While VRES should be carefully considered in system-wide simulations or other hybrid systems outside the Nordics, further investigation is necessary to draw any firm conclusions.

Balancing the Breeze: Offshore Grid Connectivity and Demand Flexibility in Future Power systems

Student: **Steiro, Hanna**
Supervisor: **Korpås, Magnus**

Abstract
The European power system is transitioning into a zero-emission system, leading to significant changes in both consumption and generation. Electrification measures are increasing consumption levels, while the generation mix is shifting from conventional generators to VRES The rise of VRES complicates the task of maintaining a balance between consumption and production and increases flexibility requirements within the system. These shifts in the power sector alter the dynamics of the power market. To adequately address the demands of the evolving system, proactive actions must be made today.

OWP is central to the European Union's strategy for achieving climate targets, with an ambitious expansion target of reaching an OWP capacity of 300 GW by 2050. Similarly, Norway aims to allocate offshore areas corresponding to 30 GW by 2040. This new OWP capacity will require grid expansions, and the configuration of the offshore grid will significantly influence the efficiency of integrating this technology.

This master's thesis examines the impacts and challenges of Norway achieving an OWP capacity of 21 GW by 2040. It explores the effects of varying levels of demand flexibility in Norway and the implications for Norwegian offshore wind. Additionally, this thesis seeks to assess the effects of different grid configurations in the North Sea. The analysis is based on power market simulations of the European power system projected for 2040, using SINTEF's power market simulator EMPSW.

The case study investigates two scenarios for demand flexibility in Norway—one with 15.97% flexible demand and another with 29.19% flexibility. Furthermore, it analyzes three scenarios depicting distinct grid configurations in the North Sea. The study evaluates how increased connectivity and flexible demand influence electricity prices, net production, demand, power flow and economic surplus within the European power system in general, and in the Norwegian system in particular.

The simulation results revealed significant bottlenecks in the Norwegian grid, creating a low- and high-price area. This posed challenges for the power flow within Norway. The low-price area, with a high concentration of OWP capacity, experiences lower prices due to the merit order effect and congestion, while the high-price area faces power deficits, leading to price peaks. Current transfer capacities are inadequate to balance power distribution effectively, suggesting that enhancing transfer capacities or strategically relocating OWP capacity could mitigate these disparities and lead to more uniform pricing across Norway.

Increased demand flexibility was found to lower electricity prices and reduce price volatility in the high-price area, where peak spring prices decreased by an average of 130 euro/MWh. This reduction was achieved through the use of more cost-effective demand flexibility options with lower activation prices. The study also noted that less than 5% of flexible demand capacity is activated throughout the year, but it is nearly maximized during peak price

periods. The low utilization rates for demand flexibility sources could make investment in these technologies less profitable.

The grid scenarios revealed that increasing connectivity in the NSR through meshed grids enhances the distribution of OWP and reduces curtailment. However, the economic benefits of increased transfer capacities are marginal despite the high costs of grid extensions. Nevertheless, improved connectivity offers non-economic advantages such as enhanced supply security and sustainability.

Finally, this thesis's findings are subject to uncertainties concerning future developments, and particularly regarding gas prices, demand distribution, and generation capacities. Simplifications in the modeling of gas prices, consumer distribution, and marginal costs for generators and consumers introduce potential inaccuracies. Additionally, the EMPSW model's approximation approach may limit the precision of results, especially in regions with high shares of hydropower.

Cost-Optimal Renewable Energy System for an Industrial Area

Students: **Marie Sølvik**
Hanna Teige
Supervisor: **Karen Byskov Lindberg**
Contact: **Gaute Riise Engen**
Collaboration with: **Aneo**

Problem description

Land-based industries in Norway rank as the third largest source of greenhouse gas emissions and have significant energy consumption. According to recent nationwide recommendations from the Norwegian government, this sector has substantial potential for energy savings. These recommendations advocate for decarbonizing industrial processes and implementing enhanced energy efficiency measures

The task

This thesis contains a techno-economic study on the industrial area of Valsneset in Trøndelag, with a specific focus on a fish feed factory operated by salmon producer Mowi. The factory has a combined thermal and electric energy demand of over 70 GWh annually. The thermal energy demand is currently met through natural gas. A nearby wind power plant supplies electricity to the factory, as well as depending on grid import.

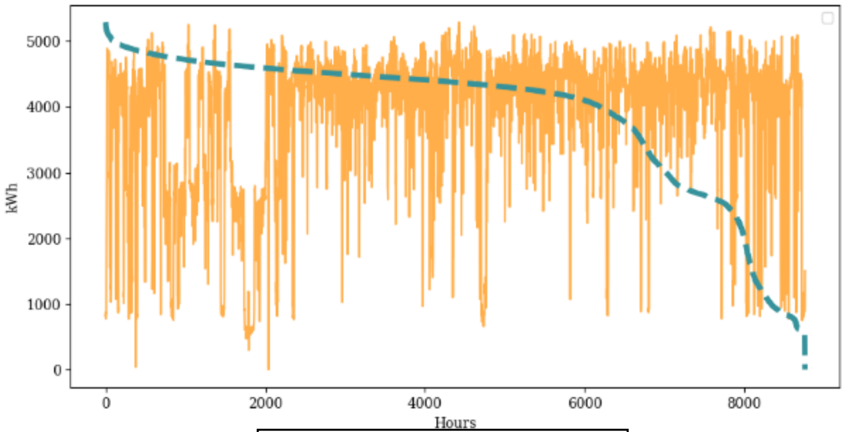


Figure 1: 2022 electricity demand with belonging load duration curve

Model/ measurements

The energy situation at Valsneset is assessed using an optimization model in the form of a deterministic mixed integer linear program (MILP). The model accounts for annualized investment costs of new technologies and energy costs. The analyzed period includes one year of operation.

