Masteroppgaver 2023

NTNU
Norges teknisk-naturvitenskapelige universitet
Fakultet for informasjonsteknologi og elektroteknikk

Summary of Master's Theses 2023

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 2023

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 2023 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

KANDIDAT	VEILEDER	TITTEL	SIDE
Abdul-Azeez, Sadiq Abba	Elisabetta Tedeschi	Hybrid BESS/STATCOM for Improved Power Quality on Oil & Gas Platforms	1
Aljahaf, Mohammed Abdulkadir Younas	Hans Kristian Høidalen	Study of rail potential and earth current for the BTRC and AT systems	3
Anfinnsen, Erlend Nilsen	Ümit Cali	Quantifying fairness in Local Energy Markets	6
Aslesen, Line Trier	Lindberg, Karen Byskov	An Improved Stochastic Load Profile Generator for EV Charging	7
Austad, Sindre	Jonas Kristiansen Nøland	HTS Winding Design and 3D FEA Modeling of Superconducting Machine for Aviation	8
Bakken, Marie - Dihle, Rikke Enger	Ida Fuchs	Flexibility in Solar and Battery Off-Grid Systems - Case Study Eco Moyo Education Centre in Kenya	10
Bardal, Kaja - Melle, Sebastian Engmo	Dmytro Ivanko	DSO-LEC Optimization Using Demand-Side Flexibility Resources: A Case Study From a German Distribution Grid	12
Bergesen, Wilhelm	Steve Völler	Optimization of the Energy Management System of a Solar Car	14
Birkeland, Egil Bergstøl	Frank Mauseth	High Voltage Subsea Connectors for Offshore Wind – Study of Interfaces	16
Blytt, William Flesland	Vijay Venu Vadlamudi	Investigation of the Application of Optimal Power Flow in the Assessment of Power System Reliability	18
Bramness, Anders Guldal	Jonas Kristiansen Nøland	Computational Analysis of a Double-sided Linear Induction Motor for a Hyperloop Transportation System	19
Brennmoen, Vilde	Ümit Cali	Predictive Maintenance and Analytics in Hydroelectric Power Plants	21
Brøndbo, Ingrid Røstad	Steve Völler	Seasonal storage for excess solar energy on farms in Norway	23
Båtbukt, Jon Olav	Salman Zaferanlouei	Real-Time Home Energy Management Systems for Operating a Residential Energy Storage	25
Dihle, Rikke Enger - Bakken, Marie	Ida Fuchs	Flexibility in Solar and Battery Off-Grid Systems - Case Study Eco Moyo Education Centre in Kenya	10
Dupont, Kristian Astad	Ümit Cali	Energy Certificate Trading using Distributed Ledger Technologies	27
Eilertsen, Anja Kjærnes	Frank Mauseth	DC Breakdown Strength of HVDC XLPE Cable Insulation – Short-term testing of cable peelings	29
Einarsen, Kristel Storvik	Roy Nilsen	FPGA-based real-time modeling of active front end (AFE)	31
Engen, Per Kristian	Robert Nilssen	Design and Optimisation of Axial-Flux FiberPrinted Permanent Magnet Motor	33
Evjen, Øystein Steinsvik	Jayaprakash Rajasekharan	Implementing LSTM machine learning in long-term hydropower scheduling	34
Fagerli, Brynjar	Kaveh Niayesh	Converter stress on transformer insulation materials	36
Falck-Johansen, Christoffer S	Pål Keim Olsen	Thermal Analysis of ModHVDC Generator using Thermally Conductive Electrically Insulating Materials for Improved Heat Transfer	37
Folgerø, Kamilla Bakkane	Gilbert Bergna-Diaz	Networked Control of Complex Cyber-Physical DC Microgrids: On the Potential of Scalable Stability Features of PI Consensus Estimators	39

Forbord, Sivert - Sølberg, Håkon	Olav B Fosso	Integration of Power Transfer Distribution Factors and Internal Grid Constraints in Short-Term Hydropower Scheduling	41
Fossmo, Andreas Ersdal	Robert Nilssen	Application for axial flux motor	43
Giraud, Bastien	Olav B Fosso	Constraint-Driven Deep Learning for N-k Security Constrained Optimal Power Flow	48
Gundersen, Jørn Andre Mørck	Eilif Hugo Hansen	Analysis and Testing the Influence of Circuit Parameters on Serial Arc Detection	49
Hagejordet, Thomas Wagensveld Van	Hans Kristian Høidalen	Investigating Contributing Factors to Rogowski Coil Accuracy: COMSOL Simulation and Laboratory Testing	52
Hansen, Erik	Kaveh Niayesh	Investigating Transient Overvoltages due to Multiple Reignitions when Switching Small Inductive Loads	53
Hatletveit, Magnus Rein	Olav B Fosso	A Case Study on the Impact of Vehicle-to-Grid on Reliability of Supply in a Norwegian Distribution System	54
Heimvik, Torbjørn	Mohammad Amin	Battery for Capacity Expansion: A Techno-Economic Case Study in Trøndelag	56
Holt, Daniel Steinar - Sjøli, Tobias	Salman Zaferanlouei	Exploring the Effects of Integrating Power Link Island into the North Sea through Transmission Expansion Planning	57
Horstad, Torbjørn Indrekvam	Ümit Cali	Co-Simulation Model for Optimal Wind-Hydro Coordination Using Wind Farm Control Dynamics: A Case Study of a Hybrid Wind and Hydro Plant System	59
Husby, Karen Margrete	Gro Klæboe	A comparison of the SDP and SDDP method for medium-term scheduling of Meråker hydropower system	61
Hysing, Hans Dreyer	Robert Nilssen	Investigating the Potential Integration of Alva Industries Technology in Axial Flux Motor Design	62
Iden, Ruben Vilnes	Jonas Kristiansen Nøland	Design of Superconducting Propulsion Motor for Hydrogen-Powered Zero-Emission Aviation	63
Jakobsen, Emil Aune	Vijay Venu Vadlamudi	Performance Efficiency and Reliability Analysis of Offshore Wind Power Plants: Case Study of Utsira Nord	65
Jørgensen, Stian	Frank Mauseth	Future Design of Subsea High Voltage Cables for Offshore Renewables - Water tree growth from contaminants of oxidized polyethylene	66
Karlsen, Anniken Eriksrud	Hans Kristian Høidalen	Traveling Wave Fault Location on HVDC-MMC Transmission Lines	68
Kristiansen, Vegard	Gro Klæboe	Optimization of Hybrid Power Plant	69
Kvale, Ingrid Rodahl	Magnus Korpås	Prediction of power, energy and hydrogen demand in a zero-emission port	71
Lappen, Per Christian	Hossein Farahmand	Enhancing Long-Term Hydropower Scheduling Through Scenario Reduction Using Shape-Based Clustering	73
Lenes, Vemund Hjertvik	Karen Byskov Lindberg	Optimal performance of a housing cooperative with PV and smart use of electric water heaters	74
Li, Ben Liang	Eilif Hugo Hansen	Effektivitetsanalyse av AC- og AC/DC-hybridsystem i boliger	76

Lindal, Ferdinand	Gro Klæboe	Impact of Industrial Size Battery Storage Systems on Electricity Price Distribution	77
Lorentzen, Sofie	Irina Oleinikova	Potential of Hydrogen Technology for Coastal Electrification: Minimizing Distribution Grid Impacts through Flexibility	79
Løtveit, Ane Emilie	Olimpo Anaya-Lara	Study on Rotary Transformers as Inertia Providers in Wind Energy Applications	80
Madsen, Øyvind Kvalheim	Roy Nilsen	Intelligent Frequency Support for Offshore Wind	82
Marskar, Emilie Birgitte	Magnus Korpås	Optimizing hydrogen pathways using Norwegian energy resources dominated by offshore wind	84
Medhus, Kari	Magnus Korpås	Analysing the Impact of 30 GW Offshore Wind Power in Norway using the Market Model FanSi	86
Melle, Sebastian Engmo - Bardal, Kaja	Dmytro Ivanko	DSO-LEC Optimization Using Demand-Side Flexibility Resources: A Case Study From a German Distribution Grid	12
Mikkelsen, Eirik Kvåle	Jonas Kristiansen Nøland	Design and analysis of a 2.5 MW Coreless Aero Generator for Hybrid-Electric Aircraft	88
Müller, Clemens Martin	Olav B Fosso	Physics informed neural networks in radial load flow calculations	90
Nerby, Mathias Fjeldberg	Dimosthenis Peftitsis	Temperature Dependency and Active Gate Driver enabled Active Temperature Control of SiC Power MOSFETs	92
Nergård, Ingrid Nytun	Arne Nysveen	Detection and diagnosis of field-joint fault and static eccentricity in synchronous generators through analysis of the stray magnetic field.	94
Nygaard, Lars Skjelbred	Magnus Korpås	Investments in Low-Carbon Power Generation and Energy Storage under Uncertainty	95
Olsen, Ingvild Eline	Magnus Korpås	Multimarket Services for Stationary Batteries - Considering Activation of Frequency Containment Normal Operation Reserves	97
Osberg, Helene Grimstad	Frank Mauseth	New Environmentally-friendly Insulation Gases: Breakdown Mechanisms along Insulating Cylinders when implementing Barriers and Triple Junction Gaskets	99
Picazo Bou, David	Robert Nilssen	Design of a laboratory setup to investigate stability criteria of series-connected synchronous machines	101
Rasmussen, Marius	Irina Oleinikova	Potential of Hydrogen Technology for Coastal Electrification: Minimizing Distribution Grid Impacts through Flexibility	102
Ringdal, Sebastian Bruu	Arne Nysveen	Analysis of Demagnetization Faults in a Permanent Magnet Synchronous Machine utilizing the Stray Magnetic Field	103
Rostad, Jonas Eidsvåg	Kjetil Obstfelder Uhlen	Frequency Control Evaluation for a Variable Speed Wind Power Plant in an Isolated Power System	106
Rørstad, Vegard Yssen	Pål Keim Olsen	Experimental verification of control methods for series connected VSCs applied to a modular HVDC power train for offshore wind	108

Sadullaeva, Shirin	Olimpo Anaya-Lara	Valuation of energy storage technologies in the Nordic power systems and markets context with growing wind power penetration	110
Sassetto, Mercuzio	Irina Oleinikova	Tree High Impedance Fault Modelling	112
Serck-Hanssen, Kristin - Sletta, Hanna Birgitte	Ümit Cali	Integration of Renewable Energy Sources into Electricity Markets via Optimized Wind Farm and Hydropower Scheduling	113
Shankar, Varshan Erik	Steve Völler	Off-Grid Microgrid Design Consideration for Rural Electrification	115
Shields, Johan	Bjørn Gustavsen	Impact of Transformer Vector Group on Voltage Quality During IPO Breaker Operation in a Solidly Grounded Radial Systems	116
Sigurdsøn, Astrid	Gilbert Bergna-Diaz	Stability Analysis of a New Class of Inner Loops for Voltage Regulations in DC/DC converters	118
Sjøli, Tobias - Holt, Daniel Steinar	Salman Zaferanlouei	Exploring the Effects of Integrating Power Link Island into the North Sea through Transmission Expansion Planning	57
Skagemo, Jørgen André	Irina Oleinikova	Assessment of cyber-security and communication protocols in smart grid	120
Sletta, Hanna Birgitte - Serck-Hanssen, Kristin	Ümit Cali	Integration of Renewable Energy Sources into Electricity Markets via Optimized Wind Farm and Hydropower Scheduling	113
Smisethjell, Ingrid	Kaveh Niayesh	Investigation of PD formation on AlN Ceramic Substrates: Impact of Square Voltage Pulses and Dielectric Liquids	122
Steinset, Erlend Kummeneje	Kaveh Niayesh	Thomson Coil Actuated DC Switch to Investigate Fast Elongating Arcs	124
Sudkamp, Maurice	Roy Nilsen	Sensorless control of PMSM with sinusoidal filter	126
Sundfør, Ingrid Maria	Olav B Fosso	Flexibility in Distribution Systems through PyDSAL	127
Surdal, Emilie Bøe	Gilbert Bergna-Diaz	Robust Control of Nonlinear Wind Energy Conversion Systems: A scalable and adaptive energy-based approach for cascaded interconnections	128
Sølberg, Håkon - Forbord, Sivert	Olav B Fosso	Integration of Power Transfer Distribution Factors and Internal Grid Constraints in Short-Term Hydropower Scheduling	41
Taksdal, Mathias Hagen	Robert Nilssen	Dynamic Modelling of Twin Harmonic Counter-Rotating PMSM for Booster Pump in Pumped Storage Hydropower	130
Teigenes, Martin Gulleik	Kjetil Obstfelder Uhlen	Provision of Primary Frequency Control from Electric Vehicles in the Nordic Power System	132
Turi, Bjørnar Hætta	Frank Mauseth	On-line Condition Assessment of 420 kV Terminations - design and development of partial discharge sensors	133
Tørrisplass, Halgrim Ove	Ida Fuchs	Etablere en energidelingsmodell som simulerer lønnsomhet for energideling i et off-grid hyttefelt	135
Uosef, Abdallah Ammar Hoseny	Roy Nilsen	Sensorless Control of Six-Phase Permanent Magnet Synchronous Machines	137

Vabø, Erlend	Jayaprakash Rajasekharan	Electric water heaters as flexible energy resources in the power grid	139
Wirgenes, Karl Fredrik Anker	Hans Kristian Høidalen	Proposal and Evaluation of a New Short Circuit Protection Algorithm for Active Meshed Distribution Grids	141
Waage, Erlend	Olav B Fosso	Distribution grid planning with flexible measures	143
Øverby, Kristoffer	Hans Kristian Høidalen	Addressing Reliability Challenges in Digital Substation Automation Systems	145
Aabrekk, Erling Andreas	Jonas Kristiansen Nøland	Production and development of HTS terminations for future HTS coil manufacturing	146
Aasen, Anna Liv Leikanger	Olav B Fosso	Integration of Fast-Charging Station in the Distribution System - Exploring the Potential of Alternative Grid Connection Agreements	148

Hybrid BESS/STATCOM for Improved Power Quality on Oil & Gas Platform

Student: **Sadiq Abba Abdul-Azeez**
Supervisor: **Prof. Elisabetta Tedeschi**
Co-Supervisors: **Joseph Kiran Banda, Salvatore D'Arco**
Contact: **sadiqabba2@gmail.com**
Collaboration with: **SINTEF Energi AS**

Problem description

The power system of offshore oil and gas platforms (OOGPs) is often described as a weak, independent AC system. The sharp increase in reactive power demand and subsequent drop in bus voltage during the startup of induction motors represents a significant problem associated with weak grids. This situation can lead to generator overload, imbalance in active power, and consequently, frequency instability along with other related disturbances. To address these challenges, a battery energy storage system (BESS) is proposed for achieving active power equilibrium. Additionally, STATic synchronous COMpensators (STATCOMs) can provide reactive power support in leading or lagging modes. The integration of both BESS and STATCOM, referred to as BESS/STATCOM, is a growing trend to maximize the benefits of active and reactive power support.

The task

The primary objective of this thesis is to compare and assess three multilevel converter topologies: Neutral Point Clamped (NPC), Cascaded H-Bridge (CHB), and Modular Multilevel Converter (MMC). The aim is to identify the most suitable topology in terms of size, performance, and control for effectively addressing voltage and frequency stability issues during the direct starting of an induction motor on an OOGP.

Model/ measurements

Fig. 1 shows the proposed OOGP simulation model in Simulink provided by **Joseph Banda**. It has two gas-turbine generators, rated 11kV, 25MVA, 60Hz, lumped as one generator in the simulation model. The 11kV is stepped-up to 13.8kV with the help of a transformer. The platform has three heavy induction motors (IM), rated 13.8kV, 5.5MW, and 60Hz. A 5MVA 5L-CHB BESS/STATCOM as shown in Fig. 2, is considered as the preferred topology for this application, and is directly connected to the 13.8kV bus to provide voltage and frequency support.

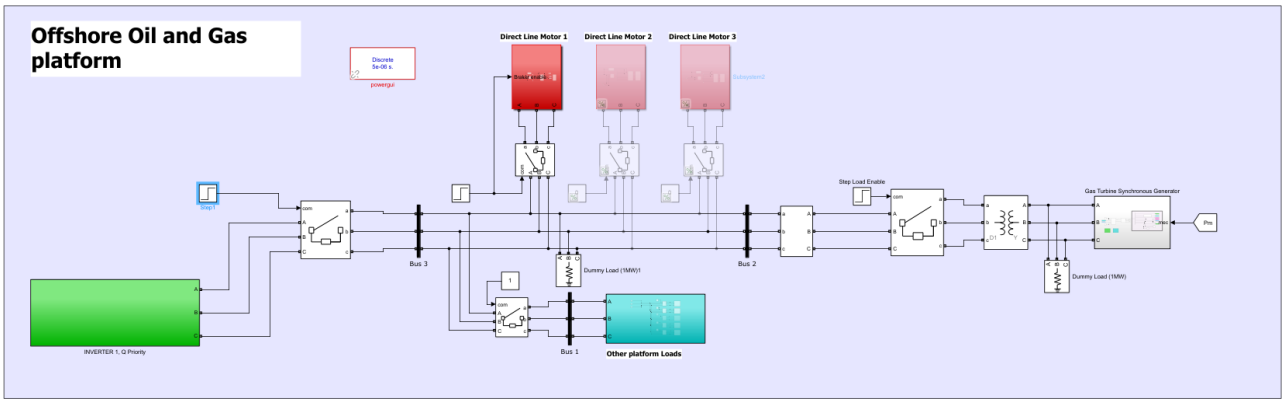


Fig. 1: Simulink model of the OOGP and the BESS/STATCOM

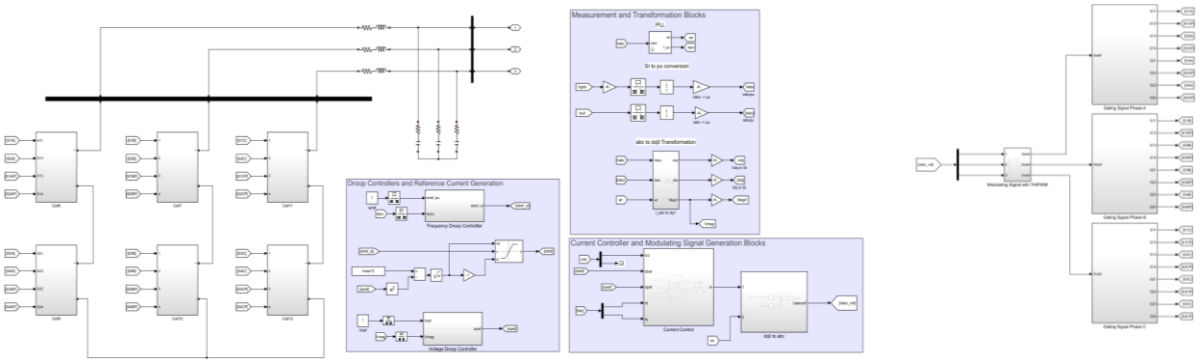


Fig. 2: 5L-CHB and associated control and modulation model in Simulink

Calculation

The simulation conducted for this study utilized the MATLAB/Simulink environment. Initially, a base simulation case was studied, where the OOGP model operated alone, and the system's behaviour was analysed during the starting of an induction motor. Two other cases were studied: the first one involves a 5MVA BESS/STATCOM converter operating with reactive current priority, and the second case involves active current priority. In both cases, voltage and frequency droop control is utilized.

Figs. 3 and 4 show the bus voltage and system frequency for all the three cases. Even though the voltage and frequency in the base case are within the limit for transient operation, improvement could be made. It can be observed that there was an improvement in the bus voltage in the two cases compared to the base case. In addition, it can be observed that there was less frequency deviation in the two cases compared to the base case, which indicates that the proposed control effectively maintains a more stable operation. In both figures, the constant region is the area allowed for continuous operation, while any area outside is allowed for transient operation upto ±20% for the voltage and ±10% for the frequency according to the NORSOK standard.

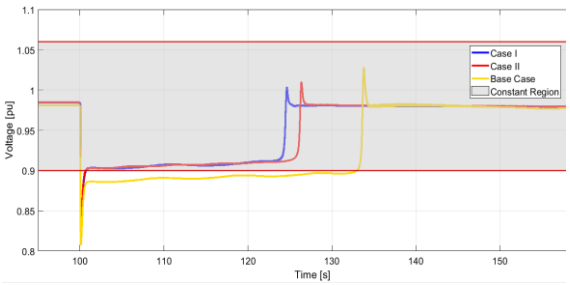


Fig. 3: Bus voltage during direct online starting of the IM: all cases

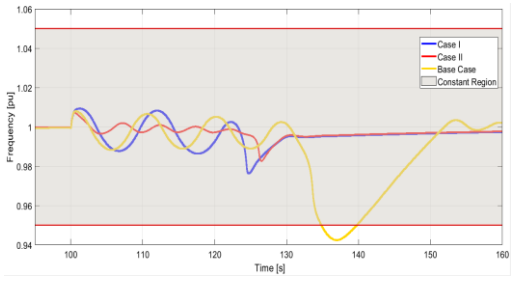


Fig. 4: System frequency during direct online starting of the IM: all cases

Conclusion

Three multilevel converter topologies have been assessed to identify the topology that offers the best features in terms of voltage quality, number of components, and control complexity. The cascaded H-bridge (CHB) topology has been identified as the best choice for BESS/STATCOM in an OOGP due to its advantages over the NPC and MMC topologies. Simulation results have shown that the utilization of voltage and frequency droop control can provide adequate support during the starting process of an induction motor (IM).

The simulation results have shown a significant improvement in the bus voltage, increasing from 0.88 pu to 0.9 pu. Furthermore, the frequency undershoot has reduced from 0.94 pu to approximately 0.98 pu. The proposed system not only improved voltage and frequency but also reduced the starting time of the IM and minimized stress on the gas turbine generators.

Study of rail potential and earth current for the BTRC and AT systems

Student: **Mohammed Abdulkadir Younas Aljahaf**
Supervisor: **Hans Kristian Høidalen**
Co-supervisor: **Bente Langeland Roheim**
Collaboration with: **Bane NOR SF**
Contact: **mahammedinfo@gmail.com**

Abstract

The booster transformer (BT) system is one of the AC traction feeding systems that were introduced early in Norway due to its good protection against the induction effect. In later years, the autotransformer (AT) system was also introduced. The AT system has better voltage stability and can supply heavy and high-speed trains. These systems are classified according to their electric and mechanical designs. This master's thesis aims to study the BTRC (Design C) and AT (Design E) systems and compare them. Particularly, rail potential and earth current levels in the return circuit are studied since these can be dangerous for people or cause damage to neighbouring equipment.

This thesis used the ATPDraw program to simulate the BTRC and AT systems. In preparation for the simulation, the necessary values of series impedances were calculated and verified in the ATPDraw program. Four models were simulated in this thesis: two for the BTRC system with 3 km and 6 km spacing between booster transformers and two for the AT system with 12 km and 14 km spacing between autotransformers. Figure 1 shows the AT system Design E. The red arrows refer to the return current, which is forced by the autotransformers to the negative feeder (NF) to return it to the feeding stations (frequency converter stations).

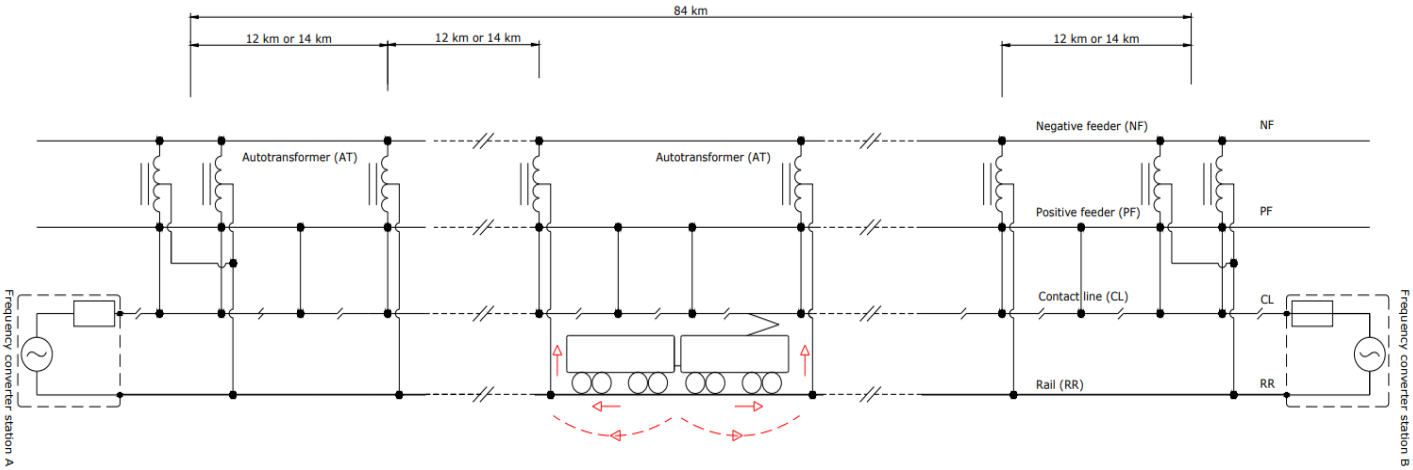


Figure 1: AT system design E (12 km or 14 km).

The parameters of the models were the levels of rail-to-earth leakage conductance (gE), train position on the track line, and the spacing between booster transformers (BTs) and autotransformers (ATs). The rail-to-earth leakage conductance (gE) is measured in S/km and primarily represents the connection between the rails and the earth. The study was divided into three case studies: Case Study 1 was conducted during normal operation and had the train position and gE (0.05 S/km - 2 S/km) as parameters. The transformer spacing in Case Study 1 is 3 km for the BTRC system and 12 km for the AT system. Case Study 2 is varied transformer spacing between BTs to 6 km and ATs to 14 km. Case Study 3 was during short-circuit conditions and had gE and spacing between BTs (3 km and 6 km) and ATs (12 km and 14 km) as parameters.

For the BTRC system, it was observed that the maximum levels of rail potential and earth current occur when the train is at the first or last booster transformer, while for the AT system, they occur when the train is in the middle of the track line between two ATs. It was also observed that the rail potential levels decreased while the earth current levels increased when the gE levels varied from 0.05 S/km to 2 S/km. Further, increased spacing between BTs and ATs increases the rail potential and earth current levels. For example, during normal operation, the rail potential levels of the AT system (12 km) decreased by a factor of 0.29, while the earth current levels increased by 6.75 when gE varied from 0.05 S/km to 2 S/km. The results for this example are shown in Figure 2 and Figure 3, respectively. The rail potential and earth current levels increased by a factor of 1.1 when the spacing between autotransformers increased from 12 km to 14 km.

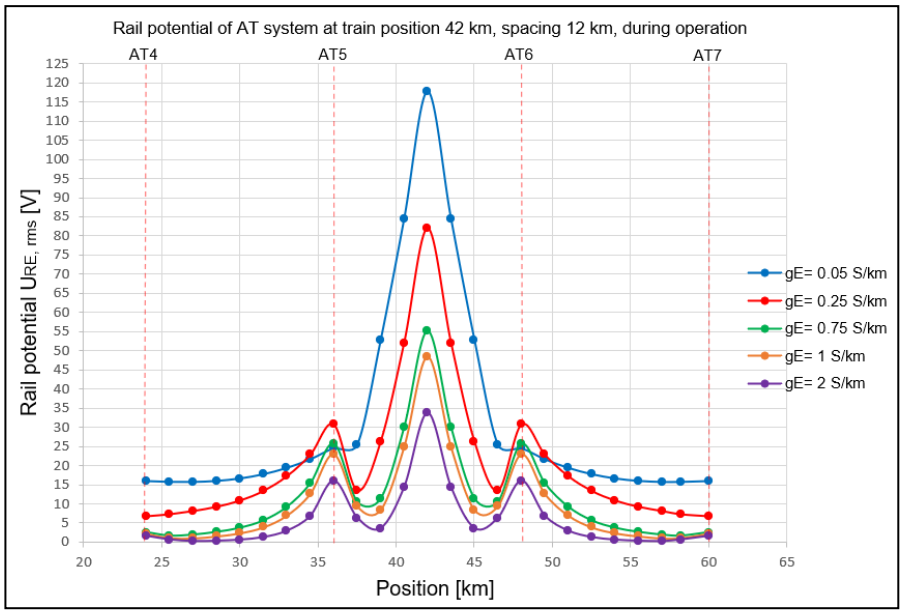


Figure 2: Rail potential, train at 42 km, spacing 12 km, during normal operation.

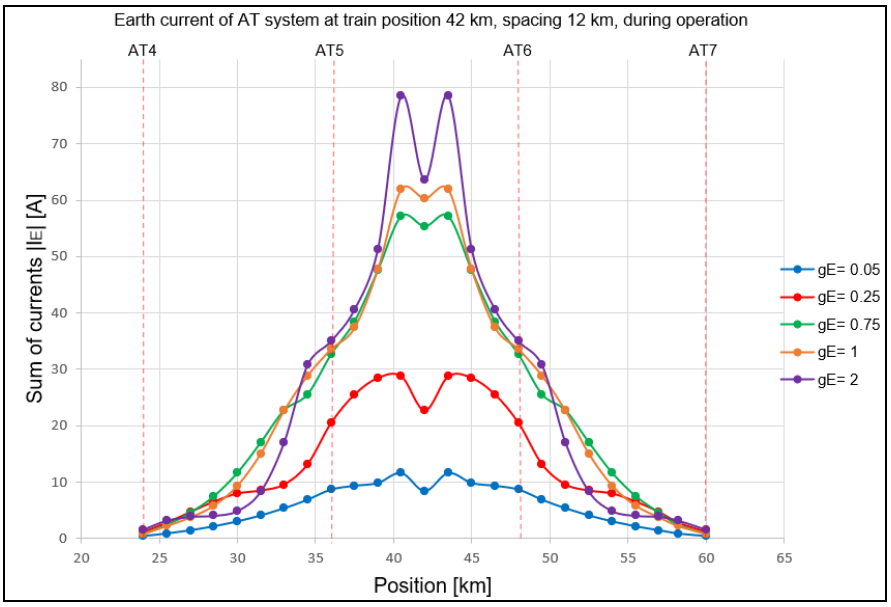


Figure 3: Earth current, train at 42 km, spacing 12 km, during normal operation.

Varju has many studies on the Norwegian feeding systems, such as comparisons of the BTRR, BRTC, and AT systems and investigations of the AT system and the combination of the BT and AT systems. Therefore, the thesis's results were compared to Varju's results for verification purposes. The comparison shows that the thesis's results agreed with these, with some variation due to the different simulation methods and data used in this thesis.

Furthermore, the results of the rail potential were verified by the EN 50122-1 standard. Most of the rail potential results met the EN 50122-1 requirements except for some values at low levels of gE, especially at 0.05 S/km. For earth current levels, there is no requirement for the permissible levels of current in the return circuit. Earth current results can be useful for other studies, such as EMC management plan and induction effects on neighbouring lines and systems.

The results showed that levels of gE, train position, and transformer spacing have a significant effect on the rail potential and earth current levels. It also showed that transformer spacing can be increased from the recommended spacing by Bane NOR's technical regulations, which is 3 km for the BT system and 10 km for the AT system (single track line).

Finally, the ATPDraw program provided a good possibility to simulate the AC traction feeding systems, but it was necessary to assume some simulation methods and values. For example, it was assumed that the gE and rail impedance were constant values for the whole system.

Quantifying fairness in Local Energy Markets

Student: **Anfinnsen, Erlend Nilsen**
Supervisor: **Cali, Umit**
Co-supervisor: **Fogstad Dynge, Marthe**

Abstract

The integration of renewable energy sources, vital for achieving United Nations Sustainable Development Goals (UNSDGs), presents challenges if not properly managed within the current power grid. Local energy markets (LEMs) emerge as a potentially effective tool in facilitating this transition. However, the establishment of a real-world LEM faces numerous challenges, especially the potential social consequences that could lead to greater societal disparities. This thesis employs lemlab, an open-source tool using agent-based modeling (ABM), to simulate varying scenarios of photovoltaic (PV) and battery deployments in LEMs, taking into consideration the unique characteristics of market participants.

Three key performance indicators (KPIs), Quality of Service (QoS), Quality of Experience (QoE), and Energy Index (EI), are used to measure market performance across these scenarios. Despite their widespread use, these KPIs had limited utility in the scenarios tested. QoS, mainly measuring equality rather than equity, failed to adequately capture perceived market fairness. Both original and modified versions of QoE proved resilient to changes across the different scenarios, due to minimal standard deviations of perceived prices compared to the difference between retail price and Feed-in Tariffs (FiTs). Meanwhile, EI emerged as a valuable tool for illustrating economic distribution within the market, highlighting disparities among households with varying demands or fixed generation capacities.

Importantly, this thesis proposes that subjective participant satisfaction in LEMs, drawing from philosophical and research-based definitions of happiness, could be a more significant factor in market acceptance than objective fairness. This stresses the importance of understanding motivational factors for participation in LEMs, taking into account cognitive biases when interpreting self-reported data. Future research is recommended to explore this area further, employing strategies to ensure a more accurate understanding of participants' experiences and perceptions of fairness in LEMs.

An Improved Stochastic Load Profile Generator for EV Charging

Student: **Aslesen, Line Trier**
Supervisor: **Lindberg, Karen Byskov**

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

HTS Winding Design and 3D FEA Modeling of Superconducting Machine for Aviation

Student: **Sindre Austad**
Supervisor: **Jonas Nøland**
Co-supervisor: **Runar Mellerud**
Co-supervisor: **Christian Hartman**

Problem description

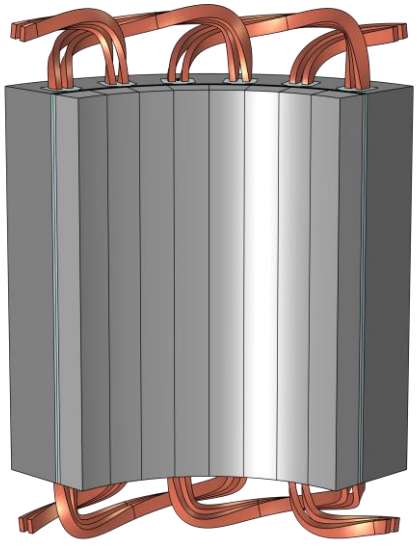
This thesis addresses the modeling of a superconducting machine (SCM) for aviation, aiming to increase power-to-weight ratios and efficiency in the aviation industry. The lack of comprehensive 3D models and guides for modelling of rotating machines and superconductors poses challenges to design and study of complex parts of the machine, such as the windings.

The task

The main task of this thesis is to create 3D models of the proposed SCM for aviation. The goal is to enhance modeling and analysis capabilities, especially with complex geometries such as end-windings, which are difficult to represent accurately in 2D models. The thesis aims to provide a reference and guide for future modeling endeavors in the field of superconducting machinery by developing end windings, explaining important parts of the modelling process, and including some relevant studies using the models developed.

Model/ measurements

In the thesis, the commercial finite element analysis (FEA) software, Comsol Multiphysics, is employed to develop 3D models based on a 2D design of the SCM. The 3D models are used to develop and implement two different end winding designs, and include magnet segments. The mathematical models of the two end windings, a rounded saddle coil, and a skewed and twisted saddle coil, are described in detail, along with the method of implementation in Comsol. The thesis also explores the use of high-temperature superconductors (HTS) in windings, and investigates the implementation of the 3D homogenized T-A formulation for HTS tapes through a replication of a well known study.



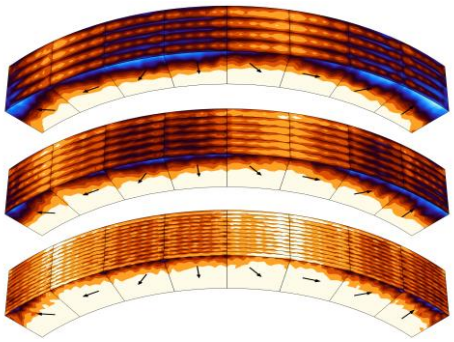
Calculation

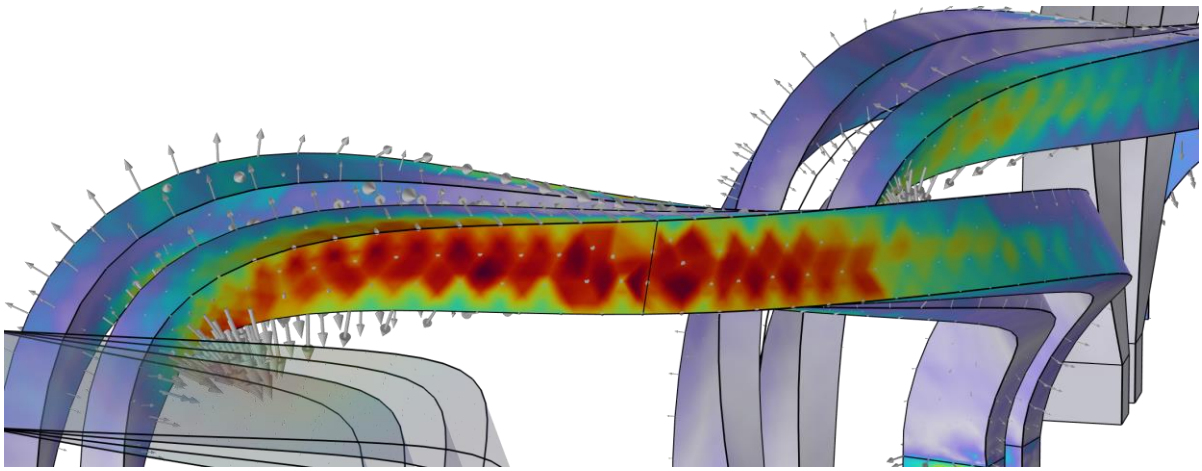
Validation of the implementation of the T-A formulation is done by comparing the current density and magnetic flux distribution with the original implementation replicated. The feasibility of the end windings is investigated, and their effects of the end winding designs on the machine and the HTS tapes are evaluated with respect to magnetic flux and resulting magnetic forces. Additionally, the thesis examines magnet losses in the SCM with respect to axial segmentation in the rotor's Halbach array, and the distribution of losses in the magnets and the array.

Conclusion

In this thesis. 3D models are developed for a superconducting machine designed for aviation, including end windings and magnet segmentation. Two end windings are designed and developed from scratch and successfully implemented in the machine. The implementation of 3D homogenized T-A formulation was investigated through a replication study, and methods used were found to be unsuccessful. The analysis of end-winding designs reveals the suitability of the skewed saddle coil, which shows promising results with low harmonic disturbance, but gives concentrated flux penetration, and magnetic forces which may give need for complex holding structures. Furthermore, the study of magnet losses highlights the importance of shorter magnet segments to minimize losses, and the presence of asymmetrical losses in the rotor.

Overall, this thesis contributes insights into the modeling of rotating machinery using superconductors. The developed 3D models and formulations are meant to serve as an inspiration or source of reference for future research and advancements in superconducting machine design, and to encourage the widespread use of 3D models.





Flexibility in Solar and Battery Off-Grid Systems – Case Study Eco Moyo Education Centre in Kenya

Student: **Marie Bakken & Rikke Enger Dihle**
Supervisor: **Ida Fuchs**
Contact: **mariebakk3@gmail.com, rikke.dihle@gmail.com**
Collaboration with: **Solar Energy Without Borders**

Problem description

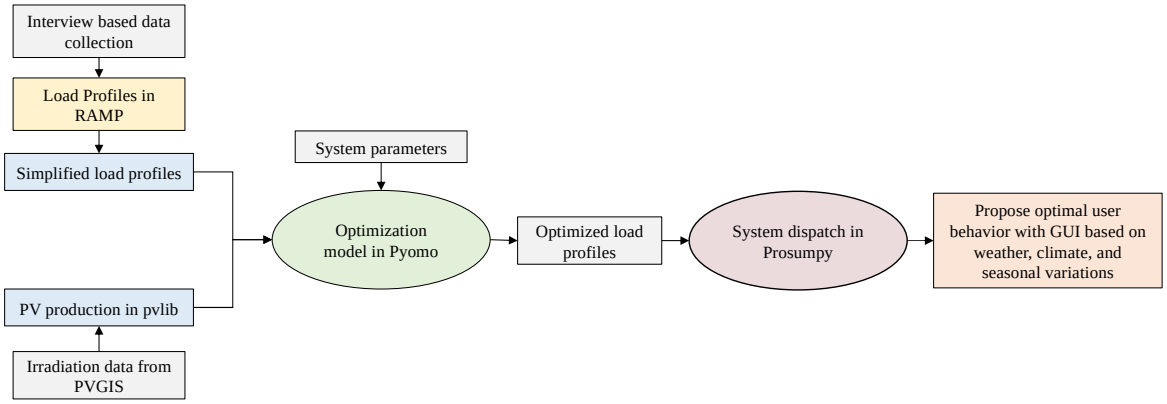
Accelerating rural electrification is crucial to achieve SDG number 7 by 2030. While progress has been made in reducing the number of people without electricity, the COVID-19 pandemic and increased costs pose challenges. Kenya has made significant progress toward universal energy access, but rural areas still lag behind. Eco Moyo Education Centre is a Norwegian/Kenyan charity project offering free primary education to underprivileged children in the Dzunguni village in Kenya. The school has an off-grid solar and battery microgrid to supply basic electricity needs in the Staff Room. This thesis is based on a case study of the existing system at the school, with data collected during field trips in November 2022 and April/May 2023. The thesis addresses the expressed need of the school to provide electricity to additional buildings and focuses on how flexible operation of the loads can be used to extend the system.

The task

The case study of Eco Moyo Education Centre highlights the potential of flexible solar and battery off-grid systems to optimize energy supply in rural areas. These systems are often based on unreliable RESs, such as solar power, and BESSs are typically used to compensate for periods with limited power generation. Hence, user behavior patterns are the primary tool to increase flexibility in off-grid systems. The main objectives of the master's thesis are to develop an optimization model for scheduling flexible loads and a user-friendly early-stage GUI draft for end user communication. By minimizing the disutility cost of shifting loads, the potential of DR in the shape of load shifting is investigated. The GUI incentivizes user flexibility and increases the end user knowledge of the system.

Model/ measurements

To obtain the objectives, load profiles generated in the RAMP model and PV production modeled in pvlib python serve as input to the optimization model developed in Pyomo. The purpose is to determine the optimal scheduling of flexible loads to minimize the disutility cost of load shifting. Additional appliances are introduced to assess the feasibility of powering other buildings using the existing system at the school.



Three scenarios are considered; Scenario 0, Scenario 1, and Scenario 2, which involve implementing zero, one, and two additional batteries, respectively. To incentivize user flexibility, the surplus energy of the system must be visualized easily and understandably in a GUI. The GUI is an early-stage design including different functionalities to increase the consumers' understanding of the system and suggest flexible consumption behavior.

Calculation

Tabell 1: Output data from Prosumpy for the initial system dispatch in Scenario 0.

Total Covered Demand	3842 kWh
Total Uncovered Demand	73.49 kWh
Total Shifted Load	0.000 kWh
Total Energy Surplus	2075 kWh
Amount of Energy Provided by the Battery	2200 kWh
Average Depth of Discharge	0.6278

Tabell 2: Output data from Prosumpy for the system dispatch after optimization in Scenario 0.

Total Covered Demand	3844 kWh
Total Uncovered Demand	71.30 kWh
Total Shifted Load	20.24 kWh
Total Energy Surplus	2075 kWh
Amount of Energy Provided by the Battery	2196 kWh
Average Depth of Discharge	0.6267

The results in Scenario 0 show that 20.24 kWh of the total demand is shifted by the optimization model. As expected, the covered demand is increased, and the uncovered demand is decreased. However, after optimization, the uncovered demand is only reduced by approximately 2 kWh. The total energy surplus is persistent before and after optimization, as the loads only are shifted for a few time steps. As a result, the consumption is not remarkably increased during the time periods when the PV production is high. Followingly, the decrease in the amount of energy provided by the battery and the DoD is not remarkable.

Conclusion

This thesis demonstrates that DR is an effective strategy for addressing unmet demand in off-grid microgrids. By load shifting and adapting to seasonal variations, the existing system can supply additional buildings at the school, with a cost of only 7% of the price of a new system. Most of the year, the system can cover the additional demand with an extension of the system. However, the main challenge occurs when the generation is drastically reduced. When including additional batteries, the number of days when the optimization model is unable to fulfill the constraints and cover the demand is reduced. The initial uncovered demand is decreased with additional battery capacity, but the reduction in uncovered demand due to load shifting is persistent in all the scenarios. Hence, load shifting mainly affects the uncovered demand caused by load peaks exceeding the system's capacity. By including the additional batteries, the disutility of the users is decreased. However, the cost increases to 20% and 35% of implementing a new system, with one and two additional batteries, respectively. The user experience will be enhanced, but the lack of financial resources at Eco Moyo Education Centre plays a vital role in the decision. Furthermore, the GUI will contribute to cover the demand when extending the existing system at the school.