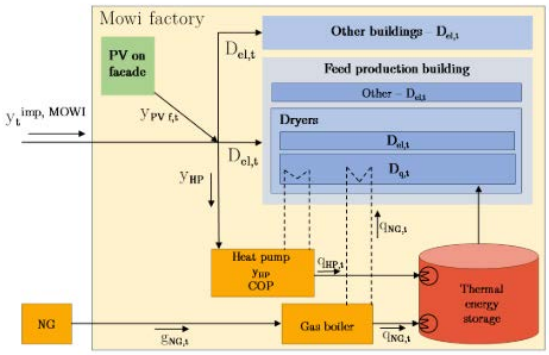


Figure 2: Proposed system to accommodate heat

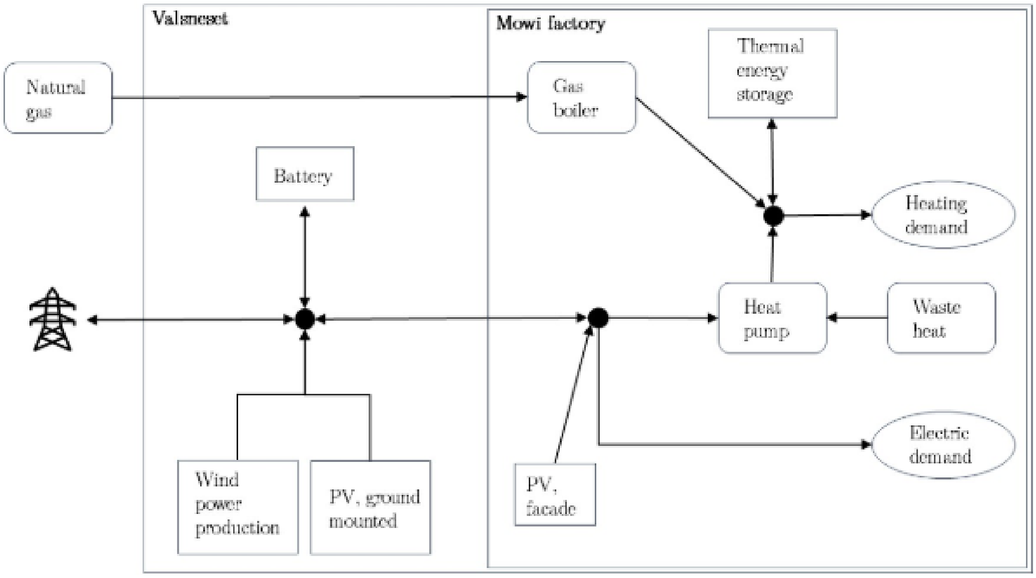


Figure 3: Overall proposed system

Calculation and conclusion

The model results showed substantial cost savings by investing in heat pump technology to accommodate the heat demand to serve the base load, while utilizing the existing natural gas boilers to serve the peak load in hours where the spot price is high. Additional wind power investment was favorable under nearly all conditions, while PV investments were generally not considered as part of a cost-optimal solution. An electric battery was not part of the cost-optimal system composition under any conditions.

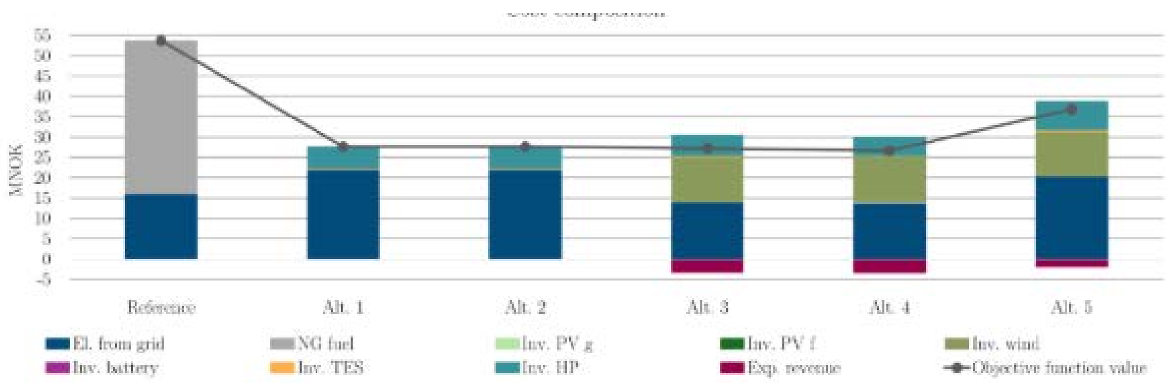


Figure 4: Investment costs across different alternatives

Efficient and More Sustainable Operation of Voltage Source Converters in Offshore Power Systems through Multimode Operation

Student: **Muhammad Umer**
Supervisor: **Prof. Elisabetta Tedeschi & Arkaitz Rabanal (PhD Candidate)**
Contact: **mumeratwork@gmail.com**
Collaboration with: **Aker Solution**

Problem description

The efficient and sustainable operation of offshore oil and gas platforms presents a significant challenge due to their reliance on power generation systems that primarily use gas turbines and diesel generators. These systems are not only inefficient but also contribute substantially to greenhouse gas emissions. To address the growing need for sustainable energy solutions and to meet Norway's ambitious greenhouse gas reduction targets, the integration of renewable energy sources with offshore platforms has become essential. One of the promising technologies in this regard is the use of Voltage Source Converters (VSCs) in back-to-back High Voltage Direct Current (HVDC) fashion. VSCs offer enhanced control over voltage, power, and frequency, making them crucial for stable and flexible power transmission between offshore platforms and onshore grids/DRES. This thesis aims to develop control systems for VSCs operating in both grid-following (GFL) and grid-forming (GFM) modes, ensuring seamless mode switching from GFL to GFM and vice versa.