DSO-LEC Optimization Using Demand-Side Flexibility Resources: A Case Study from a German Distribution Grid

Student: **Kaja Bardal & Sebastian Engmo Melle**

Supervisor: **Dmytro Ivanko**

Problem description

Due to the shift towards a more sustainable future, the need for power is increasing rapidly. To address the challenges brought on by the climate crisis, fossil fuels are being phased out, and the world is transitioning towards greener energy sources like solar and wind power. This transition poses new challenges for the power system as the demand increases, and power production becomes more intermittent and harder to control.

As a result, the need for flexibility in the grid is increasing, which can no longer be provided by conventional power plants without major infrastructure expansions. New flexibility resources are being investigated. The concept of local flexibility markets offers a promising approach to utilizing the distributed flexibility resources available within the demand side of the grid. By enabling the end-users to participate and utilize their flexibility potential, these markets provide a platform for more effective use of resources, reducing waste and strengthening the overall efficiency and stability of the power system. Increasing end-user engagement and integration will be essential to utilize their flexibility potential as the power grid moves towards a decentralized structure.

The task

The thesis focused on DSO-LEC coordination, utilizing the realistic test case made based on data provided by the German DSO S.W.W. Wundsiedel. The thesis will further investigate how demand-side flexibility can be economically beneficial and how it can aid the DSO with grid regulations. It will also focus on how these flexibility resources can support the integration of intermittent distributed energy resources. Additionally, it is a goal to provide general improvements to the model and code to make it more user-friendly.

The main objectives of the thesis can be summarized as follows:

- Further improve the provided code to make it more user-friendly.
- Create a realistic test case using grid and load data from the German DSO and flexibility data of different pilot projects and test how this demand-side flexibility can aid the DSO, by reducing operational costs and offer tools for voltage regulation and congestion management.
- Introduce a script to the model that allows realistic information communication between the market operator, DSO, and LECs, through mail exchange.
- Include distributed power generation in the distribution grid and observe how flexibility can aid intermittent power generation by simulating different generation scenarios.
- Add flexibility to the Day-Ahead optimization of the model so that power producers can utilize demand-side flexibility resources in their operation planning.

Model/measurements

The model used in this thesis is an SoC AC/AC-OPF model. The goal was to optimize the coordination of one DSO and two LECs. In addition to the OPF, the ADMM algorithm was

applied to decompose the optimization problem into smaller sub-problems to reduce the problem size. Decomposing the problem makes it easier to solve mathematically and makes it possible to tackle more extensive problems. The decomposed model consists of four sub-problem groups that each need to be solved, two for the Day-Ahead market and two for the LFM. These are solved by minimizing the deviation between power imported in the LEC and power exported from the DSO. In addition, a sophisticated communication scheme was introduced to ensure information security and corporate integrity concerning sensitive data by transferring only necessary data between market participants through the simple mail transport protocol (SMTP) and internet mail access protocol (IMAP).

A realistic test grid was made based on data provided by the German DSO to test the model. The data provided included real-life line and node data and typical load profiles, making it possible to further evaluate the model's robustness. The flexibility data was mainly based on a Belgian pilot project to make it as realistic as possible.

Different test cases were made to test the objectives described earlier. Firstly, two economic optimizations were simulated to demonstrate the benefits of including demand-side flexibility. Then, three voltage regulation test cases were made to illustrate how demand-side flexibility can aid the DSO when voltage problems arise. Lastly, a distributed generator was included in the distribution grid to illustrate how intermittent power producers can benefit from these flexible resources when actual power production deviates from forecasts. Here, flexibility was added to the DA market as well.

Results

The thesis' results further strengthened the theory that the inclusion of end-users and their flexibility resources in the power market offers potential benefits for several participants. The economic optimization showed that including demand-side flexibility reduced the operational costs of the DSO and both LECs. Due to excessive capacity compared to load, one of the LECs achieved a negative operational cost, meaning they could deliver more back to the grid than they imported. This indicates that a community can become largely self-sufficient with good capacity expansion. In addition, the need for imported active power from the TSO was reduced by 54% and the transfer losses by 15%. Reduction in imported power and transfer losses was seen for all test cases when flexibility was included. The voltage problem test cases also provided good results, with the inclusion of demand-side flexibility eliminating the need for load shedding in the LECs. The test cases with intermittent power generation showed that with a significant expansion of demand-side flexibility, the end-users could aid the power producer when power generation is lower than forecasted. The inclusion of flexibility to the DA market made the expected costs almost equal the actual operational costs of the flexibility market, which was not true for any other test case. This indicates that demand-side flexibility can also offer advantages in the planning phase of operations.

Conclusion

This thesis shows that the optimal coordination between the DSO and LECs, with the inclusion of demand-side flexibility and battery resources, will provide extensive economic benefits and stability to the grid. However, there are still several challenges related to integrating demand-side flexibility into the power market. As such, further work should be conducted on the topic, for example, a thorough review of the technical challenges and possible solutions or a deeper dive into the coordination scheme of the market.

Title Optimization of the Energy Management System of a Solar Car

Student: **Wilhelm Bergesen**
Supervisor: **Steve Völler**

Problem description

The World Solar Challenge (WSC) is a Solar Car (SC) event held in Australia every two years, where SC teams from across the world compete in a race. The SCs function like tiny mobile microgrids running solely on the output of Photovoltaic (PV) generators. The newly founded SC team, Nordlys NTNU, wishes to compete in the WSC in 2025, but lack the background knowledge required.

SC racing is a vast field of study incorporating material sciences, electrical engineering, mechanical engineering, thermal engineering, and even aerospace engineering. This thesis serves as an introduction to several of these fields, focusing on electrical engineering. It familiarises the reader with the rules of the WSC, the solar- and weather conditions for the route, the SC's electrical system, and the SC's load during the race.

The task

The thesis has four main objectives:

- Create a solar profile for the route.
- Determine the SC’s PV system’s output through the route.
- Determine the SC’s load through the route.
- Choose suitable components for the SC.

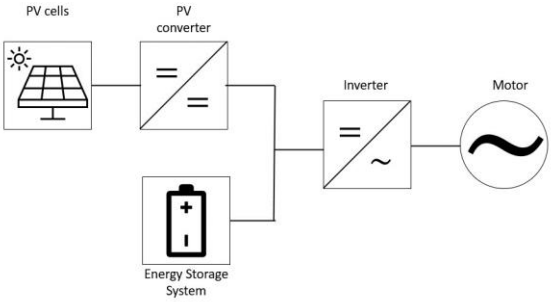
The thesis also determines the optimal way of utilizing the SC’s relatively small Energy Storage System (ESS). The thesis investigates the factors that will affect the PV system's performance and the load's behavior.

Model/ measurements

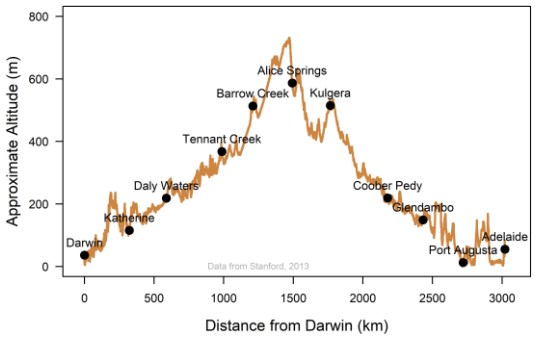
The chosen approach to the aforementioned objectives was an extensive literature study, investigating previous contestants and simulating the SC using Python. The literature study covered aspects such as weather conditions, PV systems and semiconductor physics, ESS dynamics, and mechanical aspects of SCs.

The calculations and simulations were made using an original library created by the author called scpylib. The library contains several modules that collect SI- and weather data through PVGIS, and predicts the performance of an SC participating in the WSC.

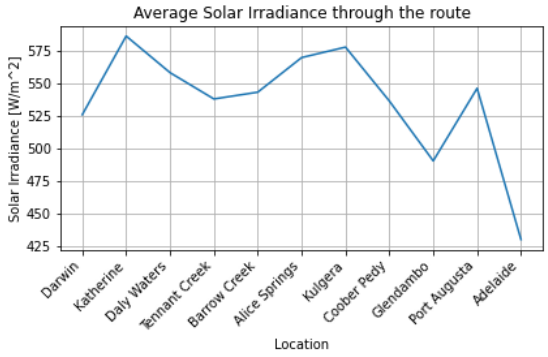
Calculation

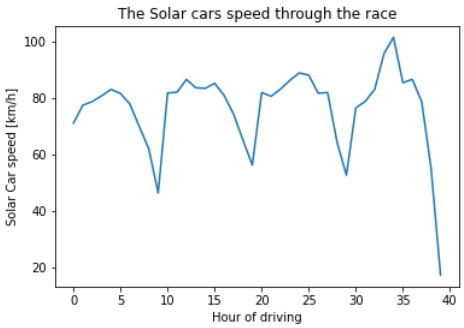


SC grid topology



WSC elevation profile





The SC's cruising speeds during driving hours

Conclusion

The literature study and contestant investigation conclude that the SC's optimal grid topology is to base its main voltage on the ESS. Its stable and predictable voltage levels grant the system stability. The ESS should also be Lithium-ion-based due to its high energy density. The PVs should be monocrystalline silicon due to its high energy efficiency. However, research into high-temperature applications for perovskite-based technologies should be done. The DC-DC converter should be equipped with a Maximum Power Point Tracker to utilize the PVs to their full potential. The inverter should be a three-level three-phase one as the neutral point on its dc-link would minimize switching losses.

The results from the simulations conclude that scpylib's simulations provide realistic outputs. However, scpylib needs an updated load model to include acceleration. The utilized data retrieval method also needs an update to enable real-time simulations.

The simulations also proved that an even discharge of the ESS resulted in the fastest finishing time and that discharging more energy at lower speeds results in better SC performance. Future investigations into ESS utilization strategies are suggested

High Voltage Subsea Connectors for Offshore Wind – Study of Interfaces

Student: **Egil Bergstøl Birkeland**
Supervisor: **Frank Mauseth and Sverre Hvidsten**
Contact: **egil.b.birkeland@haugnett.no**
Collaboration with: **SINTEF**

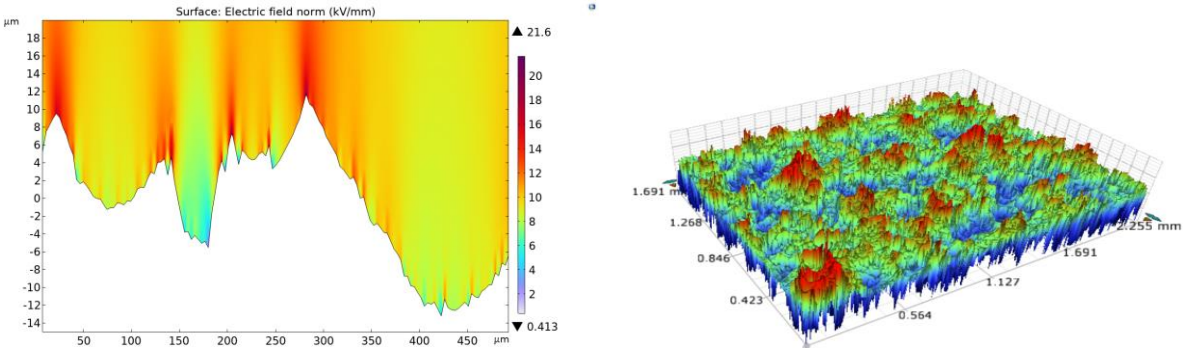
Problem description
The background for the project is the development of technology to design 245 kV dry-mate connectors to use at large-scale offshore wind farms. The thesis addresses the impact of the interface between the electrode and insulation materials for the development of technology to design the dry-mate 245 kV connectors.

The task
There are multiple factors that might affect the insulation performance of a connector, which is why the thesis is focusing on some specific factors. Factors that will be considered are surface roughness, electric field, and adhesion. If other factors, such as defects or contaminants are detected, the cup is discarded. The impact of the surfaces subjected to each preparation method will be examined through measurements with voltage stressing over the test objects. The objective of the thesis is therefore to examine the impact of electrode surface roughness on insulation performance.

Model/ measurements
The interface can be examined by casting insulation cups around aluminium discs with known surface roughness parameters. The aluminium discs will function as electrodes that have undergone different kinds of surface preparation methods. The applied surface preparation methods in the thesis are sandblasting with two different particle types and polishing combined with hot AC anodising. All the test objects were cast with the casting procedure that was deemed best in the specialisation project.

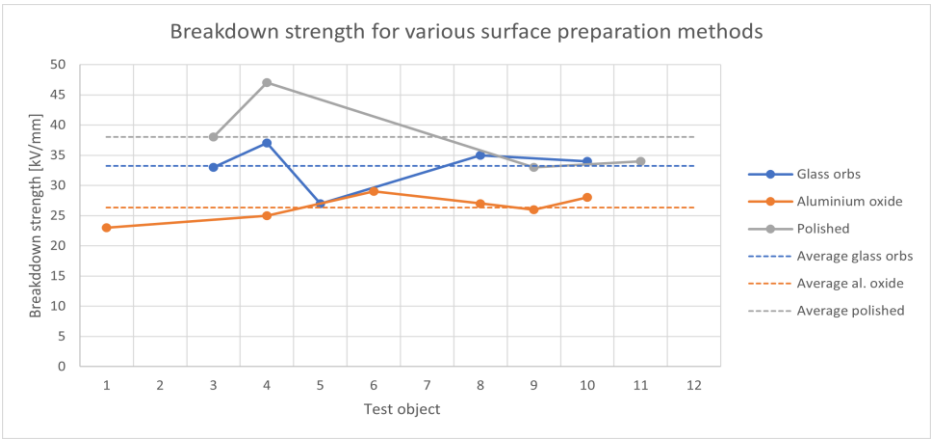
Results
The profilometry results from the discs revealed that the aluminium discs had relatively equal surface roughness within the surface preparation methods, which enabled an accurate comparison of the impact of surface roughness.

The impact of the surface roughness on electric field distribution was analysed with 2D simulations in COMSOL. The simulations showed the electrical field distribution over surface profiles for each preparation method.



The differences in the surface preparation methods were more apparent for the PD measurements conducted to find the electric field where electrical tree growth was initiated. Discharge magnitudes PRPD plots were used to decide the growth of electrical trees.

Lastly, breakdown tests were conducted to measure the breakdown strength of the insulation cups. There was a significant difference between the polished and hot AC anodised electrode and the electrode sandblasted with aluminium oxide, with breakdown strengths of 26 kV/mm and 38 kV/mm respectively. Additionally, the electrode sandblasted with glass orbs had a breakdown strength in between them at 33 kV/mm. These results show that the breakdown strength is heavily impacted by surface roughness.



Conclusion

- Higher surface peaks give a higher local field enhancement. Additionally, it was concluded that if there are several surface peaks in close proximity to each other, the maximum field at each peak will be reduced by the surrounding peaks.

- Electrical tree initiation starts earlier for rougher surfaces. The average electric field for electrical tree initiation was approximately 14 kV/mm, 17 kV/mm and 21 kV/mm ranging from roughest to smoothest surface.

- An increase in surface roughness will cause a decrease in the insulation performance.

Investigation of the Application of Optimal Power Flow in the Assessment of Power System Reliability

Student: **William Flesland Blytt**
Supervisor: **Vijay Venu Vadlamudi**
Co-supervisor: **Matias Vistnes**

With the modernisation of the electric grid, it is crucial to have smart solutions for effective and secure system planning and operation. Traditional power system optimisation methods are being reevaluated and are becoming relevant for new applications. One such method is the Security Constrained Optimal Power Flow (SCOPF), which is an extension of the Optimal Power Flow (OPF) problem. In this thesis, the objective of SCOPF is to minimise cost of load curtailments, while satisfying all system constraints not only in normal operation conditions, but also in anticipated contingencies such as line outages and generator outages.

The objective of this Master's thesis is to make use of a non-sequential Monte Carlo Simulation and integrate it with a DC optimal power flow (DCOPF) approach using the Python programming language and the Pyomo framework. The primary focus is on assessing the reliability (adequacy aspect) of composite power systems. A novel DC preventive security constrained optimal power flow (DC-PSCOPF) approach has been developed for assessing the reliability of composite power systems. The main contribution of this thesis is the implementation of DC-PSCOPF in the OPF analysis of the algorithmic approach in calculating the reliability indices.

This thesis intends to pioneer the application of SCOPF in the assessment of power system reliability, representing a research area that has not been extensively explored before. The integration of SCOPF techniques, in this case DC-PSCOPF, in the composite system adequacy assessment, further develops the framework for evaluating the reliability of power systems available at the Department of Electric Energy (formerly, Department of Electric Power Engineering), NTNU. By considering both pre- and post-contingency constraints, this fresh perspective aims to offer helpful insights into the adequacy assessment of composite power systems. One of the goals of this thesis work is to create a reproducible method, which could be used as a stepping-stone for future research on the topic. Reliability indices utilising DCOPF and DC-PSCOPF are presented. A comprehensive deployment of the methodological approach used is presented, including the necessary adaptations and underlying assumptions. The details provided offer a clear understanding of the approach utilised, ensuring transparency in the method.

Two main scripts are developed for the implementation of DCOPF and DC-PSCOPF in the Pyomo framework in Python. These scripts are used in conjunction with the previously developed in-house scripts at the Department of Electric Energy, for evaluating and quantifying power system reliability indices. The first script focuses on the standard composite system adequacy assessment, utilising the DCOPF approach applied to the Roy Billinton Test System (RBTS) and the IEEE-Reliability Test System (IEEE RTS). The second script builds upon the first script by incorporating DC-PSCOPF, and it is also applied to the RBTS and IEEE RTS systems. In order to give some sense of verification of the developed code, a comparison of the obtained reliability indices is conducted using similar methodological approaches.

Computational Analysis of a Double-sided Linear Induction Motor for a Hyperloop Transportation System

Student: **Anders Guldal Bramness**
Supervisor: **Jonas Kristiansen Nøland**

Problem description

The Hyperloop Transportation System (HTS) is an exciting prospect, as it is theorized to be the fastest possible mode of transportation on land, with top speeds of >1000 km/h. However, the current technologies proposed to fulfil these demands are deemed too costly to be implemented on a large scale. A mode thought to be more cost effective is a Linear Induction Motor (LIM). LIM has low capital cost and is a good fit with Electrodynamic Suspension (EDS), a magnetic levitation suspension system thought to be the most stable of them all. However, studies so far have suggested that LIM has a low efficiency compared to the other systems, and the operating cost is therefore too high. However, little research has been made in simulations of these motors, particularly regarding Finite Element Analysis (FEA). The hope is that further analysis will highlight the performance of a LIM, and truly decide if it is a good option for HTS.

The task

The aim of this thesis was to investigate a mode of propulsion for HTS at its critical acceleration phase. This thesis was particularly aimed at exploring a Double-sided Linear Induction Motor (DLIM) in a setup that is realistically simulating its capabilities for HTS. Theory was established to argue for the setup used in simulations, discussing simulation parameters, highlight power losses and calculating analytical results. The motor was simulated at steady state as well as over time to provide different types of results and further interpret their meaning when discussing the LIM performance. Thrust force and efficiency was selected as parameters to quantify this performance.

Model/ measurements

The model used for simulations was a 2D model built in COMSOL, a FEA program. The model was based on a model made in master thesis last year. The model is shown in Figure 1.

Figure 1: The model used for stationary simulations. A DLIM is surrounding a 2-meter-long aluminum beam segment.

To calculate analytical results, a per-phase equivalent circuit used for conventional induction motors was adjusted for a LIM and implemented in Simulink. The Simulink model is shown in Figure 2.

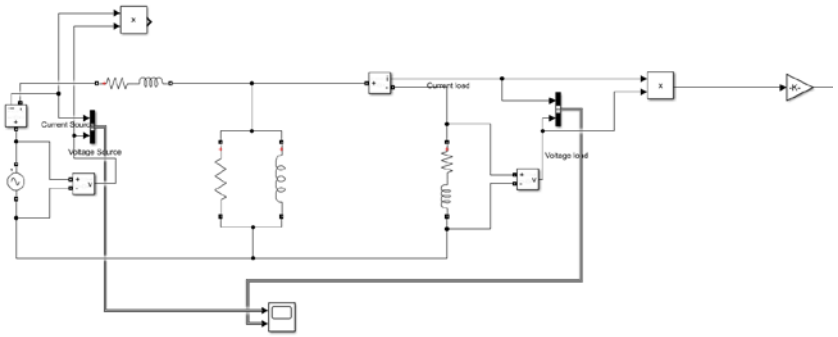


Figure 2: A per phase-equivalent circuit created in Simulink to calculate analytical results.

The parameters in the equivalent circuit were retrieved from stationary simulations, resembling tests of a real motor to find parameters to determine its characteristics. Operating points for the motor was selected based on the motor's force speed characteristic which also is calculated in stationary results.

Calculation

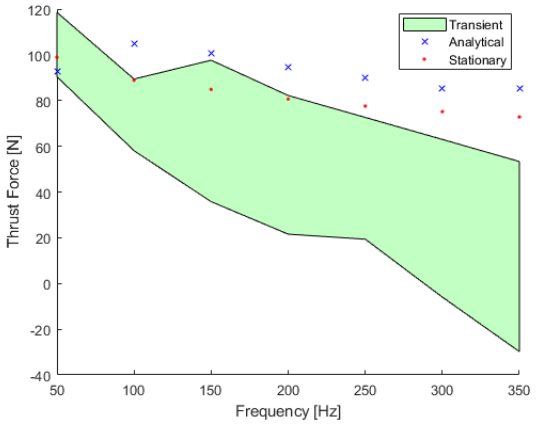


Figure 3: Collected results of efficiency for all frequencies tested.

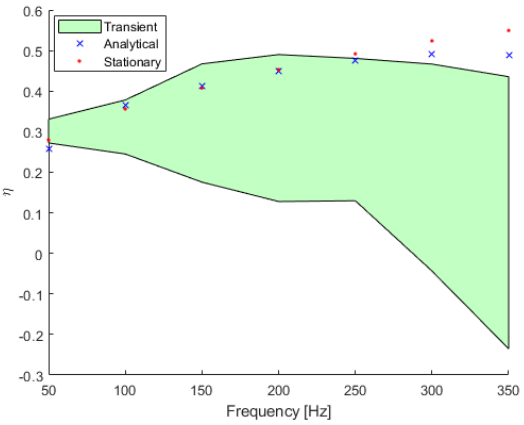


Figure 4: Collected results of thrust force for all frequencies tested.

The results for thrust force and efficiency is shown in Figure 3 and Figure 4, respectively. The analytical results show a higher thrust force than in stationary results. This is reasonable, as analytical results neglect many complexities of a LIM which impact its performance, such as edge effects. This is further explained in the thesis.
The transient results are shown as an uncertainty area due to a large ripple. This ripple could be caused by edge effects and other LIM characteristics, but it is more likely that it is caused by a zero initial condition, resulting in a large step response that does not disappear due to a short simulation time.

Conclusion

Based on the findings in this thesis, the LIM is not a viable option for HTS. The analytical and stationary results are reasonable, but the ripple in transient results is unsustainable and will cause an uneven acceleration. The efficiency is also too low. However, this thesis has not attempted to perfect the design of the motor, which could improve the performance. A longer simulation time along with a shorter computation time would also clarify the results, which is needed before potentially put a final nail in the coffin that is LIM for HTS.

Predictive Maintenance and Analytics in Hydroelectric Power Plants

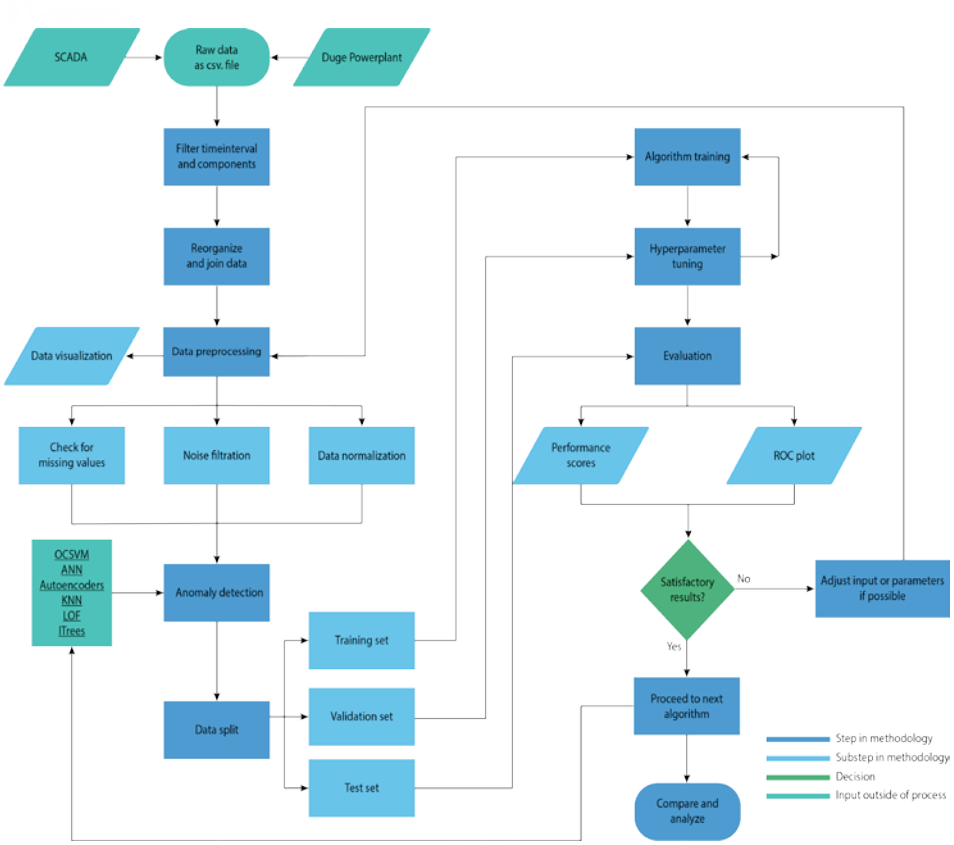
Student: **Vilde Brennmoen**
Supervisor: **Ümit Cali**
Co-supervisor: **Ugur Halden**

Problem description
This master's thesis investigates and evaluates predictive maintenance and predictive analytics applications, with a particular emphasis on the implementation of anomaly detection techniques driven by artificial intelligence (AI) and machine learning (ML) in the hydroelectric power sector. This study's primary objective is to evaluate the capacity of these proactive technologies to improve the efficacy of maintenance procedures and the operational effectiveness of hydroelectric power systems. The ultimate goal is to increase productivity, decrease downtime, and promote a more reliable and sustainable energy industry. This thesis aims to provide a comprehensive overview of the potential benefits and obstacles associated with the integration of AI and ML within the predictive maintenance and analytics of the hydroelectric power sector through a detailed analysis of these integral aspects. The ultimate objective is to contribute to the development of a more sustainable and reliable energy future by advancing maintenance procedures and operational efficiency in the renewable energy sector.

The task
To achieve these objectives, the study will employ an approach with two phases. The broader aspect involves examining the general use of predictive maintenance and predictive analytics in hydroelectric power plants, gaining an understanding of the current landscape, and identifying gaps where AI and ML could add value. This will provide a broad perspective on the state of these technologies in the industry and lay the groundwork for the next phase of the study. The narrower aspect will then concentrate on employing diverse ML algorithms for detecting anomalies in power transformers by analyzing recordings of winding tem□perature and hydrogen concentration. In this section, the chosen algorithms will be applied to a test scenario involving a data set acquired from the Duge power plant. This method will allow for the evaluation of the effectiveness of these algorithms in detecting anomalies and identifying potential faults in the power transformer.

Model/ measurements
The methodology is presented in the form of a flowchart and can be roughly divided into the following steps:

- Conduct literature review and choose algorithms with desired qualities.
- Collect and analyse data to prepare a test case.
- Data preprocessing using noise filtration, data normalization and checking for missing or duplicated values.
- Develop the models using a training set and tune hyperparameters using a validation set.
- Evaluate the models using a test set by plotting the receiver operating characteristic curve (ROC), and calculate performance metrics recall, precision and F1-score.



Calculation

Six different algorithms were chosen, each with desired capabilities for anomaly detection, to compare and discuss their performance. Those six algorithms are: One-Class Support Vector Machines (OCSVM), Isolation Forest (iForest), Autoencoders (AE), K-Nearest Neighbours (KNN), Artificial Neural Networks (ANN), and Local Outlier Factor (LOF). The algorithms are trained and tested one at a time. The models got an area under the cuve (AUC) score ranging between 0.56-0.76. Performance metrics are listed in the two tables, and given this is a binary classification problem, it is possible to partition the scores into two distinct classes. Class 0 denotes the non-anomalous points and Class 1 corresponds to the anomalous points.

Algorithm	Precision	Recall	F1-score
K-nearest neighbors	1	1	1
Local outlier factor	1	0.97	0.99
Isolation forest	1	0.97	0.99
One-class support vector machines	1	0.98	0.99
Artificial neural networks	1	1	1
Autoencoders	1	1	1

Algorithm	Precision	Recall	F1-score
K-nearest neighbors	0.67	0.15	0.25
Local outlier factor	0	0.15	0
Isolation forest	0	0.46	0
One-class support vector machines	0	0.54	0.1
Artificial neural networks	0.20	0.15	0.17
Autoencoders	0.03	0.23	0.05

Conclusion

The OCSVM model demonstrates the best performance by attaining the highest AUC and recall score when combining all observations. The performance shown by iForest is comparable in terms of both AUC and recall score. Although these two models demonstrate a high degree of efficiency in detecting anomalies, they also have a tendency to misclassify a small proportion of non-anomalous data points. The KNN model is notable for its accurate performance, as ranks third in terms of AUC score, and even though the recall score may have been below-average, the precision score was significantly higher.

Seasonal storage for excess solar energy on farms in Norway

Student: **Ingrid Røstad Brøndbo**
Supervisor: **Steve Völler**

Problem description

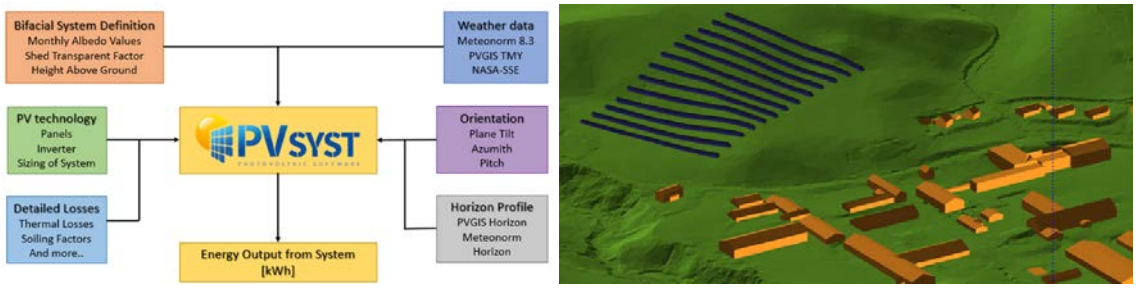
Large-scale solar installations found at farms face the challenge that not all the produced electricity can be used locally nor supplied to the grid. Farms in Norway are usually located in areas where the grid is weak. In combination with a high penetration of solar photovoltaics (PV), weak grids can limit the solar power feed-in. Storage can then be an option to prevent new investments in the grid while simultaneously increasing the farms self-sufficiency of electricity. This thesis conducts a case study to examine the technical feasibility of two different seasonal storage solutions in combination with large-scale solar PV. Skjetlein High School in Trondheim, Norway, was chosen as the research case due to their agricultural profile and interest in renewable energy.

The task

The thesis will investigate the implementation of agrivoltaics (APV) and seasonal storage at Skjetlein High School. APV is simply the combination of agriculture and solar production on the same land area, intended to increase the land-use efficiency. Additionally, the cost-effectiveness of seasonal storage will be discussed. Possible APV scenarios will be simulated and used in a storage optimization model. The model is constructed to find a suitable storage size (capacity and power rating) according to one of two control strategies.

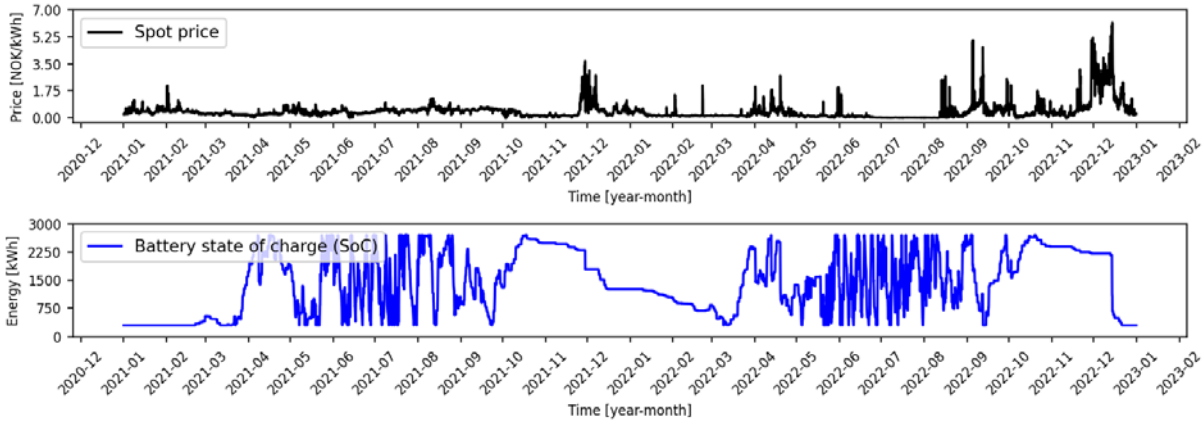
Model

In order to investigate the possibilities for seasonal storage at Skjetlein, four solar power scenarios were simulated using PVSyst. The first scenario (base case) contained all the solar PV systems which are already installed at the school. The remaining three scenarios consisted of different APV systems.



PVSyst simulation flowchart and 3D scene of one APV scenario.

Only a few storage types are capable of seasonal storage. Pumped hydro, compressed air and heat storage are not considered in this study due to their geographical limitations. Compressed hydrogen and vanadium redox flow batteries (VRFBs) were chosen as the only viable options. A mixed-linear programming (MILP) optimization model was constructed to analyse how different optimal capacitates, power ratings and cost saving vary for different solar PV scenarios at Skjetlein.



Scenario North (700 kW APV + 200 kW Rooftop PV) showing VRFB storage charge-discharge pattern throughout year 2021 and 2022 with the aim of minimizing the yearly electricity bill.

Conclusion

The cased showed that large-scale solar PV installations come with challenges if the produced energy cannot be consumed locally or injected into the grid. A storage for daily balancing (e.g., day/night) might be used. This type of storage was suggested by the optimization algorithm when the annual storage costs were included in the model. This suggests that storage for daily dispatching may be a cost-effective solution for the use case. However, larger storages were suggested when the objective changed to minimizing the yearly electricity bill, and a seasonal charging/discharging pattern was achieved.

Real-Time Home Energy Management Systems for Operating a Residential Energy Storage

Student: **Jon Olav Båtbukt**
Supervisor: **Salman Zaferanlouei**

Problem description

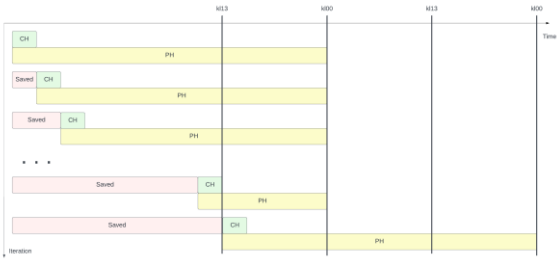
In the Norwegian power market today, consumers have primarily a passive role. However, with the increased adoption of DERs, the concept of active consumers and prosumers is gaining traction. With the constantly rising electricity consumption and volatility of electricity prices, solutions for participating in the power market for producers and consumers is a prominent field that will only become increasingly relevant.

The task

This thesis investigates the benefit of incorporating a Home Energy Management System (HEMS) as a residential Battery Energy Storage System (BESS) in a household. More precisely, the goal is to reduce the spot price cost for a household and comment on whether an investment is worthwhile from an economic standpoint. The optimal real-life battery scheduling is solved with an adapted version of the Rolling Horizon (RH) algorithm with Long Short-Term Memory (LSTM) forecasting and applied to hypothetical households in different power regions of Norway over a year.

Model/ measurements

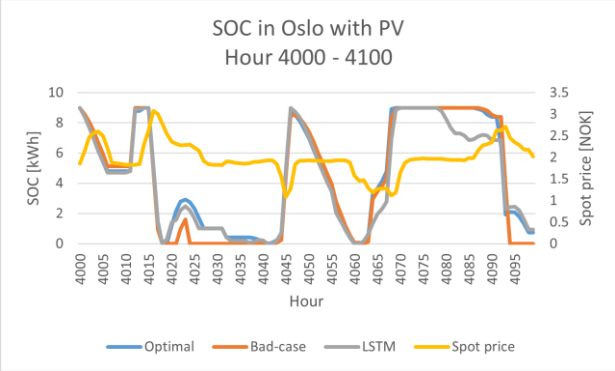
A baseline for each region is calculated and used as the reference point when calculating reduced spot price costs. The result is compared to RH with a simple bad-case forecast (using previous measurement as forecast), perfect information, and the best solution by solving the whole year as an optimisation problem. LSTM model was created to forecast values for demand and PV production, which was applied to an altered version of RH that follows the timeline when spot prices are known. For each iteration of RH, an optimisation problem describing the battery behaviour, grid, PV, and goal of minimising spot price costs is run.



Calculation

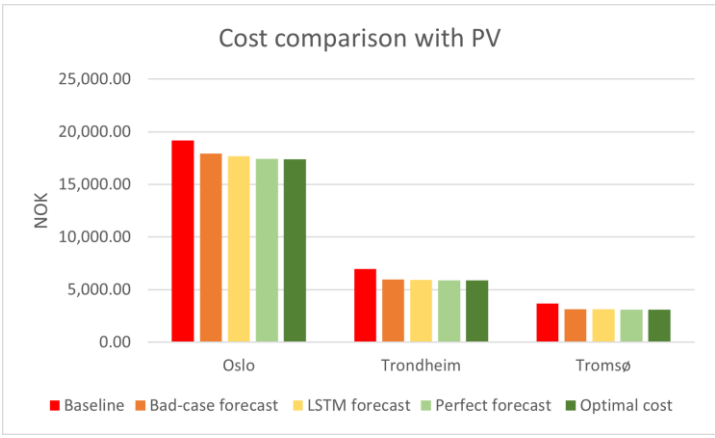
By applying a residential BESS to a household with an existing PV system, a reduction in spot price costs over a year is found to be -7.84%, -14.91% and -15.18% for Oslo, Trondheim and Tromsø respectively, when applying the RH algorithm with LSTM forecasting. With no PV system, these cost reductions are -8.06%, -14.40% and -14.67%. Even though Oslo has the lowest relative reduction in cost due to the high price levels for NO1, Oslo has the highest cost reduction in absolute reduction. Using NPV calculations, applying a residential BESS to a household in Oslo with no PV infrastructure is the only scenario justified from purely an economic standpoint.

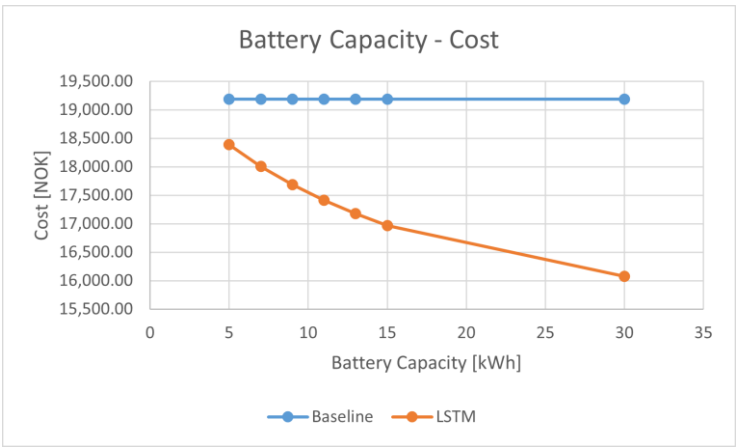
By increasing the PV capacity a household possesses, the spot price reduction capabilities of the HEMS reduce drastically since the PV output reduces the cost from the baseline scenario with which the comparison is made. Based on the sensitivity analysis results, it can be concluded that battery capacity has the most significant impact on the reduction of spot price costs from the parameters that consumers control when making investment decisions.

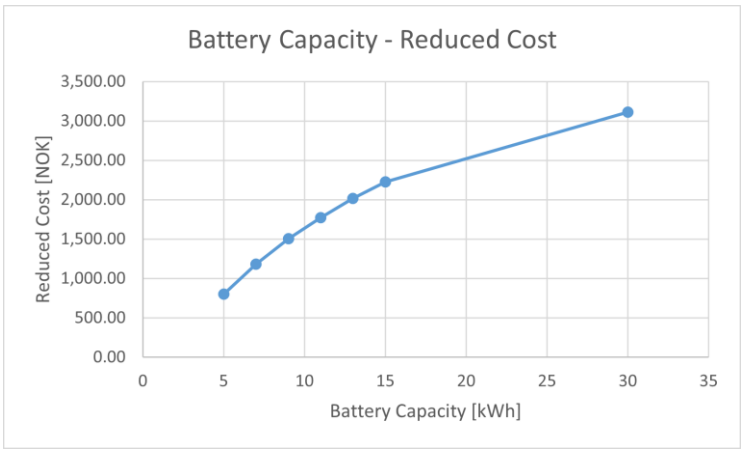


Conclusion

For all cases, including a BESS significantly reduced the spot price cost for the household. There are significant discrepancies in the spot price bills between power regions, so a considerable cost reduction relative to the baseline does not necessarily guarantee profitability for the investment. Not including the use cases a BESS could have outside of being a tool to save money, implementing a HEMS is only monetary beneficial in Oslo (NO1) if there's no PV attached. This configuration has a yearly cost reduction of 2 053.50 NOK (- 8.06%), resulting in an NPV of 4 932.52NOK. All other configurations of city and PV had a negative NPV. A simple bad-case forecast dramatically reduces the cost towards the optimal solution, and more accurate predictions will further reduce the gap.







Energy Certificate Trading using Distributed Ledger Technologies

Student: **Kristian Astad Dupont**
Supervisor: **Ümit Cali**
Contact: **Kristian@astaddupont.dk**

Problem description

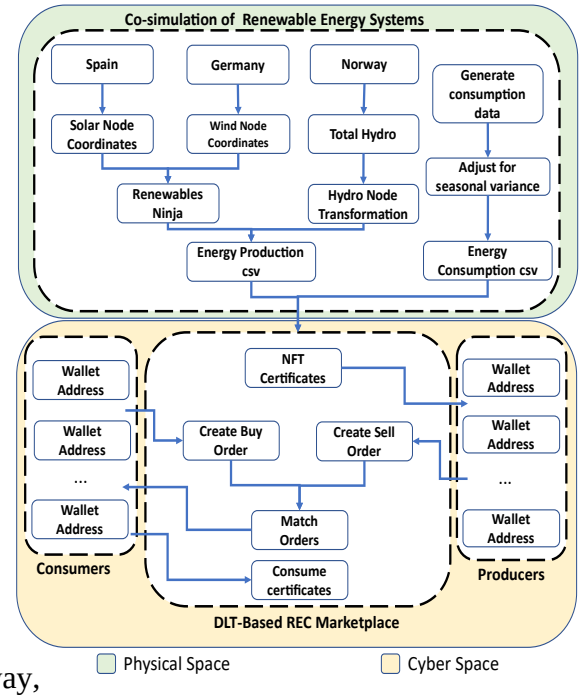
As the world moves from a dependency on fossil fuels and gray energy, to a greener and more sustainable place, the importance of traceable energy increases. Within the European Union (EU), the European Energy Certificate System (EECS) has introduced Guarantees of Origin (GO)s to provide such energy provenance for consumers and producers. Currently, GOs are being bought and sold on a plethora of platforms, both peer to peer or through auctions. After the purchase, the concrete transfer of the GO is done on a separate system involving third parties needed to ensure the legitimacy of the trade.