The task

The primary task of this thesis is on developing control strategies for both grid-following (GFL) and grid-forming (GFM) operation modes, as well as ensuring seamless switching between these operating modes. This involves:

1. Designing a Phase Locked Loop (PLL) based GFL system for VSCs to regulate power flow and ensure a reliable energy supply to offshore installations.
2. Developing a matching control-based GFM system to enable seamless performance in island operation or when connected to a weak grid.
3. Analyzing and testing the proposed control systems using a reference test case provided by Aker Solutions, based on an ongoing project in the North Sea, using MATLAB/Simulink.

Model

This thesis includes the development and analysis of a reference test case provided by Aker Solutions. This test case features a power system configuration with two offshore platforms generating electricity at different frequencies, interconnected through a back-to-back HVDC system to an onshore grid. This power system is shown in Fig 1.

The performance of the control systems is critically assessed using time-domain simulations in MATLAB/Simulink. Various operating conditions, such as grid-following, grid-forming, and mode switching, are simulated to evaluate the effectiveness of the proposed control strategies.

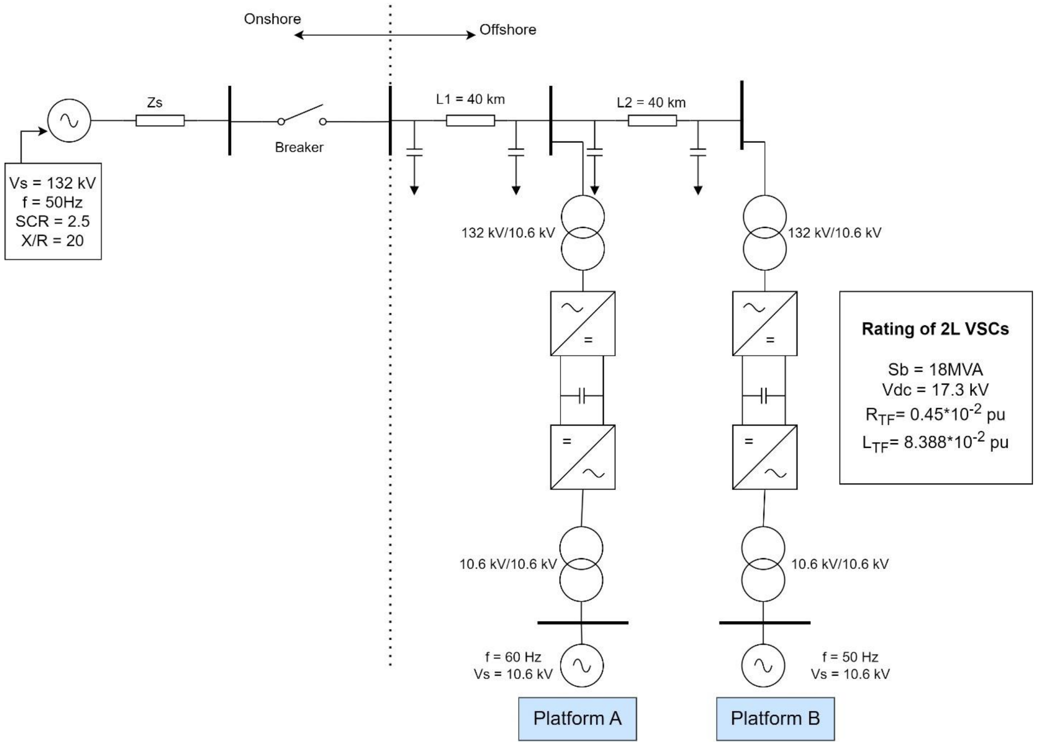


Figure 1: Single line diagram of power system under study

Analysis / Calculation

- **Frequency and Voltage Regulation**: The control systems' ability to maintain stable frequency and voltage levels under different operating conditions (GFL & GFM) is measured.
- **Power Flow Control**: The effectiveness of the PLL-based GFL system in regulating active power flow is assessed.
- **Transient Effects**: Strategies to mitigate transient effects during mode switching are analyzed.

Conclusion

This thesis successfully demonstrates the design and implementation of control systems for Voltage Source Converters (VSCs) in offshore power systems. Through extensive simulations, the study proves the efficacy of both grid-following (GFL) and grid-forming (GFM) control strategies in managing power flow and maintaining system stability. The PLL-based GFL system effectively regulates voltage and synchronizes with the grid, while the matching control-based GFM system ensures stable frequency and voltage in island operation. Seamless mode switching between GFL and GFM modes enhances operational flexibility and reliability. The findings indicate that these control strategies significantly improve the efficiency and sustainability of offshore power systems, facilitating the integration of renewable energy sources into offshore platforms.