The task

This thesis proposes that Distributed Ledger Technology (DLT)s may fulfill the role of both the marketplace and the trading mechanism. Specifically, it looks at blockchain technologies, their functionality, use cases and flaws. Modern blockchains are designed for general information storage and trade, and the inclusion of smart contracts has enabled users to create complex conditions for how and when an asset should be transferred. Potentially, GOs could be both sold, bought and transferred on a blockchain, where the entire history of each certificate would be transparent for any auditing body to check.

Model/ measurements

For this thesis, a two-part job has been done. The main work consists of creating, testing and evaluating a marketplace for GOs based on blockchain technologies, but to accommodate the certificates employed on the marketplace, there is also a co-simulation used to create realistic time-series data for power production. The on-chain marketplace and the power co-simulation forms the basis for a physical layer simulation and a cyber layer simulation. An overview of the entire methodological structure can be seen in the figure to the right. Note that there are two flows of data to the cyber layer, one flow for the energy produced, which in turn determines the amount of certificates created, and one flow for the energy consumed, which will determine the certificates consumed by each node.



The physical co-simulation creates fifteen imaginary trade nodes spread around Germany, Spain and Norway, where they respectively produce energy from wind, solar and hydro.

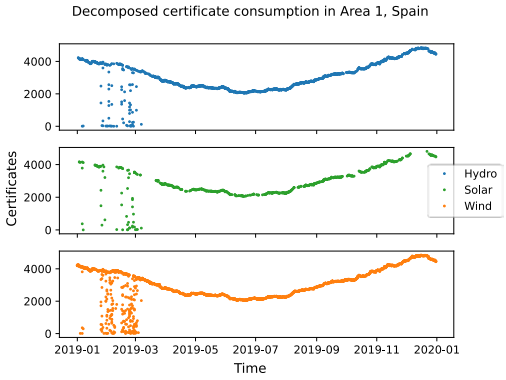
The REC-marketplace is implemented with two different Ethereum NFT standards, so that a comparative analysis can be made. These two standards are compared on the metrics of blockchain storage space used per certificate traded, and time spent per certificate traded. The

two implemented standards are the ERC721 Ethereum standard, and the ERC1155 Ethereum standard.

Results

The two tested standards showed marked differences, with the ERC1155 standard being both significantly faster and occupying less storage space than the ERC721 standard. The nature of the ERC1155 standard allows for complexities that do not scale with the number of certificates being traded, only with the amount of transactions done. Comparatively, the ERC721 standard scales in both time and storage space with the number of certificates per transaction, as well as the number of transactions.

This resulted in the marketplace simulations being done using the ERC1155 standard, as the other standard was too computationally heavy. The marketplace simulation handled one year worth of energy certificates, which corresponded to 314 690 721 total certificates. In the figure to the right, the consumed certificates for one of the nodes in Spain can be seen. Spanish nodes consumed only solar certificates, so all wind and hydro certificates have been bought from other nodes through the on-chain marketplace. For most of the year, the certificate consumption of the node covers the energy consumption of the node, but there is a period during the first three months where there is a certificate deficit within the entire system. In other words, as all certificate stockpiles started at zero, the net clean energy production was less than the consumption between the start and the time of the certificate purchase.



Conclusions

Overall, this thesis explored the potential for a DLT-based marketplace for energy certificates, and a proof of concept model was developed and implemented. The goal was to improve the fluidity, trackability, transparency and automaticity of the system. Fundamentally, the idea was to represent each certificate as a Non-Fungible Token on the blockchain, as they provide one to one traceability of each certificate. However, the NFT implementation standard (ERC721) was compared to a newer standard (ERC1155). Intrinsically, the ERC1155 standard provided less transparency than the ERC721 standard, but they provided much better scalability, especially with regards to blockchain space and operational speeds.

A full year simulation was done for fifteen energy producers and consumers, spread across Germany, Spain, and Norway. These nodes acted as participants in the developed on-chain marketplace and conducted trades necessary to fulfill their energy consumption with corresponding energy certificates. The simulations showed a functioning marketplace, and the results showed all available certificates being consumed in times of certificate deficits, a decrease in stored certificates in times where the consumption was greater than the production, and an increase when it was the opposite. In all, it provided a proof of concept showing the potential of a DLT marketplace for certificates. There are, however, components lacking for a fully optimal simulation, and these include among others an improved auction mechanism, better testing data, and an expanded node network.

DC Breakdown Strength of HVDC XLPE Cable Insulation – Short-term testing of cable peelings

Student: **Anja Kjærnes Eilertsen**
Supervisor: **Frank Mauseth**
Contact: **anja.2411@hotmail.com**

Problem description

The electrification of the society leads to higher total electricity demand and the aim for sustainable solutions. For such solutions extruded high voltage direct current (HVDC) cables are a key factor. Additionally, HVDC cables are essential concerning renewable energy sources, for instance, as links between land and offshore wind parks.
The use of extruded 525 kV HVDC cables are increasing, and designs for even higher voltage levels are in development. Consequently, it is an increased interest in understanding how crosslinked polyethylene (XLPE) ages under thermo-electrical stress.
Aging behavior is crucial, considering the reliability of high voltage transmission systems.

The task

This project aims to investigate to what degree the electrical breakdown strength of the insulation layer of HVDC cables change as the material ages. In addition, the effect of radial position on the DC breakdown strength is assessed.
It is collected data on the breakdown strength of XLPE cable insulation under the application of DC voltage and subsequently a statistical analysis of the data is conducted.
The breakdown tests were performed on XLPE insulation in the form of cable peeling. The cable peeling was cut from a full-scale cable HVDC cable, which had been manufactured following the typical processes. Both pristine, 'fresh' and aged XLPE cable insulation was tested.

Model/ measurements

The DC breakdown tests were performed using a DC source and a test cell established in a preliminary study. The circuit also provided the ability for secure measurement of the breakdown voltage. The electric circuit can be seen in Figure 2, where box 1 is a half-wave rectifier and box 2 is a voltage divider for voltage measurement.
The cable peeling, seen in Figure 1, was sandwiched between two electrodes, and the voltage was increased in steps of 1 kV per minute until breakdown occurred. For each cable peeling, a series of 20 tests were conducted on three regions: insulation close to the inner semiconductor, middle insulation, and insulation close to the outer semiconductor. The thickness of the breakdown channels was measured, and the DC breakdown strengths were determined in kV/mm. All data were treated using 2-parameter Weibull distribution.

Figure 1: XLPE cable peeling.

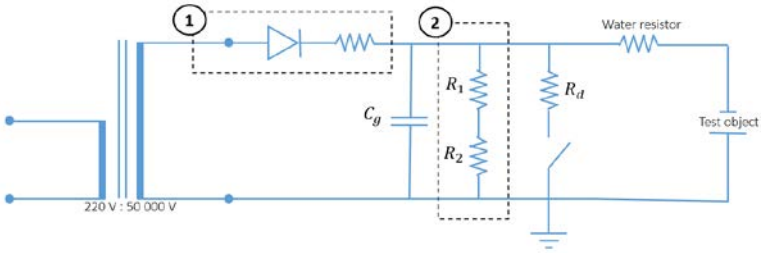


Figure 2: Electric circuit used for DC breakdown testing.

Calculation

From the DC breakdown tests performed on the fresh insulation, the 63.2% characteristic breakdown strengths were in the range of 550-580 kV/mm for the three regions of the insulation. For the aged insulation, the breakdown strengths were in the range of approximately 380-400 kV/mm. It was seen no statistically significant difference in the breakdown strength of the different regions in either of the insulation specimens.

The fresh insulation tested in this project shows higher breakdown strength than the results from previous studies conducted on the DC breakdown strength of XLPE cable peeling. The 63.2% characteristic breakdown strength is over 100 kV/mm greater than in the previous studies.

Figure 3 shows a bar chart comparing the 63.2% characteristic breakdown strength of the fresh and aged XLPE cable peeling. The breakdown strength has been reduced by over 150 kV/mm. Consequently, the reduction is approximately 30\% in breakdown strength for all regions.

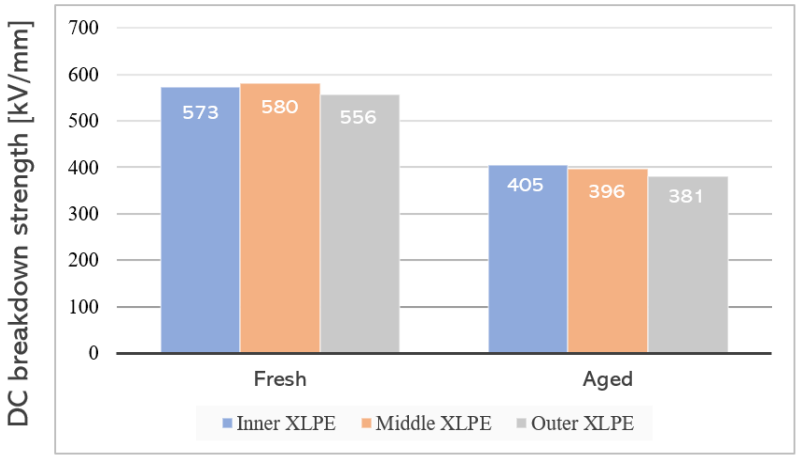


Figure 3: Bar chart comparing the 63.2% characteristic breakdown strength of the fresh and aged XLPE cable peeling.

Conclusion

In this work, three main findings are obtained:

1. Due to no significant difference in the breakdown strength of the regions in either of the insulation specimens, the conclusion is that the DC breakdown strength of XLPE is not dependent on the radial position of the cable insulation.

2. Since possible volume effects are minor, the higher breakdown strength of the fresh insulation tested in this project relative to previous studies conducted on the DC breakdown strength of XLPE cable peeling suggests a better XLPE matrix of the tested insulation in this project.

3. A reduction of 30% in breakdown strength after 40 years of thermo-electrical stress suggests a longer residual lifetime. Therefore, an expectation of 40 years of lifetime for this type of HVDC cable can be considered conservative.

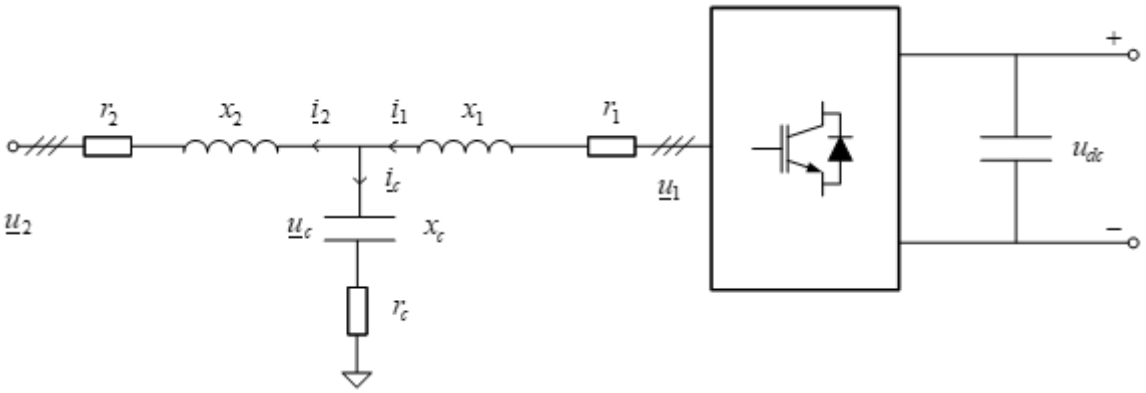
FPGA-based real-time modelling of active front end (AFE)

Student: **Kristel Storvik Einarsen**
Supervisor: **Roy Nilsen**

Problem description
In the emerging field of renewable energy, new control methods are being considered and have been researched for quite some time. Many studies can be found on the converter control techniques. This thesis is considering the AFE connected to a LCL-filter, the traditional PC computer simulations of the models take quite some time, and therefore the emulated real time simulation have been used for research and design. By employing FPGA implementation, tasks can be executed in parallel manner, enabling real-time simulations.

The task
The present thesis aimed at developing a real-time FPGA-based emulator of an AFE connected to an LCL-filter using the PESC control platform developed by NTNU.

Model/ measurements



During the development of the Emulated Real-Time Simulator, a simulation process is employed using Matlab, Simulink to analyze and evaluate how a AFE connected to a LCL-filter behaves. First, a simplified model where the AFE is represented by an ideal current source is studied. Followed by a more realistic model, where the converter is represented the power electronic insulated gate bipolar resistors (IGBT) switches, the result is a more realistic and complex model.
To further enhance the PESC control platform, an emulated model of the LCL filter is built using the mathematical model derived from the equations. The emulated model developed aims to capture the dynamic reactions of the LCL filter accurately.
Further the emulated mathematical model is discretezied. These discretized equations serve as the foundation for constructing the FPGA-based emulator, where the FPGA logic is developed in the Xilinx system generator for DSP add on in the simulink library.
Finally, the emulated model and a project file is configured with the PESC control platform, where the emulated model is ready to be tested. Simulation of different scenarios is done within the PESC control platform.

Conclusion

In this Master's thesis, the AFE is implemented using a hysteresis controller with a grid-following control scheme. The frequency and voltage are regulated by conventional synchronous machines, making the grid-following scheme adjusting for the active and reactive power based on the given voltage and frequency in the power system.

Furthermore, the PLL in the system was also tested. The emulated model for the PESC control platform has been successfully developed. Simulations play a crucial role in evaluating the performance of the control platform and analyzing its response under different operating conditions. Functions such as the phase-locked loop (PLL) and the effect of active damping are tested. Hence, the conclusion for the PLL is that the gain value, K_p, is desired to be as high as possible, but it is crucial to ensure that unwanted frequencies do not slip through, since the power electronics are vulnerable to disturbances.
To delete the harmonics coming from the grid and avoid destroying the components, active dampening is included in the model.

Ultimately, the successful implementation of this FPGA-based control platform will pave the way for improved motor drive applications and potentially other domains that require real-time control and high-performance processing. The FPGA simulation model provide with a fast simulation to achieve real-time. This is highly required in design procedures, for neglecting faults, big costs etc.
An important thing to consider for FPGA is the numeric representation and the scaling. The advantage of the Pu model is the broader application for the connected converter representation, as there is no need for different models for the higher rated voltage application and the lower voltage applications when the pu modelling is used.

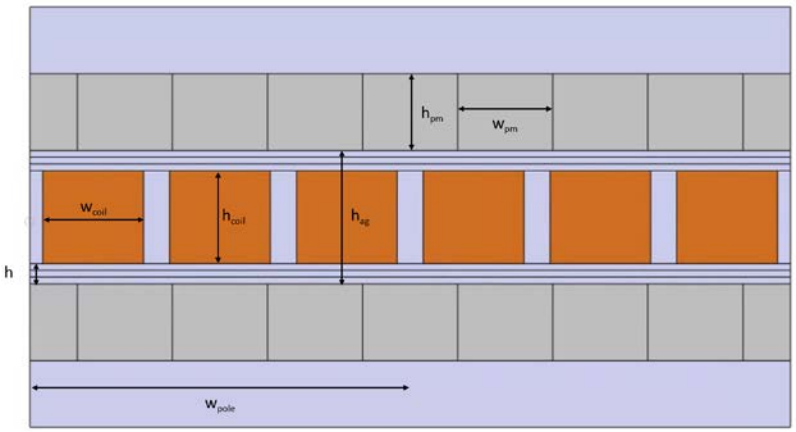
Design and Optimisation of Axial-Flux FiberPrinted Permanent Magnet Motor

Student: **Per Kristian Engen**
Supervisor: **Robert Nilssen**
Co-supervisor: **Alexey Matveev**
Collaboration with: **Alva Industries AS**

Alva Industries has developed the FiberPrinting™ technology for the production of stator windings. This technology is currently being applied to the manufacturing of radial-flux motors. These motors have a short axial length compared to diameter, giving them dimensions similar to axial-flux motors. Therefore, it has been decided to investigate whether an axial-flux topology will be more beneficial for motors of this size. This thesis investigates the applicability of using Alva Industries FiberPrinted windings for the use in axial-flux motors.

The applicability has been investigated by first making an initial axial-flux motor design. This design was implemented as a 2D FEM model in COMSOL Multiphysics. This FEM model was used as the basis for an optimisation study using the COMSOL optimisation module. Two optimisation studies were carried out, one in which the objective function was to maximise the torque density and one to maximise the efficiency of the motor.

The objective function *maximise torque density* gave the most optimal axial-flux motor design. The resulting design was a dual rotor, single stator motor with a radius of 89.5 mm and an axial length of 15.5 mm, with a magnet height of 2.23 mm, a current density of 11.456 A/mm^2, torque density of 10.39 Nm/kg and an efficiency of 97.5 %.



Parameter	Coordinate Search
J $[\frac{A}{m^2}]$	$11.456 \cdot 10^6$
h_{PM} $[mm]$	2.23
l_{axial} $[mm]$	7.76
$\alpha_{hb}[deg]$	34.7
m_{tot} [kg]	0.554
m_{cu} [kg]	0.140
m_{PM} [kg]	0.380
m_{epoxy} [kg]	0.029
T_d $[\frac{Nm}{kg}]$	10.39
T_{out} [Nm]	5.75
P_{out} [W]	2708
η[%]	97.5
I_{peak} [A]	65.87

Furthermore, two parameter studies were carried out. One investigating the impact of the air-gap height and one investigating the impact of the inner-to-outer radius ratio. The air-gap height study showed that having the air gap as short as possible is the optimal solution. The inner-to-outer ratio study showed that the optimal ratio was $1/\sqrt{3}$.

Making an axial-flux motor using Alva Industries FiberPrinting™ technology shows promising potential. The design proposed achieves better performance than its radial-flux counter part, while using approximately the same amount of materials and having half the volume. The design still has some uncertainties, as several simplifications have been made in the design process. More research is necessary before determining the final performance of an axial-flux motor made with FiberPrinting™ winding. Overall, the results show that there is a high potential in the axial-flux configuration.

Implementing LSTM machine learning in long-term hydropower scheduling

Student: **Øystein Steinsvik Evjen**
Supervisor: **Jayaprakash Rajasekharan**
Co- Supervisor: **Jinghao Wang**

Problem description

The world is currently experiencing a growing energy demand. This demand for energy, along with the environmental crisis, has made most of the newly created power plants renewable. Renewable power plants have the disadvantage of being unpredictable and not possible to schedule compared the fossil power plant. Hydropower plants have the advantage that they can be scheduled and therefore counteract the disadvantage of renewable energy plants. The downside of the hydropower plant is the complexity of the scheduling, especially if the hydropower plant has cascading reservoirs. This complexity makes the hydropower scheduling a highly computational time-have task that might need suitable hardware or might take too long time to be done as often as needed. Machine learning might be a good substitute for the optimization model used in the hydropower schedules to reduce the computational time but to be a good substitute must, the accuracy of the machine learning prediction must be good.

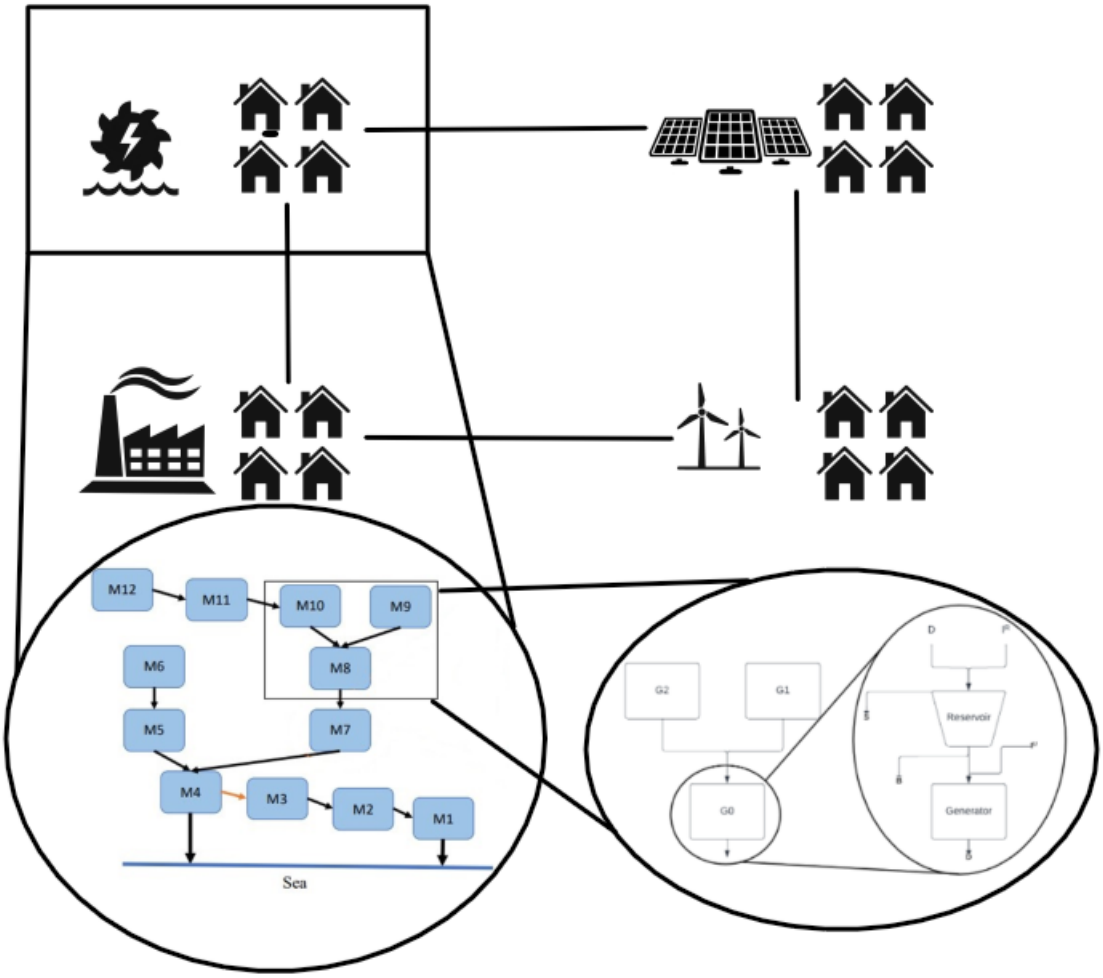
The main research question for this master thesis is: Can the optimization model in long-term hydropower scheduling be substituted by a machine learning model in order to reduce the computational time?

The task

From the literary review, the state-of-the-art hydropower scheduling technique found the FanSi model. This model combines optimization with simulation and will be the model with which the machine learning model will compare its results. Further from the literature review, have the long short-term memory (LSTM) Neural Networks been found to have potential as a substitute for the optimization model.