Control and Protection of Dual-Winding PM Machines for a Gearless Marine Propulsion

Student: **Yulia Vagapova**
Supervisor: **Roy Nilsen**
Co-supervisor: **Raghbendra Tiwari**
Collaboration with: **Wärtsilä Norway AS**

Problem description

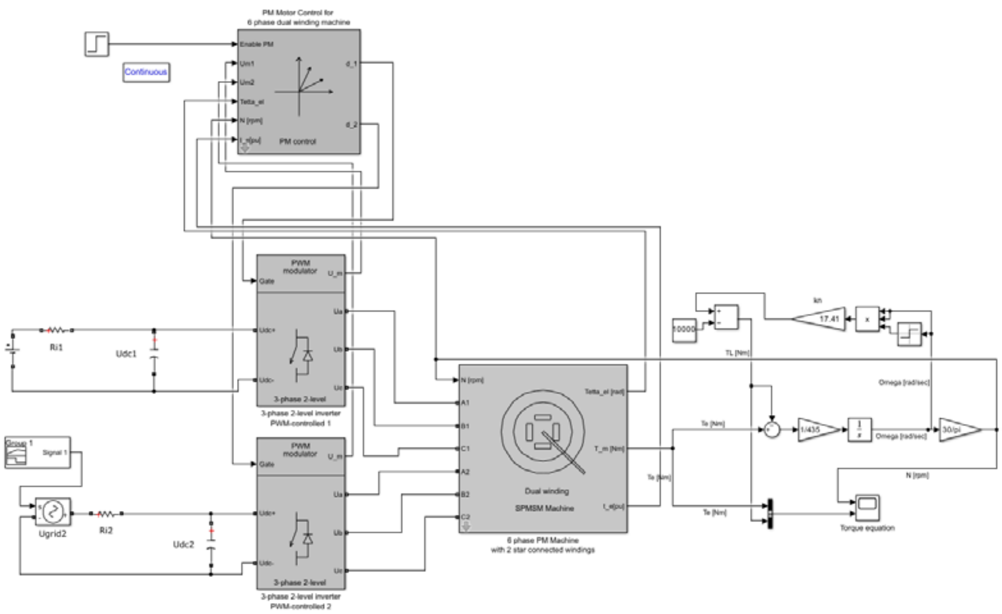
In many cases, gearless propulsion systems are inevitable in marine applications. For large power requirements, dual-winding PM machines are preferred. In this project, the student will focus on studying the control of PM machines under faulty conditions. The example cases could be single-phase to ground, phase-to-phase, and three-phase faults on one set of winding. The study will also investigate how the system can be protected by controlling the inverter feeding the healthy set of windings. Simulation tools like MATLAB Simulink will be used to model the system and study the dynamic behaviour. In marine applications, even though the inverter supply is disconnected during fault, the propeller keeps on rotating at its wind-milling speed and feeds the fault. Methods to apply braking torque to stop the machine will be studied.

The task

The tasks in the thesis include modelling and control of the six – phase permanent magnet synchronous machine (PMSM) and investigate inverter control during faults like - single phase and double-phase open circuit fault, single phase-to-ground, phase-to-phase, three-phase short circuit faults.

Model

A MATLAB Simulink model of a six phase PMSM was provided by Prof. Roy Nilsen and extended further to include fault cases and braking implementation. Inner and outer controllers were tuned using modulus optimum and symmetrical optimum to achieve satisfactory controllers response.



Results

The open circuit faults and phase-to-ground short circuit faults were found to be non-critical, where the faulty inverter should be shut down. The three phase and phase-to-phase short circuit cases required braking. The worst fault instant for the motor was found to be at an angle of 0 for both three phase and phase-to-phase short circuit faults. The worst current for the healthy inverter occurred at another point due to the phase shift between the two three phase groups. The current peak was also larger than 2 p.u, which was the chosen trip threshold. The peak was controlled by retuning current controller constants. The results showed that the peak could be decreased with faster controller. The braking showed that the desired speed was reached in 0.87s for three phase fault by applying maximum braking current of -1.5 p.u. The speed was reached in 0.63s for phase-to-phase fault by applying braking current of -1.2 p.u, shown in Figure 1. The healthy inverter currents were then below 2 p.u during braking, shown in Figure 2. Applying maximum braking current led to healthy inverter currents larger than 1.5 p.u, which is why braking with less current was tested.

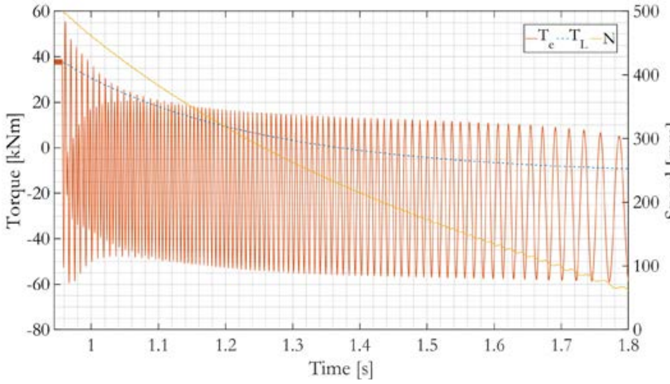


Figure 1: Torque and speed. Braking with $i_{q,ref2}$ = -1.2 p.u, phase-to-phase short circuit fault.

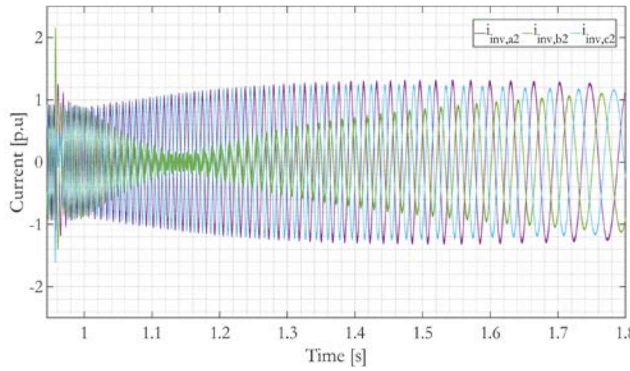


Figure 2: Currents of healthy inverter. Braking with $i_{q,ref2}$ = -1.2 p.u, phase-to-phase short circuit fault.

The available braking torque in this case was calculated to be $0.28+0.92i_{q2}$, while for the three phase case it was $0.63+0.92i_{q2}$. More braking current was needed in the three phase fault case due to larger demagnetising currents.

Conclusion

Open circuit faults and phase-to-ground fault were not critical for further operation. The worst fault cases, such as three phase and phase-to-phase short circuit faults were investigated in detail, where braking torque was applied with the healthy inverter. It was found that the worst fault for the healthy inverter occurred at the worst fault instant for the faulty motor with the according phase shift between the two three-phase groups. The current controllers were found to be slow, and faster controllers would be required to control the peak current of the healthy inverter. The available braking torque was limited by the mutual reactances. The braking current should be lower than the maximum to account for braking chopper limitations. $i_{q,ref2}$ = -1.2 p.u was found to be sufficient in braking in the phase-to-phase fault. The simulations should be tested with different machine data, preferably a larger machine.

Scheduling for Electric Water Heaters for Potential Participation in the Balancing Markets

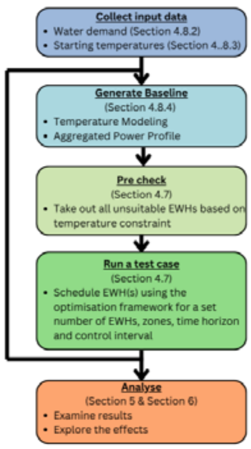
Students: **Anna Widzisz and Seline Tovslid Vagle**
Supervisor: **Jayaprakash Rajasekharan**
Co-supervisor: **Surya Venkatesh Pandiyan**

Problem description

Due to global warming and the ongoing energy transition where more renewable energy is integrated in the power system, there is a call for new sustainable methods to ensure grid stability. Through aggregation of flexible resources, it is possible to provide a significant amount of flexibility. Utilising the flexibility and participating in the balancing markets, help mitigate the challenges stemming from the intermittency of wind and solar power.

The task

The thesis aims to create a schedule for aggregated EWHs using an optimisation framework. The goal is to maximise flexibility for a number of EWHs and examine the effect of various factors on the simulation time and extracted flexibility. Firstly, a simple temperature model for an EWH was developed and implemented in the optimisation framework. Several simplifications were applied to reduce computational complexity. The water demand data, originally stochastic, was made deterministic based on a probabilistic model.



Methodology

The methodology for obtaining the schedule is divided into five steps. Firstly, input data is collected, including water demand and starting temperatures for the specific EWHs. Following, baselines for both the temperature and the aggregated power profile are generated. This is important as the flexibility from the EWHs is measured as down-regulation. Prior to running the optimisation framework, a pre-check is done. EWHs unsuitable to provide flexibility are removed based on a temperature constraint. The test cases are run varying the different factors, such as number of EWHs, zones, time horizon and control interval. Finally, the results are examined based on simulation time and amount of flexibility extracted.

Results

The results demonstrate how various factors in the optimisation framework impact both the extracted flexibility and the simulation time. Among the tested EWH temperature models, a 6-zone model balances simulation accuracy and time effectively compared to 3-zone and 9-zone models. However, for simplicity and reduced computational load, the 3-zone model may be preferable. A 3-hour time horizon is ideal for optimising EWH control strategies, striking a balance between simulation time and flexibility. Shorter control intervals, such as 5-minute versus 10 or 15 minutes, offer finer control resolution but increase computational demands substantially. Implementing optimisation for individual EWHs or through collective aggregation via minimum bid size presents significant computational challenges. Test cases examining minimum comfort temperatures and water demand patterns provide insights valuable to potential commercial aggregators. Maximising flexibility correlates with average water demand over high or low demand scenarios. Additionally, collaboration between aggregators and customers to reduce minimum comfort temperatures could enhance revenue opportunities for both parties.

Conclusion

There is progress to be made for EWH aggregators to participate in the market. However, the results show that there are simplifications to alter the optimisation framework to be more efficient. Additionally, improvements to the optimisation framework are necessary. Together with changes in market requirements and regulatory aspects, EWHs have potential for market participation.

Multimarket Services for an Electic Vehicle - Considering Activation of Frequency Containment Normal Operation Reserves

Student: **Valle, Astrid Elise**
Supervisor: **Korpås, Magnus**

Abstract
In order to reduce green house gas emissions, significant investments in renewable energy sources are made. Renewable energy generation poses challenges to maintaining equilibrium between electric power generation and demand. The demand of flexible resources that can contribute to the power balance are therefore in high demand. This thesis studies an Electric Vehicle as a part of a home energy management system, to investigate the potential of the electric vehicles serving as an flexible resource through participation in the FCR market. A optimization model of the home energy management system is defined with the objective of minimizing total energy cost. The model includes both the day-ahead market and the FCR-N market. The results show that a multi-market participation has positive impact on the modelled objective.