Model

A case study was created to investigate how the machine learning model performed. This case study included three cascading reservoirs in a hydropower plant. The case study uses a modified data set provided initially for all 12 reservoirs. This data set provided 50 years of data to ensure proper training and testing data for the machine learning model was 2507 extra years of synthetic data based on the original. The original and synthetic data was sent through the FanSi model to create training and testing data for the machine learning models. Four machine learning techniques were used, Ridge, XGBRegressor(XGB), LSTM, and Ensemble. Ridge and XGB were created as baseline models that the LSTM model had to outperform, and the Ensemble model was a combination of the three other models to test if this would exceed the performance of the LSTM model.



Figur 1 Case study

Calculation

The results showed that the LSTM model had a 99.7% reduction in computational time compared to the optimization model used in the FanSi model. This is an extraordinary result. However, the accuracy of the LSTM model yielded different results. The LSTM model slightly outperformed the Ridge model at one location and had MAPE scores of 94.7%, 67.5%, and 75% on the three different reservoirs when predicting production. The 94.7% is an excellent result, but when the accuracy is good, below 80%, it starts to lack what is needed from the model. The Ensemble model did beat the LSTM model on one occasion as it was close on others, but in most cases, did this not outperform the LSTM model.

Conclusion

The LSTM model had a fantastic computational time reduction and performed best in overall accuracy, however, it was outperformed once by the ridge model, and it had accuracy scores as low as 67.5%. From the case study conducted in this thesis, can it be concluded that the LSTM machine-learning model can be a great supplement, but it is not ready to substitute the optimization model used today.

Converter stress on transformer insulation materials

Student: **Fagerli, Brynjar**
Supervisor: **Niayesh, Kaveh**

Abstract
An increasing amount of technologies connected to the power grid utilize power electronic converters, both on the consuming and generating side. This affects how the insulation materials of the electric equipment in the grid are stressed. The converters are approaching ever higher switching frequencies and shorter rise times to minimize the power losses in energy conversions. These stresses are contrary to the traditional 50 Hz sinusoidal voltages, which most electric equipments are dimensioned for. This study aims to compare how these two kinds of voltage stresses lead to partial discharges (PDs) in two different transformer insulation liquids. A thorough investigation of the characteristics of surface discharges (called streamers) in liquid/pressboard arrangements exposed to a highly divergent electric field was performed. The insulation material used in the laboratory tests is based on the most typical type of transformer insulation, namely dielectric liquid in combination with liquid-impregnated pressboard. With this insulation system, the PDs were investigated by applying voltage to a sharp-edged electrode.

The mineral oil Nytro 10XN and the synthetic ester Midel 7131 were used and compared in the experimental tests. To test the insulation materials, a predefined number of 30 Hz bipolar square voltage pulses with varying rise times was applied for each voltage level, with voltage values ranging from 8 kV to 25 kV. In addition, it was performed tests with 30 Hz sinusoidal voltages ranging from 18 kV to 35 kV. To obtain experimental data, three different measuring devices were utilized; photomultiplier tubes (PMTs), an oscilloscope, and an intensified CCD camera. To quantify and compare the measurements, the PDs were studied by post-processing data from the oscilloscope in MATLAB.

The discharge probability and maximum PD amplitude were higher for lower rise times, for every given voltage level in both dielectrics. Further, the positive polarity discharge probability was generally higher compared to the negative polarity discharges in both dielectrics, except for the sinusoidal measurements performed in Nytro, where the negative polarity discharge probability was significantly higher. The maximum PD amplitude in Nytro was higher than Midel for all the square voltage measurements, but in the sinusoidal measurement, there were no clear differences until 25 kV was reached. From 25 kV the maximum PD amplitude in Midel was consistently higher than in Nytro for the sinusoidal measurement. In Nytro, a viscous gel would form during every measurement, where the amount of gel correlated with the size and the number of discharges. The gel functioned as a protective shield against discharges. This, together with the space charge effect, was assumed to be the main reason why the sinusoidal measurements in Nytro deviated from the other measurements. The results also indicated that higher maximum PD amplitudes in Nytro occur earlier in relation to the applied square voltage.

Finally, a more in-depth analysis of discharges occurring in Nytro (16 kV) and Midel (23 kV) was performed. The results showed that every first discharge (except one in Midel) on a new location on the electrode in both dielectrics was initiated on the positive half-cycle of the voltage. When a negative polarity discharge appeared, it was in 58.8% (Midel) and 65.4% (Nytro) of the cases after a positive polarity discharge had occurred in the preceding half-period of the voltage. There were generally fewer half periods between each following discharge on a specific location in Midel compared to Nytro. This confirms that Nytro is more prone to the space charge effect.

Thermal Analysis of ModHVDC Generator using Thermally Conductive Electrically Insulating Materials for Improved Heat Transfer

Student: **Christoffer S. Falck-Johansen**
Supervisor: **Pål K. Olsen**

Problem Formulation

Traditional electrical insulating materials used in high voltage machines for windings, slot liner and back-iron provide a thermal barrier that impedes heat flow out of the machine, this also limits the power density and in worst case lead to demagnetisation of permanent magnets.

To increase heat flow a *Thermal Conductive Electrically Insulating* (TCEI) material is placed between the yoke and frame to improve the heat transfer from machine core to frame surface

Objective

The first steps to identify the way forward was determined as:

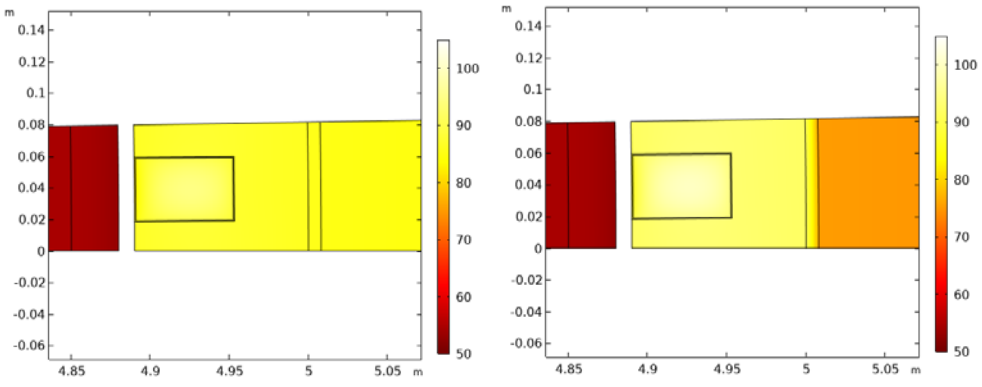
- Determine an ideal approach for cooling that builds on passive solutions
- Finding a suitable Thermal Conductive Electrically Insulating material

The chosen TCEI material and method of cooling will be implemented in an analytical and numerical model. For this, the success criteria are set to be:

- Lowered core temperature compared to the traditionally insulated machine
- Improved heat flux through new insulating material compared to traditional

FEM Model

The thermal conductivity of the traditional insulating material is compared with that of the TCEI ceramic. The thermal barrier provided by the mycalex is quite visible on the figure on the left. The higher core temperature of the windings should also be visible.



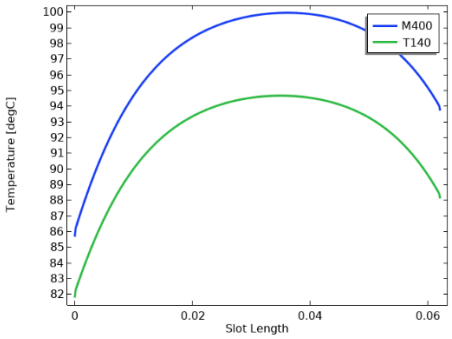
Estimations

The accuracy between the *Lumped-Parameter Thermal Network* (LPTN) and that of the FEM analysis, seen in the table, is quite satisfactory and is seen as a confirmation of correct modelling.

However, the similarity between the LPTN and the full-scale FEM model is not so accurate. This is likely accredited to the area difference of around 13% between the two models.

Regardless, the models showed a highly similar trends and the lowered core temperature is considered as a positive indicator of the improved heat transfer capabilities in the insulation. The diagram shows estimated core temperature of the two materials investigated at 600min.

T140	FEM eq	LPTN	$\Delta°C$	$\Delta\%$
Frame	85.2	85.2	0	0
Insulation	85.6	86.2	0.6	0.7
Stator	88.2	87.4	0.8	0.9
Winding	94.7	93	1.7	1.8
Magnet	54.6	50.1	4.5	8.2
Rotor	54.6	50	4.6	8.4



Conclusion

The success criteria for this thesis were defined *as Lowered core temperature compared to the traditionally insulated machine* and *Improved heat flux through new insulating material compared to traditional*. With the use of TCEI material between the frame and yoke it could be found that the core temperature of the windings where lowered. There was also an increase to frame temperature, something that is consistent with the increase of heat flow through the insulating layer. In this regard the use of TCEI between frame and yoke has attained the intended goals.

Overall, the implementation of TCEI between frame and yoke seems insufficient to handle most of the thermal challenges on its own. Other, preferably passive, solutions are needed to achieve sound and proficient Thermal management.

Regardless, use of TCEI material clearly indicates that it is possible to improve thermal conditions in the machine. Applied to other heat sources such as windings and coupled with optimised machine design, it is believed it is possible to facilitate further improvements to the thermal management.

Networked Control of Complex Cyber-Physical DC Microgrids: On the Potential of Scalable Stability Features of PI Consensus Estimators

Student: **Kamilla Bakkane Folgerø**
Supervisor: **Gilbert Bergna-Diaz**

Problem description

The energy sector must enhance its effort to transition from fossil fuels to renewable energy sources and contribute to novel net zero solutions. The demand for renewable energy sources in a limited amount of time leads to exploring new alternatives. In particular, microgrids facilitate the shift towards renewable distributed energy resources (DERs), which are typically small in scale and located at short distances from the loads.

The task

This master's thesis investigates a cyber-physical DC microgrid proposed in a research paper. The microgrid is controlled by a suitable controller, which was proposed in another research paper. The electrical network, referred to as the physical layer, consists of distributed generators, converters, transmission lines, capacitors, and constant impedance-current loads. Furthermore, the DC microgrid is challenging the traditional hierarchical network structure by having a distributed communication network called the cyber layer. The distributed generators have only access to their neighbor's data, which allows for distributed communication techniques and consensus optimization to provide the two control objectives of proportional current-sharing and voltage containment. The thesis aims to obtain a scalable stability certificate for the cyber-physical DC microgrid, allowing *plug-and-play* features so that the microgrid can expand seamlessly without instability risks. *Large-signal stability* and *energy modeling* methods are utilized to obtain the stability certificate.

Model/ measurements

The control objective of voltage containment is achieved by using hyperbolic nonlinear saturation on the input voltage from the controller. Furthermore, the control objective of proportional current-sharing is achieved by introducing an optimization problem using consensus principles. Consequently, the optimization problem obtains an optimal set point for each generator via Karush-Kuhn-Tucker conditions. The set points of all generators are identical due to the consensus algorithm and the neighbor-to-neighbor communication. The optimization problem forms the Proportional-Integral Dynamic Consensus Estimators that can be implemented in the cyber layer as part of the controller. Furthermore, the distributed optimization problem also considers the second control objective of voltage containment, resulting in sub-optimal set points for the current ratios when the voltages are saturated to avoid integrator wind up. The controller also includes a regulator state responsible for minimizing the distance between the optimal set point and the current ratio. The controller is connected to a case-specific cyber-physical DC microgrid, and simulations are carried out to confirm that the controller satisfies the control objectives as shown in Figure 1.

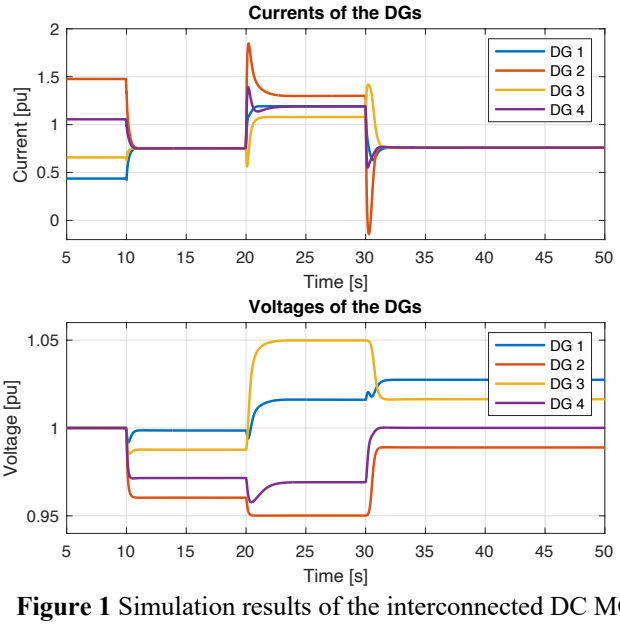


Figure 1 Simulation results of the interconnected DC MG.

Furthermore, it is demonstrated that both layers' open-loop systems admit to a port-Hamiltonian representation, and their respective passive outputs are determined, which serves as a beneficial starting point for energy control. However, in the attempt to connect the two layers, an important stumbling block appears that complicates the finding of scalable stability certificates. The thesis identifies that this issue occurs at the interface between the cyber layer and the regulator state. To reduce the system's complexity with the aim of investigating this issue further, voltage saturation is neglected in the energy modeling in this thesis.

Finally, some ideas from singular perturbation theory are used to justify using time-scale separation arguments as a potential solution to obtain a scalable stability certificate. This theory implies that the system is divided into fast and slow dynamics. Moreover, a modified controller is proposed based on this theory and the passive output of the cyber layer. In this proposal, the regulator state is considered the slow system, which behaves as a constant in the fast system and reduces the complexity of the equations. With this approach, energy analysis of the fast dynamics results in a stability certificate. However, to complete the stability proof using time-scale separation principles, the slow dynamics should also be analyzed, and only then could we conclude that the system will be robust to stability-related challenges under all circumstances. From a practical perspective, it is possible to disconnect the slow dynamics to maintain stable conditions in situations where unstable behavior begin to appear.

Conclusion

The thesis emphasizes the difficulty of obtaining both proportional current-sharing and desired voltage regulation while guaranteeing a stability certificate. The proposed controller successfully accomplishes the desired control objectives in the case-specific DC MG. However, challenges arise in preserving the port-Hamiltonian structure between the physical and cyber layers. Therefore, the system does not meet the requirements for obtaining a stability certificate, and alternative methodologies must be explored. Finally, the master’s thesis proposes the use of singular perturbations theory and time-scale separation arguments, which offers potential solutions for obtaining a scalable stability certificate. However, further research is needed to obtain a more comprehensive proof based on singular perturbation theory.

Integration of Power Transfer Distribution Factors and Internal Grid Constraints in Short-Term Hydropower Scheduling

Student: **Sivert Forbord, Håkon Sølberg**
Supervisor: **Olav B Fosso**
Contact: **Per Aaslid, Hans Ivar Skjelbred**
Collaboration with: **SINTEF Energy Research**

Problem description

This thesis aims to explore the implementation of Power Transfer Distribution Factors (PTDF) in the Short-Term Hydro Scheduling (STHS) problem to enable grid-constrained optimization. The problem definition stemmed from the projected increase in load demand and the introduction of Flow-Based Market Coupling in the Nordic Electricity Market.

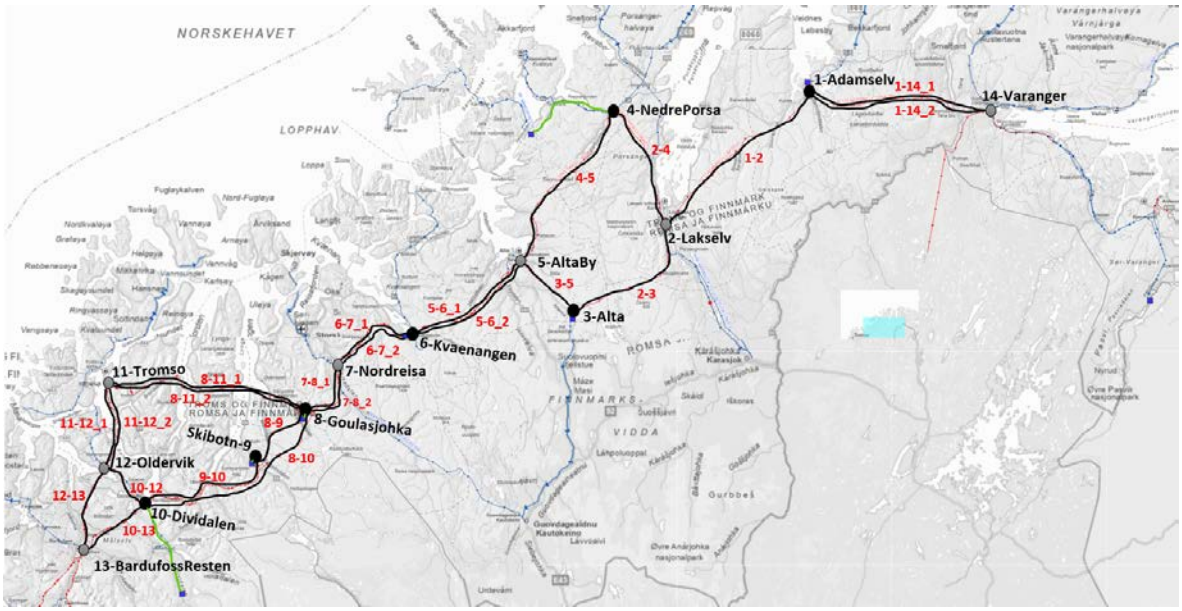
The task

The main questions to be addressed in this report is:

- How can grid limitations be taken into account for Short-Term Hydro Scheduling?
- How will the optimal operation of hydropower plants be affected by taking grid limitations into account?
- How can Power Transfer Distribution Factors be utilized in STHS?
- How can Power Transfer Distribution Factors be utilized in the electricity market?

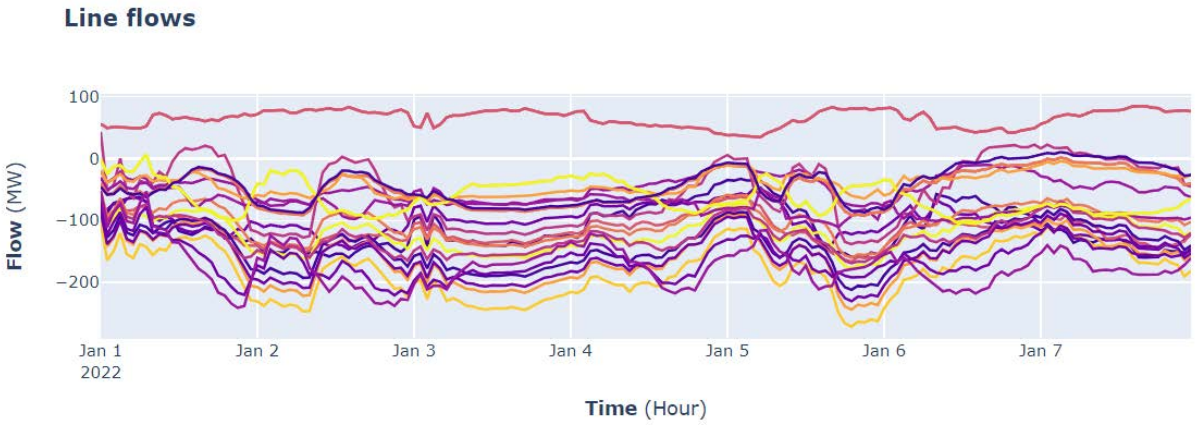
Model

To address this problem, a module was developed to generate and import PTDF factors into SHOP, a hydro scheduling tool developed by SINTEF. Utilizing transmission system modeling, a novel feature within SHOP, the PTDF factors were generated and applied to three optimization cases. These cases were based on a comprehensive system model of NO4, specifically developed for this thesis, including accurate models of hydropower plants and the transmission grid.



Results

Case 1 showcased how PTDF factors are used to generate optimization constraints within the SHOP optimization core. Additionally, these factors were employed to visualize the resulting line flows in the system. Case 2 focused on generating PTDFs for a line outage scenario, revealing how the power flow is efficiently redistributed away from the faulted line through the optimization process. Case 3 presented an example of generating PTDF for a smaller section within a larger area, emphasizing the importance of precise data regarding power flow into and out of the smaller area to obtain accurate results.



Conclusion

The discussion on the developed PTDF module concluded with recognizing the advantages of having a dedicated module capable of generating constraints for the optimization problem. In addition to PTDF, the module was also considered for incorporating contingency analysis and congestion management techniques. The insights derived from the conducted case studies in SHOP were utilized to examine different levels of PTDF implementation in the electricity market clearing process. The discussion encompassed various pricing approaches, including nodal pricing and zonal pricing with FBMC. The key conclusion drawn was that incorporating grid constraints into the market clearing algorithm introduces complexities related to market manipulation and unfair market positions. Addressing these challenges will require enhanced collaboration between Transmission System Operators and power producers.

Application for axial flux motor

Student: **Andreas Ersdal Fossmo**
Supervisor: **Robert Nilssen**
Contact: **Robert Nilssen**
Collaboration with: **Framo**

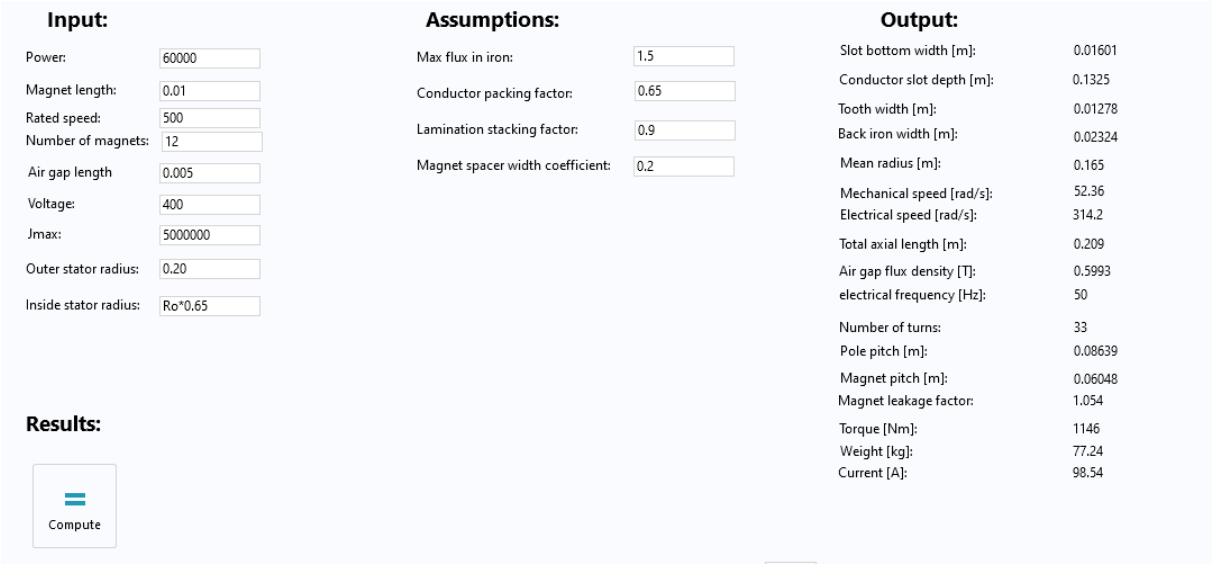
Problem description
Radial flux machines have a big share of the market of electric machines, but axial flux machine have become more popular in recent years. The primary objective of the thesis was to study how the parameters of an axial flux machine impact the performance. An app was made in order to do an optimization study in order to achieve a good axial flux machine, characterized by high efficiency and power density.