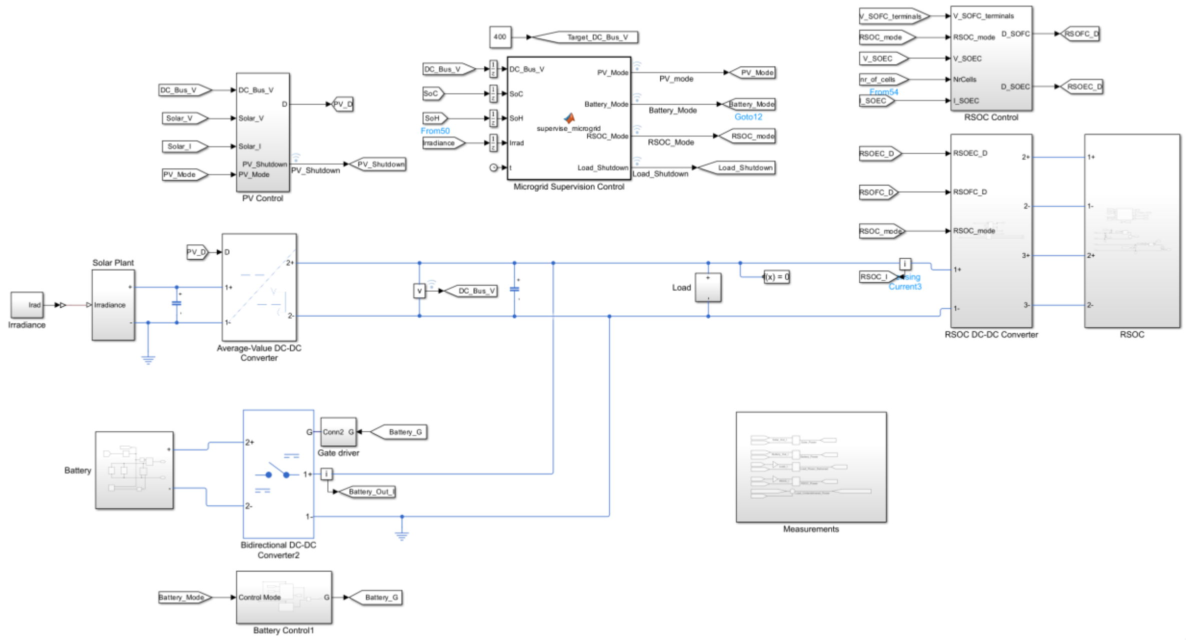
Dynamic Optimization of Microgrid with Reversible Fuel Cell and Lithium Ion Battery

Student: **Juri Volodin**
Supervisor: **Olimpo Anaya-Lara**
Contact: **juri.volodin@gmail.com**
Collaboration with: **TU Delft**

Problem Description The current challenge in the field of energy management is the integration of various energy storage components with different energy and power densities into a microgrid system. Specifically, the high energy density of lithium-ion batteries and the extensive storage capacity of reversible solid oxide fuel cells (RSOCs) need to be harmonized to enhance microgrid performance, address renewable energy variability, and manage demand fluctuations. This integration is crucial for decentralized generation systems, offering needed capacity and flexibility.

The Task This master's thesis aimed to investigate the theoretical development and dynamic modeling of an integrated microgrid system using MATLAB/Simulink. The microgrid consists of solar panels, lithium-ion batteries, RSOCs, and a DC load. The goal was to create an advanced system for improved energy management and grid stability, ensuring applicability in diverse locations and varying economic conditions.

Model/Measurements The dynamic model of the microgrid was developed using MATLAB/Simulink, focusing on the integration of RSOCs and lithium-ion batteries. The thesis included a case study at Kaya Imani Resort in Msambweni, Kenya, to develop and simulate innovative microgrid solutions. The initial step involved generating and analyzing the resort's load profile using RAMP, a Python library designed for creating detailed multi-energy load profiles. This analysis identified the specific energy requirements and electrical load patterns of the resort, which were essential for the precise sizing of the microgrid.



1 Scheme of the microgrid model

Calculation The research involved simulating the microgrid's dynamics, specifically focusing on the incorporation of RSOCs in combination with lithium-ion batteries. The simulations demonstrated the effectiveness of a rule-based control approach for managing the microgrid configuration, even with the relatively low storage capacity of batteries and the low power capacity of RSOCs.

Conclusion The thesis successfully developed a dynamic model of an integrated microgrid using RSOCs and lithium-ion batteries, showcasing the potential for stable and efficient energy management. The study highlights the innovative combination of these technologies and encourages further exploration into optimal control strategies for such configurations, demonstrating their applicability in diverse environments and economic conditions.

Study on electromagnetic fields (EMFs) from submarine power cables in offshore wind farms

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Problem description

Offshore wind is recognised as one of the most promising technologies to enhance the widespread integration of clean energy. Consequently, the offshore wind industry is in huge development and is considered one of the cornerstones in the energy transition. The development is related to both the standard size of the wind turbine generator (WTG) structures and the sheer number of offshore wind farms (OWFs) in total. Additionally, the OWFs are being placed further away from shore and at deeper sea levels due to the technological progress and advancements within the field. As a consequence of larger OWFs located further from shore, requirements on the electrical collection and transmission system are increasing accordingly. This trend in the power system is also leading to larger bulks of power being transported in sub-sea power cables along the seabed. These submarine cables emit electromagnetic fields (EMFs) when energised, which become a part of the local EMF environment, as presented in Figure 1. Several marine species are known to use the Earth's geomagnetic field for many important tasks like migrating and movement. When subject to adjacent EMFs from sub-sea transmission or collection cables, these important tasks may be disturbed and various marine species that are sensitive to EMFs may be heavily affected by this. With a highly anticipated increase in offshore installations such as wind power the anthropogenic sources of EMFs and their impact on the marine species become a major factor in the assessment of the environmental impacts during licensing processes for OWFs.

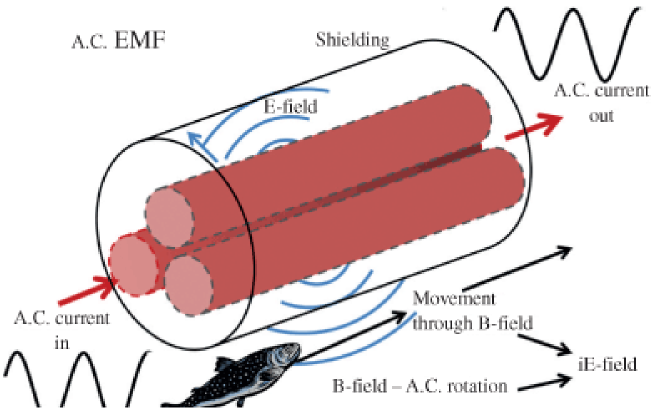

Figure 1: EMFs from AC subsea cables into the marine environment [1].

The task

Building on the challenges related to increased anthropogenic influence in the marine environment, and the uncertainties related to EMFs and their impacts on marine species, the overall purpose of the master's thesis is to quantify the EMF emissions in the marine environments caused by offshore wind farms, to support environmental impacts assessment. The local EMFs around an energised submarine power cable will be estimated utilizing numerical analytical tools to predict the behaviour of the fields in various operation conditions.

Model/ measurements

The modelling was completed by using the finite element modelling (FEM) approach through COMSOL Multiphysics and co-simulation with MATLAB/Simulink. First, a three-phase inter-array cable was modelled in the COMSOL environment, based on the project-specific characteristics. Physics interfaces were applied along with material properties to solve the cable model for electric currents and magnetic field physics, in frequency-dependent and stationary studies. The COMSOL application was then coupled with a MATLAB/Simulink environment in the form of co-simulation. The rationale behind this co-simulation strategy is rooted in the complementary strengths of both programming platforms. By amalgamating the physics-based modelling capabilities inherent in COMSOL with the dynamic system simulation features of Simulink, the goal was to analyse the EMFs under various operational conditions.

Calculation

The results reveal some overall interesting remarks in terms of EMFs produced by cables in offshore environments. First and foremost, the most essential part that continuously is proven throughout the variety of results, is the imminent relation between the current in the cable and the EMF intensities. Illustrations from COMSOL in Figure 2 and Simulink in Figure 3 are given below for reference.

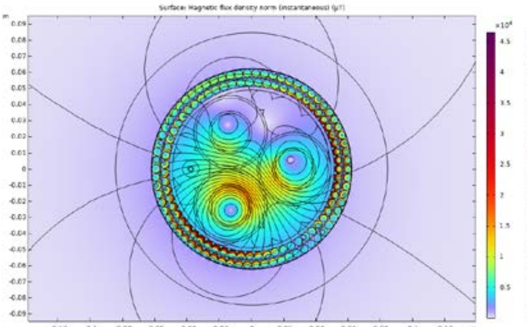

Figure 2: Magnetic flux density from the cable in COMSOL Multiphysics.

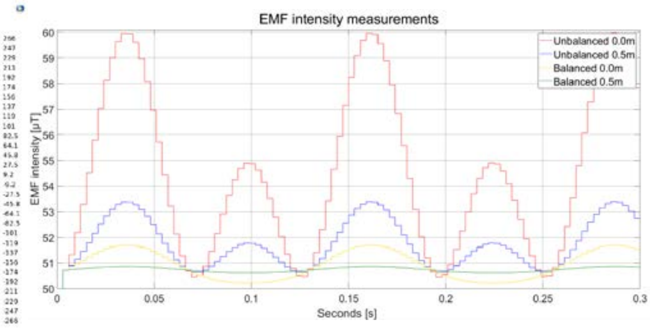

Figure 3: EMF intensity measurements form a case where the phases were unbalanced.

1. The short-term and daily variations in wind speed led to large variations in current and EMF intensities
2. Power quality issues like harmonics and phase unbalance can lead to higher EMF emissions around the cable
3. For strings of cables the EMFs are more severe due to larger amplitudes of current.
4. For cables placed very close to each other there can be cancelling or resonating effects in terms of EMF emissions.

Conclusion

The master's thesis has utilized the complex integration of co-simulation between two excellent software to model the intricate details of EMFs from subsea cables under various operational conditions. For the larger picture, the results of the thesis prove that EMF emissions from inter-array power cables persist in the local marine environment. The magnetic field around the cable is in the scope of a few tens of micro-Tesla, which is in a range that some marine species can perceive. The important part of the marine management decision is to analyse whether the thresholds that the cables emit EMFs in are in damaging areas in relation to what these species react/behave to.

[1] A. B. Gill, M. Bartlett and F. Thomsen, 'Potential interactions between diadromous fishes of u.k. conservation importance and the electromagnetic fields and subsea noise from marine renewable energy developments' available: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1095-8649.2012.03374.x.

An Experimental Approach on Early Fault Detection in Permanent Magnet Synchronous Machines Utilizing the Stray Magnetic Flux

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Contact: **Hossein Ehya**

Problem description

Permanent magnet synchronous machines (PMSMs) have become an important part in both industrial applications and in transportation. These machines are robust and reliable but can also be subject to mechanical or electrical faults. Health monitoring and fault detection, especially in an early stage, is therefore important to prevent long and expensive down-time and to minimize the risk of having a total machine failure. Several different fault detection methods are developed, both invasive and non-invasive, including motor current signal analysis (MCSA), noise and vibration monitoring, heat signature analysis and air-gap magnetic field monitoring. This thesis aims to investigate the stray magnetic field fault signatures under a dynamic eccentricity (DE) fault and a stator inter-turn short circuit (ITSC) fault using external coil sensors.