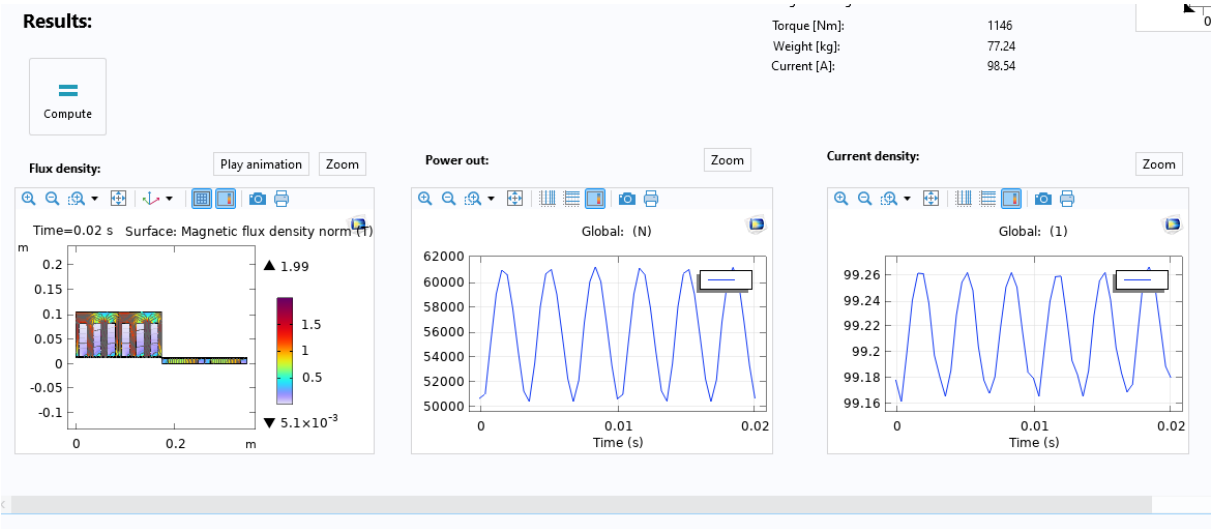
The task
This thesis aims to explore the key factors that contribute to the performance of an axial flux machine. The axial flux machine offers distinct advantages such as higher power and torque density, as well as the ability to be constructed with a slim profile, which has led to its popular nickname, the ”pancake motor.” To investigate the factors that contribute to a well-performing axial flux machine, an optimization study has been done using COMSOL Multiphysics. The primary objective of the optimization study was to study which parameter being important in optimizing the axial flux machine. Given that a good axial flux machine is characterized by high efficiency and power density when the diameter is big enough the optimization aimed to achieve these goals. The specific machine chosen for optimization was an axial flux machine with a power output of 60 kW, intended to deliver a torque of 1150 Nm at a rated speed of 500 RPM. Through the optimization process, various parameters and design elements were adjusted and analyzed to find the optimal combination that would result in the desired efficiency while minimizing the axial length. The aim was to producing a highly efficient axial flux machine capable of meeting the specified power and torque requirements. To enhance the optimization process and facilitate learning about what constitutes a good axial flux machine, an application has been developed using COMSOL Multiphysics. This app enables students to gain practical experience and learn from trial and error. By manipulating various parameters within the app, students can explore the significance of each parameter in achieving optimal performance and design of an axial flux machine. Importantly, deep knowledge of axial flux permanent magnet (AFPM) machines is not required to use the app. The idea for the app emerged during the development of an underperforming axial flux machine, prompting the question of how to improve its performance. The app serves as a platform to experiment with different parameters and

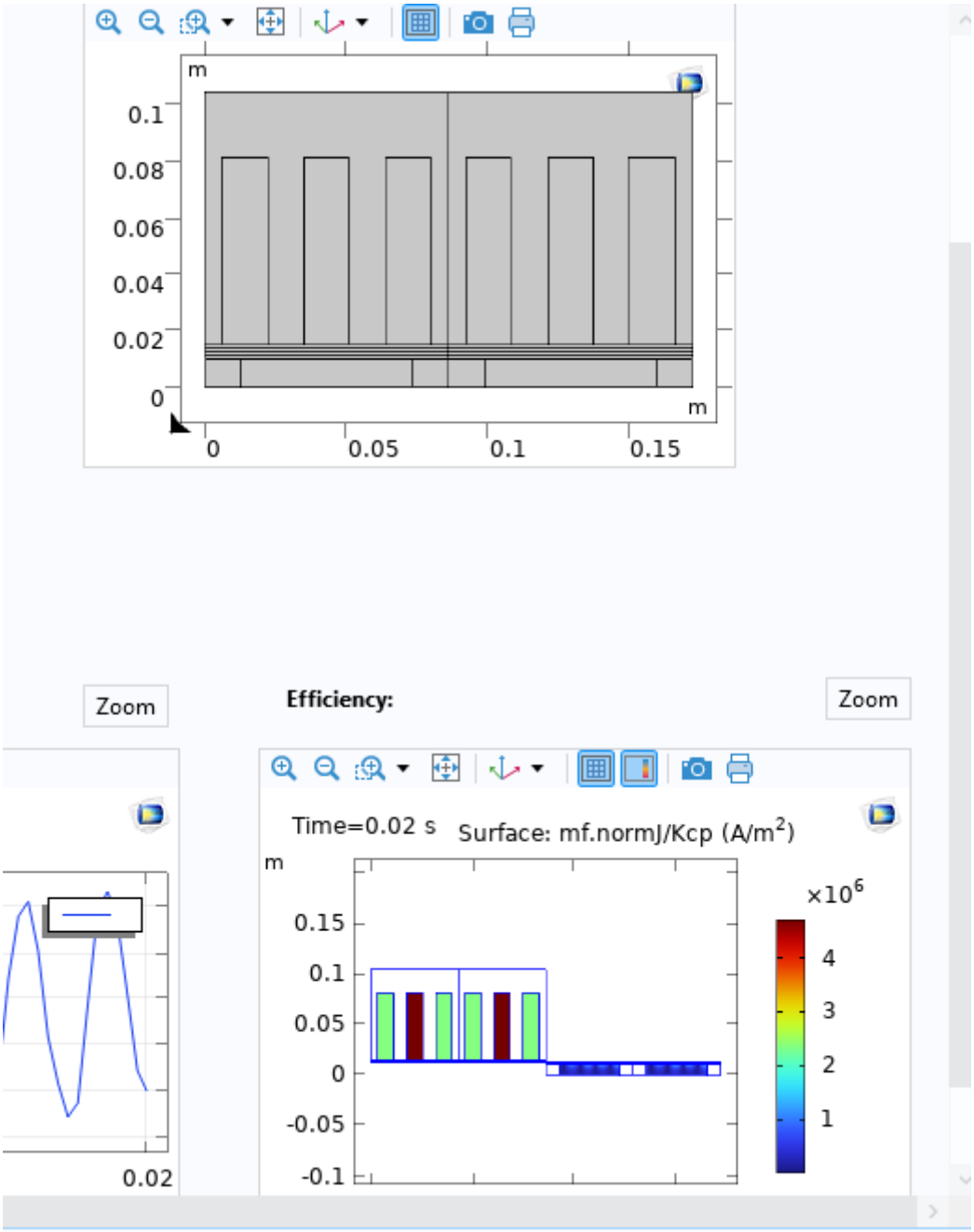
investigate which specific parameter modifications could lead to an enhanced axial flux machine. In this paper, an optimization study is done using the app, and the resulting optimizations are rigorously verified and cross-validated. By leveraging the app's capabilities, this study provides valuable insights into the optimization of axial flux machines, ensuring reliable and robust results.

Model/ measurements

The optimization was done in Comsol Multiphysics. An app was build using the "application builder" in Comsol. By changing the paraemters, a new axial flux machine could be made in the app, with new geometry and paramterers.

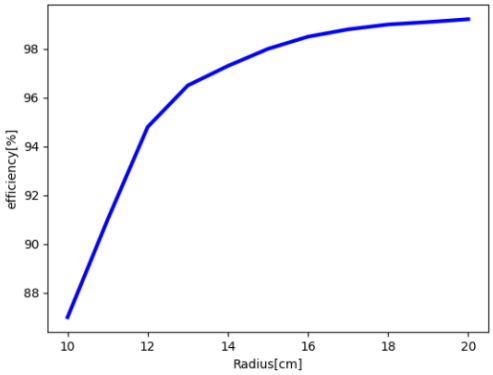




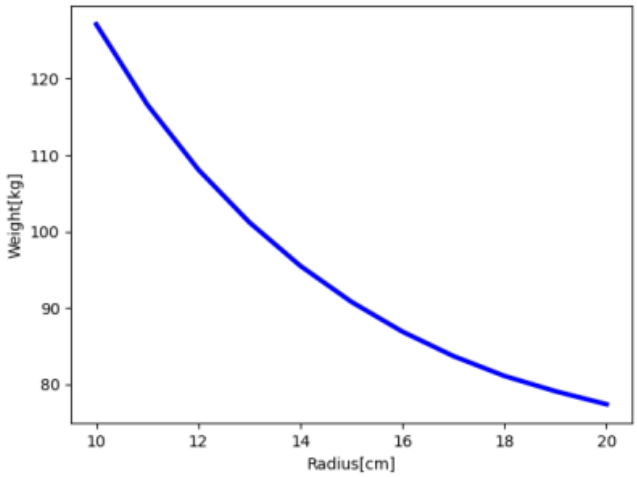


Calculation

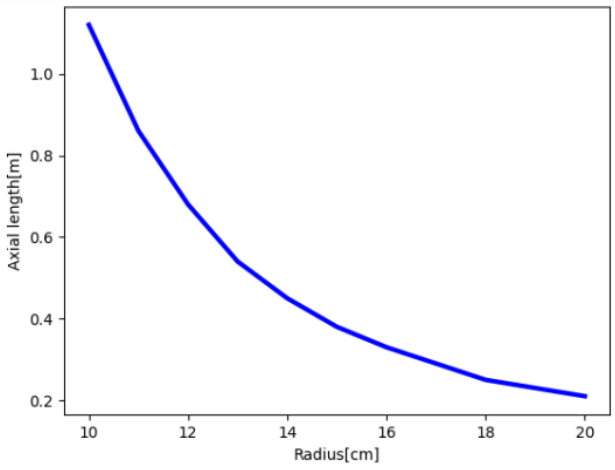
The calculation showed that the efficiency increased with increasing outer stator radius, the weight were reduced, the axial length where significantly reduced ant the cost reached decreased down to an optimum and increased after this point.



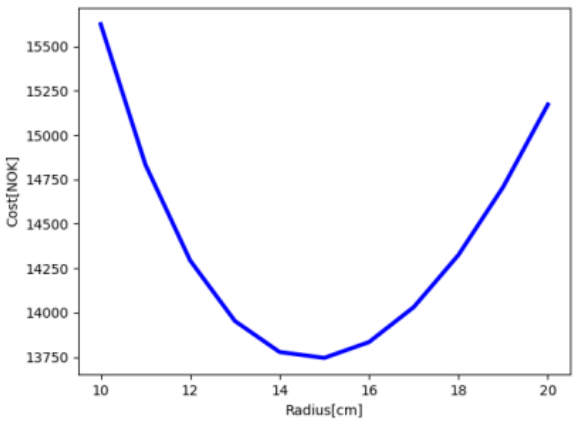
(a) Efficiency.



(c) Weight



(b) Axial length



(d) Cost.

Conclusion

A tool to design axial flux machines is made and the application is used to take a look into the impact of some of the parameters designing the performance and design of the machine A study of the outer stator radius shows the importance of this parameter for the axial flux machine, especially for the efficiency. The magnet length is an important parameter, expecially in case of the cost, which is a very important parameter for an electric motor. Not every application can have high rated speed, but in the cases where the rotational speed can be high, it looks like a very good solution. This will allow the motor to have a good efficency, low axial length, low cost and low weight. Almost every parameter will have advantage of high rotational speed. This application serves as a tool for axial flux machine, which can be used to study the machine design needed for an application. This can allow the designer to play with parameters making the machine more optimized.

Constraint-Driven Deep Learning for N-k Security Constrained Optimal Power Flow

Student: **Bastien Giraud**
Supervisor: **Olav B Fosso**
Collaboration with: **TU Delft**

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

Analysis and Testing the Influence of Circuit Parameters on Serial Arc Detection

Student: **Jørn Andre Mørck Gundersen**
Supervisor: **Eilif Hugo Hansen**

Problem description
Fires originating from the electrical installation is the largest cause of fires in Norway. Traditional circuit protection can detect overloads, short circuits, and earth faults, but series faults are not detectable. New installation protection called Arc Fault Detection Devices (AFDD's) can detect series faults such as series arcs and are set to become a mandatory requirement under the European low voltage installation standard IEC 60364. Several earlier theses and research articles have discussed situations where these devices have not performed up to expectations and the work in this thesis has look further into these problems.

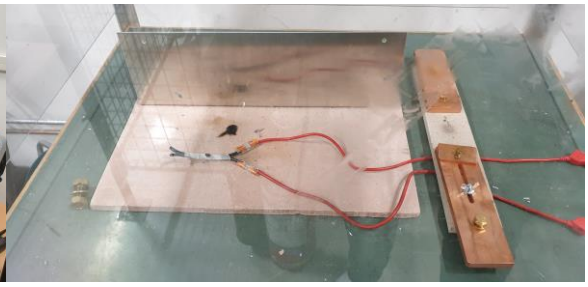
The task
To look further into problematic situations regarding arc fault detection the work in this thesis has been to:

- Identify and analyse in what situations arc fault detection can be obscured.
- Test AFDD's from different manufacturers in these situations.
- Record and analyse the influence of circuit parameters and loads on the current and determine why arc detection was influenced.

Model/ measurements
During this thesis five different tests were conducted to check the arc fault detection performance of AFDD's from four manufacturers. The tests consisted of:

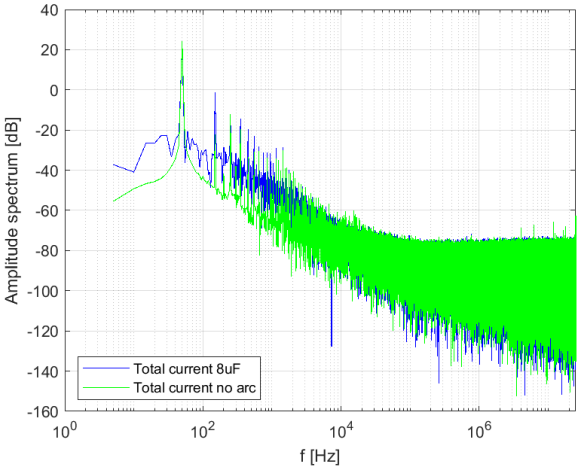
- Verification of the device's performance using a test setup from the standard *General requirements for arc fault detection devices* IEC 62606
- Testing the device's ability to detect glowing contacts or the precursors to glowing contacts which are contact arcing, usually in bad connections.
- Testing the influence of the ratio between arc current and parallel load current on series arc detection.
- Testing the influence of parallel capacitance on the detection of series arcs
- Testing the influence of a parallel connected switch-mode power supply on the detection of series arcs.

To assess how the circuit parameters influences series arc detection recording were made with the oscilloscope and used to identify characteristics in the current which could explain why series arc detection was influenced. The recordings were analyzed in the time domain and in the frequency domain with frequency amplitude spectrum and spectrograms.



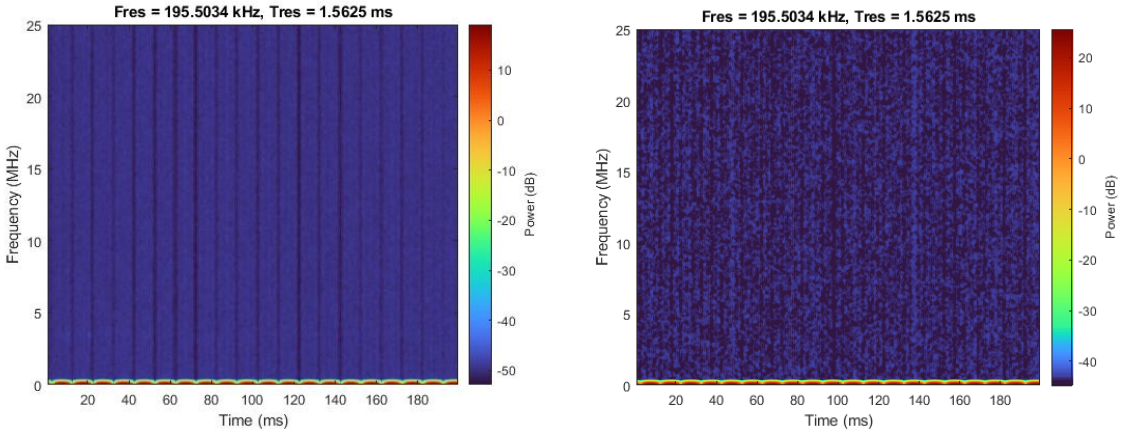
Results

To detect series arcs the AFDD's use high frequency noise in the current that originates from the arc. The high frequency noise changes when the arc extinguishes each half period, at current zero crossing.



The frequency spectrum amplitude representation did not give the desired results in verification of how the HF noise was obscured, but it gave a good visualization of changes in the harmonic frequency amplitudes.

By transforming the time recording to the frequency domain and representing as a spectrogram the HF noise from the arc was better visualized as seen below. The left figure representing the arc current, and the right figure representing the total current as measured by the device. The dark lines represent a lower HF power corresponding with the zero crossings of the current. On the right side figure the lines are obscured thus, the obscuration of the HF noise can be verified.



The results showed that all circuit configurations tested had an impact on the detection performance of some but not all the devices and it was the same two devices that had problems every time. The worst obscuring seemed to come from a low arc current with a high parallel load current, but capacitance and the power supply load also influenced the detection performance. It was also verified that all devices could detect different types of arcs, such as creepage on char, contact arcing and electric breakdown in air.

Conclusion

The most important conclusions of this thesis were that:

- The spectrogram representation gives a good indication of the obscuring of HF noise and can be used to determine how much signs of arcing is obscured in a circuit.
- The ratio between arc current and load current has a large impact on the detection performance of the devices.
- Both parallel capacitance and SMPS as a load in the circuit will impact some of the device's ability to detect arcs.

- The variation in the detection performance is worrying and cause concern regarding whether the requirements in IEC 62606 are too low or if some manufacturers have tailored their devices to detect the arcs as they are suggested by the test standard.

Investigating Contributing Factors to Rogowski Coil Accuracy: COMSOL Simulation and Laboratory Testing

Student: **Thomas Wagensveld Van Hagejordet**
Supervisor: **Hans Kristian Høidalen**
Co-supervisor: **Mohammad Khalili Katoulaei**

Abstract

This study examines the performance and accuracy of various Rogowski coil configurations via laboratory testing and COMSOL simulations, with a primary focus on positional errors, angular shifts, the effects of crosstalk, and temperature variations. Comparisons between simulated and experimental results reveal minor discrepancies in reference scenarios, with ratio errors ranging from 0.7% to 4.8%. However, significant deviations were found in cases involving eccentricity, angular deviation, and influence of external magnetic fields (crosstalk), with total ratio errors ranging from 33.26% to 84.12% across all scenarios.

The study evaluated three distinct types of Rogowski coils: a commercial Fluke i2000 Flex coil, two custom-made Stiff Core Rogowski coils, with and without a 10-degree air gap, and a custom-made Compensated Rogowski coil.

The results demonstrated that the presence of an air gap has a significant impact on the performance of the coil, with ratio errors fluctuating significantly. In addition, the study revealed that while the effect of a return wire in mitigating the effects of external magnetic fields was less than anticipated, the absence of an air gap in the Stiff Core coil significantly enhanced its performance. This coil displayed nearly half the maximum ratio error, average ratio error, and standard deviation of its air-gap counterpart.

During laboratory testing, compensation methods were evaluated to mitigate the effects of the air gap. These methods demonstrated potential for reducing overall error, indicating areas for future research and development. Particularly, the compensated Rogowski coil outperformed its uncompensated counterpart, indicating the effectiveness of air gap compensation in reducing ratio errors under various conditions.

Simulations were also conducted to assess the influence of temperature fluctuations, emphasizing the importance of proper burden value selection to counter these changes. Notably, a lower impedance burden led to a higher deviation in response to rising temperatures. Conversely, a higher impedance burden demonstrated minimal impacts - less than ΔV −measured of 0.01% with a terminal impedance of 2M Ω. This contrasts with a significant deviation ΔV −measured of 0.25% noted with an impedance of 200Ω, underscoring the effectiveness of higher impedance burdens in reducing temperature-induced deviations.

This study reaffirms the usefulness of COMSOL simulations in modeling and improving Rogowski coil designs despite these limitations. It has potentially laid the groundwork for future research and enhancements, especially concerning the advantages of compensation methods and the importance of mitigating the effects of air gaps.