Conclusion

This master's thesis has been withheld from publishing for 3 years after submission. Therefore no further abstract is available.

A Case Study of the Effects of Small Modular Nuclear Reactors on the Norwegian Power Grid, Utilizing the Nordic490 Model

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Abstract
This master's thesis explores the effects of small modular nuclear reactors (SMRs) on the Norwegian power system, seen from a power system perspective. The thesis examines the potential of SMRs to meet Norway's growing power demands, and simultaneously alleviate the strain on the power grid, through a case study. The case study examines different SMR deployment strategies, both a distributed and centralized strategy, and compares their power grid impacts to other comparable future production alternatives, such as offshore wind and power importation. The main scope of the study have been power flow analysis, investigating transmission line loading and voltage drop outcomes between the different cases. A basic economic assessment have also been conducted in order to contextualise the results.

The case study have utilized the Nordic490 Model, an open source power system model of the Nordic power grid, and the PyPower power flow solver. As part of the work, the Norwegian grid have been separated out from the model, and future grid development plans have been implemented. Alternate Current Power Flow have also been implemented and used for the power flow simulations.

Two peak power demand load scenarios have been created and analysed, one for the 2030s and one for the 2040s. In total 7 production cases have been created, each of the production cases have been analysed in combination with both load scenarios. These cases are: a load benchmark case, a distributed SMR case, three centralised SMR cases, and two comparison cases, being an offshore wind case and a power importation case.

The results of the case study indicate that SMRs have the potential to meet future Norwegian power demands with a low strain on the power grid. The case with a distributed SMR deployment strategy, with SMRs close to new major loads, experiences the best result outcome among the investigated cases. The centralized SMR deployment cases, which explore different optimal locations for a large scale SMR production cluster, also experience good result outcomes. Especially for the 2030 scenario, these cases all experience better results than the comparison cases. However for the 2040 scenario, the outcome of the different cases equalises more, and the comparison cases see results on par with the SMR cluster cases.

Implementation of Methods for Generation Adequacy Assessment with Wind Considerations

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Abstract

This thesis creates open-source Python scripts for conducting generation adequacy analysis studies (available on https://github.com/Julian-Wuijts/Generation-Adequacy-Scripts). First, scripts without wind considerations are constructed, and then the scripts have been modified to include wind considerations. Generation and load models have been implemented to obtain the reliability (adequacy) indices Loss of Load Expectation (LOLE) and Expected Energy Not Served (EENS). Two probabilistic methods have been implemented: an analytical method and a non-sequential Monte Carlo Simulation (MCS) method. Both methods use the IEEE load curve for their load model, but different generation models are used. The analytical model uses a recursive algorithm, where generation units are added one by one to obtain a Capacity Outage Probability Table (COPT). The non-sequential MCS method uses state sampling, where a uniform random number is generated for each hourly increment and a state is selected based on the state probabilities of a generator.

Wind considerations, which can be any number of turbines located on- or offshore, have been added to the scripts by modelling the power output curve of a wind turbine. The analytical method models a wind turbine as a conventional generation with multiple states, where a state probability table is based on the wind power distribution and the mechanical availability. The power distribution is obtained by converting wind speeds to power outputs using the power output curve. The MCS method, on the other hand, simulates the wind speed with a Weibull distribution and a uniform random number generator. It also uses the power output curve, and the result is combined with the mechanical availability.

The proposed scripts have been tested on two test systems - the Roy Billinton Test System and the IEEE Reliability Test System. The resulting reliability metrics have been compared with benchmark values in the literature and found to be closely matching. Furthermore, methodological clarity on how to obtain the presented scripts is given. Even though all elements of the implemented methods are present in the literature, not all are clearly explained or combined in one place. This work aims to overcome this limitation.

Additionally, the effect of turbine outage rates on the output of an offshore wind farm has been assessed. The cumulative distribution showed that the portion of the graph operating between no output and the rated output is close to linear for turbines with perfect reliability. Introducing non-zero Forced Outage Rates for the turbines results in a stepwise probability behaviour towards the upper end of the wind farm output. These steps occur around increments of the rated capacity of a singular turbine and lower the probability of operating in the intervals at the upper end of the wind farm.

An approximately linear relation between a turbine's Forced Outage Rate (FOR) and the yearly energy production can be observed. An increase in FOR, for FORs above 0.10, seems to have an increasingly bigger impact on the yearly energy production. The same behaviour can be observed in the case study that is carried out. The study looks at how many turbines are required to supply energy to the city of Trondheim, assuming that a storage solution takes care of all the power fluctuations. A constant power demand of 688 MW can be covered by a 1.43 GW wind farm with perfect reliability. The farm uses 10 MW turbines, and 3 additional turbines are needed for a 0.02 increase in FOR. From a FOR of 0.10, this value seems to increase to 4 turbines to satisfy the demand.

The results for the non-sequential MCS method with wind considerations are off by up to 15% due to a poorly fitting Weibull distribution for the wind speeds. Furthermore, a third probabilistic method has also been implemented, a sequential MCS without wind considerations in the form of the state duration method. These results are off by 5 to 10%, but there are two main reasons for this mismatch. One of them is rounding the simulated state duration to an integer number of hours to match the integer hourly load profile. The second limitation is due to the way that the generation profile is initialised. The generator is currently assumed to be operational at the start of each simulation year. However, carrying over the state and state duration from the previous simulation year would yield better results. These two limitations can be addressed in future work