Investigating Transient Overvoltages due to Multiple Reignitions when Switching Small Inductive Loads

Student: **Hansen, Erik**
Supervisor: **Niayesh, Kaveh**

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

A Case Study on the Impact of Vehicle-to-Grid on Reliability of Supply in a Norwegian Distribution System

Student: **Magnus Rein Hatletveit**
Supervisors: **Olav Bjarte Fosso, Iver Bakken Sperstad, Aurora Fosli Flataker**
Contact: **magnus.rein.hatletveit@gmail.com**
Collaboration with: **SINTEF Energy Research**

Problem description
Reducing emissions to reverse climate change is one of the primary objectives of the sustainability goals set forth by the United Nations. Extensive electrification of the world has been pointed out as the most promising alternative to lower the carbon footprint on Earth. The transport sector alone is assumed to be responsible for approximately 27 % of the world's total emissions, which has led to an extensive overhaul of the traditional car fleet from conventional fossil-driven vehicles to electric vehicles. As electric vehicles are becoming the most prominent choice of transportation, the electricity demand is predicted to increase drastically in the years to come.

As the power grids could become more congested due to electrification, services will be needed to aid the grid in critical periods. If the growth of electric vehicles persists, the batteries of electric vehicles will inhabit a significant amount of untapped potential for battery storage that might be used for additional grid services. This is the main purpose of Vehicle-to-Grid (V2G) technology, which provides an opportunity of feeding electricity back into the grid from electric vehicles in times of need. This master's thesis will attempt to answer if the Vehicle-to-Grid technology can impact the reliability of supply of the power grid in Norway. Reliability factors such as Energy Not Delivered (ENS), System Average Interruption Frequency Index (SAIFI) and System Average Interruption Duration Index (SAIDI) will be the main aspects that will be investigated in relation to the impact of Vehicle-to-Grid technology on grid reliability.

The task
The task was to conduct a reliability analysis of the impact of using V2G services in the CINELDI power distribution system provided from SINTEF. A reliability assessment program in Python called RELSAD (RELiability tool for Smart and Active Distribution networks) was used for the reliability analysis of the reference system. The task included creating a full-scale model of the CINELDI reference system using RELSAD software components, and conducting a sequential Monte Carlo simulation for a year of load data.

Model/ measurements
To investigate the impacts of V2G on reliability of supply in the Norwegian power grid, a simulation tool in Python called RELSAD was used. The tool facilitates opportunities for Monte Carlo simulations to emulate the real-life operation of distribution networks. The program also supports the simulation of V2G services in addition to other active grid components. The primary objective of the thesis work was to use an existing grid model and transform the data from this grid model into RELSAD properties to be able to use RELSADs' own Monte Carlo simulation tool. As a representation of the Norwegian distribution system, the reference grid created by CINELDI was used. The topology of the CINELDI reference grid model is presented in the image below.

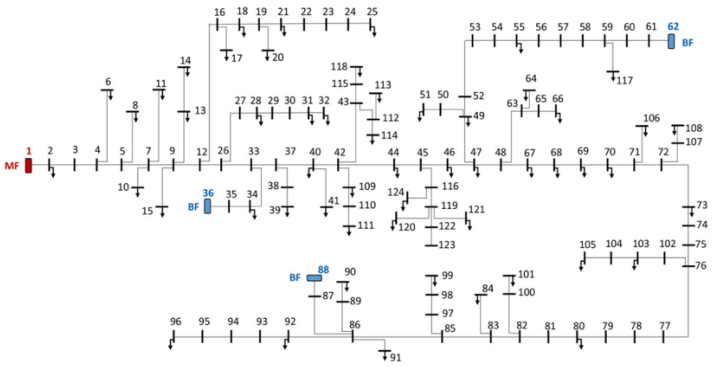


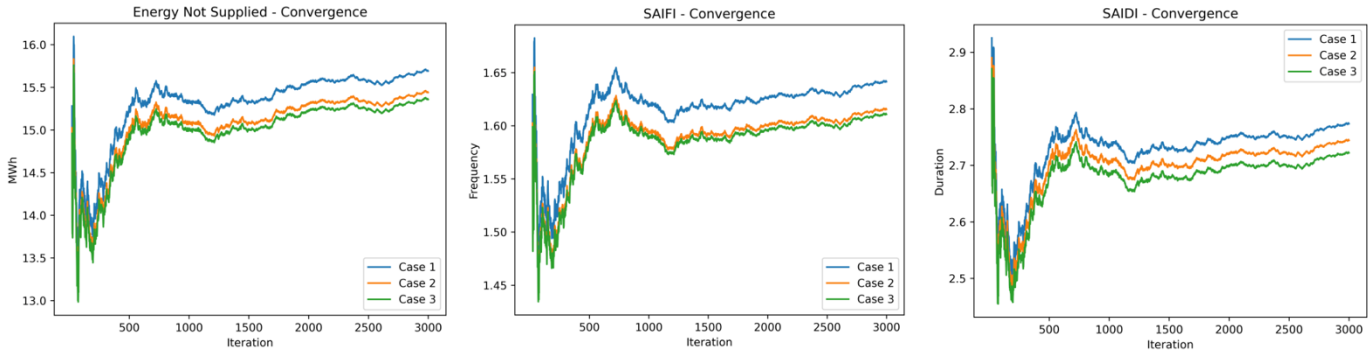
Figure 1: Illustration of the CINELDI reference system

The grid model was created as a RELSAD power system object by creating a function in Python that reads all relevant CSV-files on MATPOWER format and creates the corresponding RELSAD bus and line objects. Once this function was created, a script was written to add load data for an entire year for the RELSAD grid model. Further, a script for simulation was created, including inputs for start time, end time, time step interval and number of iterations. Three cases were tested for the simulation of the CINELDI reference grid model. These cases are presented in the image below.

Case	EV Charging Station	V2G Activated	Increased Charging Capacity
1	✔		
2	✔	✔	
3	✔	✔	✔

Results/Conclusion

When comparing cases one and two, one case being without V2G facilities and one case having V2G facilities activated, their mean ENS values after 3000 iterations were found to be 15.70 MWh and 15.45 MWh, respectively. This represents a decrease in mean ENS of 0.25 MWh. SAIFI and SAIDI values were found to be reduced between the cases, which could imply that the V2G technology can contribute to reducing the number of ENS with lower interruption frequency and duration. When comparing scenarios with V2G facilities activated, but one having an increased charging capacity from 3.7 kW to 7.4 kW for the EVs, the reduction of ENS was found to be 0.09 MWh after 3000 iterations. For these two cases, SAIFI and SAIDI was also slightly decreased. This would also suggest that the increase in the charging capacity of EVs could contribute to reducing the amount of ENS and lowering the number of interruptions with lower interruption duration.



Battery for Capacity Expansion: A Techno-Economic Case Study in Trøndelag

Student: **Heimvik, Torbjørn**
Supervisor: **Amin, Mohammad**

Abstract

To cope with climate change and population growth, electrification and new renewable energy generation are suggested as important measures. However, this causes challenges for the power grids as the peaks of power production and demand become higher. A solution to this can be the use of battery energy storage systems (BESSs), which can support the power grid with stability services and the end users with demand side management.

For the case of this study, an end user in Fosen (Trøndelag, Norway) wants to increase its power consumption. But, as there are capacity limitations in the power grid, the grid customer is not allowed to increase its consumption of grid power before grid reinforcements are in place. Therefore, this thesis aims to investigate how a BESS can be a solution, making it possible to cover an increased demand, and if it can prove to be technically and economically feasible.

Li-ion batteries are the basis for the energy storage system in the case. It represents a versatile type of battery, that can be used for many purposes, and are known to have long life spans and high efficiencies. Although the investment cost of a Li-ion battery is high, the prices of the battery packs have reduced considerably the last decade, making it a feasible solution for several other projects. The technical principles and limitations of a Li-ion battery, based on the LMO-NMC chemistry, are included in the models of this thesis. This also comprises degradation.

Optimization models for sizing and operation of the BESS have been made and solved using the Julia programming language with JuMP and Ipopt. The optimization problem for sizing includes a simple model of the power grid, with relevant constraints such as available power, operating costs and BESS investment costs. The unit costs of 2 500 NOK/kWh and 3 200 NOK/kW are the basis for the this. The optimal sizing parameters are found to be 12 500 kWh and 1330 (1500) kW. Further, these are taken as inputs for the operation model, which aims to simulate optimal operation for a period of four years, by minimizing operating costs. Degradation is also taken into account, with the results showing an aging of around 20 % after four years.

The most significant results for BESS operation are found for variations in electricity spot prices. For highly varying prices, such as for the elspot of NO5 in 2022, the net present costs of operation are found to be 2.41 % lower than a hypothetical scenario with only grid power. But for low prices with little variations (NO3 elspot, 2020) the costs are found to be 3.64 % higher. In other words, the potential costs savings from a BESS, for the case of this thesis, are quite low or none. Therefore, the feasibility of the investigated solution is mostly dependent on the investment cost, assumed to be above 54 MNOK, and the estimated revenue from increasing the power consumption. The load profile of the end user, representing few opportunities for reduction in peak power, is pointed out as a main factor of why the BESS is not generating more savings.

It is concluded that a BESS is probably not an economically feasible solution for the case of this thesis.

Exploring the Effects of Integrating Power Link Island into the North Sea through Transmission Expansion Planning

Student: **Tobias Sjøli and Daniel Steinar Holt**
Supervisor: **Salman Zaferanlouei**

Problem description

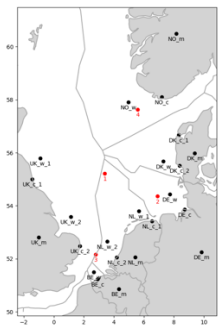
The objective is to investigate the benefits of integrating a PLI in the North Sea and optimizing the corresponding transmission grid. The research aims to optimize the transmission grid to maximize social welfare using the PowerGIM optimization model. By exploring a range of case studies with different scenarios and storylines, the ripple effect on the power market and assessment of the PLI feasibility will be examined. The case studies will investigate how the capacity size, location, and number of energy islands influence the total system cost and transmission expansion in the year 2030. Furthermore, we will examine their effects on power flows, average area prices, and the allocation of investment costs among the participating countries.

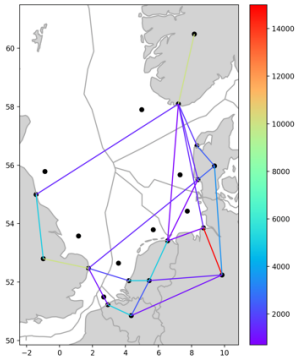
The task

Three case studies were conducted to assess the potential benefits of integrating power link islands (PLIs) into the North Sea through optimal investment and operational strategies, including power flow analysis, transmission capacity expansions, cost allocation among participating countries, and determination of area prices. The optimization model PowerGIM was used to minimize total system costs and maximize socio-economic welfare. To obtain insight into various directions for the European energy market, three datasets for future storylines were used in the simulations, each based on the TYNDP2022 report published by ENTSO-E.

Model/ measurements

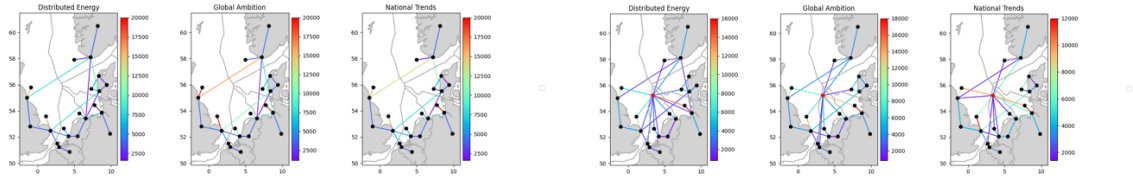
The model PowerGIM was utilized to solve the TEP problem. Datasets from TYNDP2022 was reconfigured to suit the input requirements for the model. The initial branches and nodes are shown in the figures below.





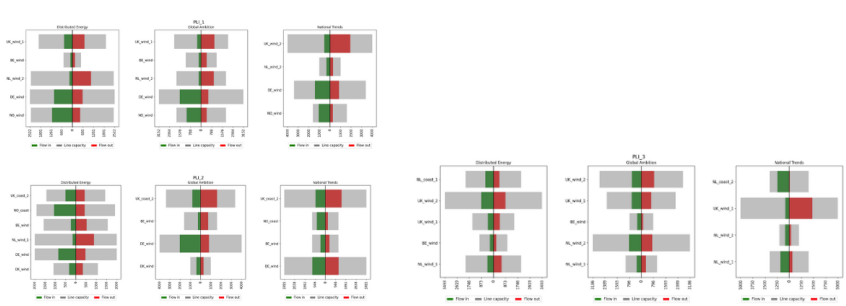
Calculation

The figures below show the optimal grid expansion for the most expensive scenario (left), and the cheapest scenario (right), for all storylines.



Total costs for all scenarios and storylines are presented in the table below and power flow is plotted in the figures for the scenario with three PLI incorporated.

Scenario	DE	GA	NT
Scenario A	1054.06	1416.41	828.01
Scenario B	1038.04	1391.56	816.54
Scenario C	1036.79	1389.72	815.65
Scenario D	1047.71	1406.56	824.23
Scenario E	1041.81	1397.64	819.67
Scenario F	1028.35	1377.88	808.61
Scenario G	1043.85	1399.71	821.74
Scenario H	1041.63	1394.79	820.02
Scenario I	1039.06	1389.76	818.18



Conclusion

National Trends turned out to be the storyline with the lowest average area price, remarkably lower than Distributed Energy and Global Ambition. This was primarily due to the low electricity demand, but it also reflected the extensive transmission expansion that was displayed during simulations. Global Ambition had the highest total costs due to its high electricity demand and emphasis on centralized generation, which demanded extensive transmission expansion. Distributed Energy proved to have the lowest investment cost as the spatial distribution of generation sources implied a reduced dependency on long-distance transmission lines.

Specifically, the case studies analyzed the impact of the PLI transmission capacity and the number of PLIs. The results displayed a clear economic advantage of investing in the PLI. The scenario that introduced a 50 GW PLI showcased the most significant cost reduction, with investment costs reduced to less than half compared to the base case scenario without a PLI, across all storylines. The implementation of multiple PLIs resulted in higher investment costs compared to installing a single PLI with the same capacity as all the PLIs combined. However, the operational costs remained the same for both scenarios. Therefore, building high-capacity PLIs in the North Sea emerges as the most cost-effective option given the model configuration

Co-Simulation Model for Optimal Wind-Hydro Coordination Using Wind Farm Control Dynamics: A Case Study of a Hybrid Wind and Hydro Plant System

Student: **Torbjørn Indrekvam Horstad**
Supervisor: **Umit Cali**
Collaboration with: **SINTEF Energy**

Problem description

The growing share of Variable Renewable Energy Sources (VRES) in power systems presents challenges for regulators, grid operators and energy producers. The VRES' operation has limited flexibility in their operations, as they are highly dependent on ambient environments. To address these challenges, decision-makers must consider multiple objectives, among these are revenue, power system services and mechanical load on wind turbines. Coordinated operation of power plants and different wind farm control strategies are examples of measures that can benefit these objectives.

The task

In this thesis, the aim is to investigate different actions to improve the operation of a congested hybrid system by implementing coordination and control of a wind farm and a hydropower plant using multi-objective optimization. To achieve this, a co-simulation framework based on the work of former master students at NTNU, Jamessen and Stave, is applied to a case study of a remote hydro plant and wind farm sharing a limited transmission capacity. The model investigates the different objectives of total revenue for the power plants and damage accumulation to the turbines of the wind farm. The second objective is analyzed by implementing wind farm control simulations using a damage-aware wind farm controller designed by Spyridon Chapaloglou at SINTEF Energy.

Furthermore, this study examines the impact of enhancing system flexibility by implementing a PHS system in conjunction with an existing hydropower plant. Additionally, it seeks to investigate the effects of employing a variable speed pump on power plant operations and compare these effects with those resulting from using a fixed speed pump.

Model/ measurements

Fig. 1 presents an overview of the proposed methodology for the co-simulation framework, including different input data and constraints of the optimization program.

A flowchart of the multi-objective optimization process of solving the model using the augmented epsilon-constraint method (AUGMECON), lexicographic optimization and fuzzy logic is further presented in Figure 2. Moreover, the process of the wind farm control simulations are described in more detail in Fig. 3, presenting the flowchart to obtain a lookup table for

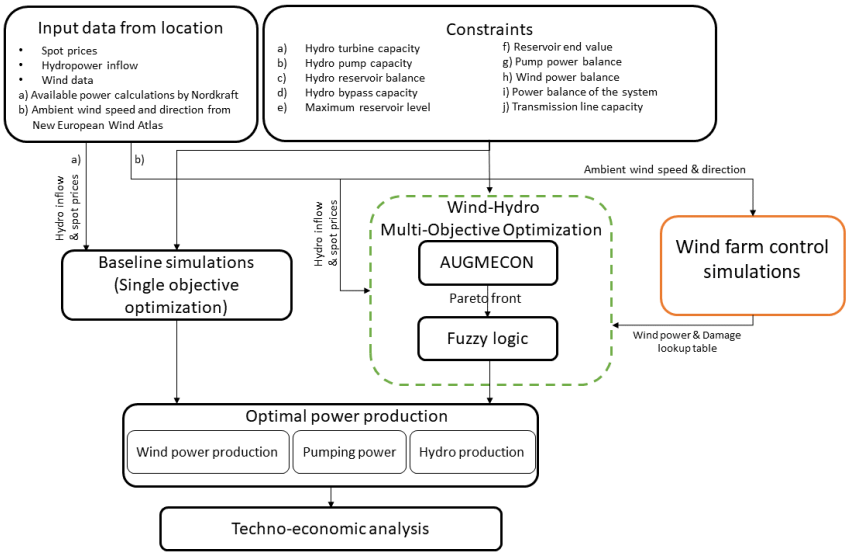


Fig. 1 Overview of the co-simulation framework

power outputs and its respective damage accumulation at each time step for different power references. This lookup table is used as an input to the multi-objective framework, as shown in Fig. 1.

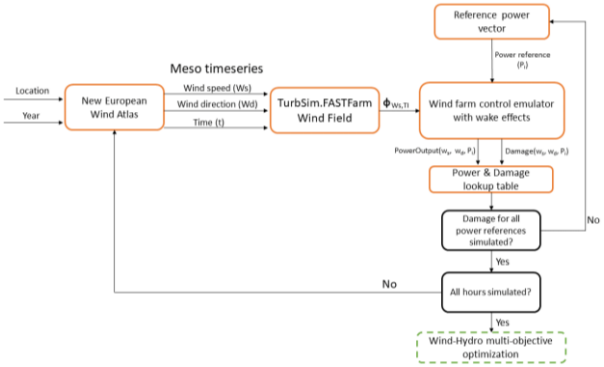


Fig. 2 Flowchart of the wind farm control simulations

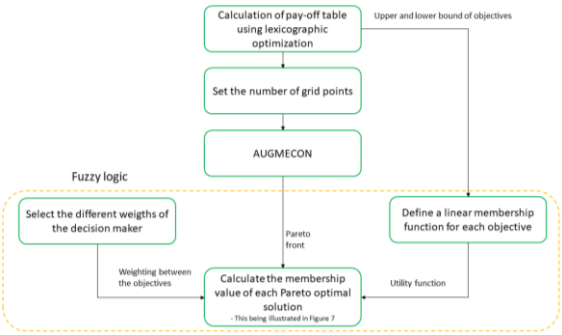


Fig. 3 Flowchart of the multi-objective optimization process

Calculations

The model provides output data of optimal hourly power production throughout the year. An illustration of this is presented in Fig. 4, where the wind power being curtailed and the reservoir level at each hour is also visualized. As there is limited transmission capacity, the wind farm is forced to curtail some of its potential power.

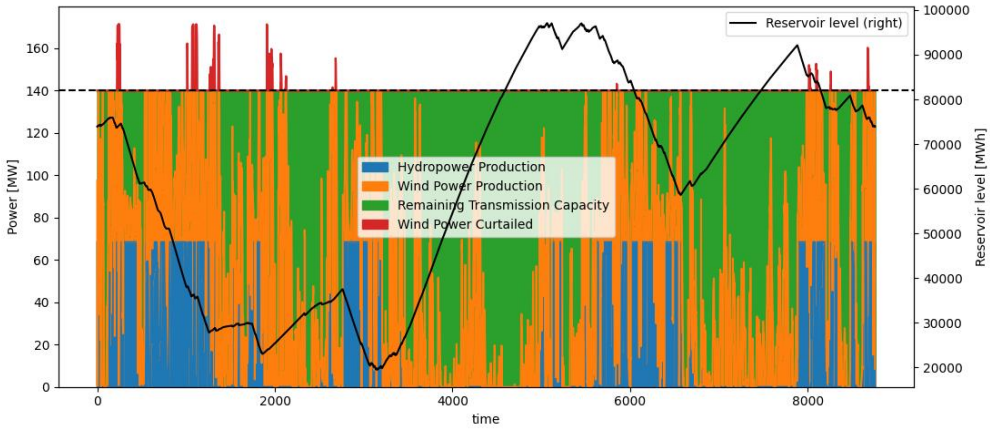


***Fig. 4** System simulations example*

In Table 1 different optimal solutions from the multi-objective optimization with different weights are presented. Where the Pareto optimal solution primarly optimizing the total revenue is used as a reference point for the other candidates, with a resulting revenue of 35.19 MEUR and 4045.66 damage. Note that the damage is represented by a damage index representing physical damage of various components of the drivetrain.

***Table 1** Realtive results of different candidates*

	Weight 1	Weight 2	Weight 3	Weight 4	Weight 5
Relative damage	0.0 %	-8.2 %	-63.3 %	-95.9 %	-100.0 %
Relativ revenue	0.0 %	-1.5 %	-26.8 %	-61.7 %	-74.3 %

Conclusion

Overall, the results highlight the importance of coordinated operation and control strategies for maximizing the benefits of the power system. The results underline this with achieved improvements in revenue and curtailed energy. As well as illustrating the potential increase in total satisfaction by implementing the co-simulation multi-objective framework. The coordinated operation of wind and hydropower optimization strategies, supported up by appropriate control strategies, is projected to deliver significant techno-economic advantages to Norwegian power market stakeholders such as transmission system operator and wind and hydropower plant operators.

A comparison of the SDP and SDDP method for medium-term scheduling of Meråker hydropower system

Student: **Karen Margrete Husby**
Supervisor: **Gro Klæboe**
Co-supervisor: **Viviane Aubin**
Contact: **Trygve Sørås**
Collaboration with: **NTE Energi AS**

Problem description

NTE are considering replacing the medium-term hydropower scheduling model they are currently using, which is a model that is based on SDP to calculate water values. One of the other options is a model using SDDP to calculate the water values.

The advantages with the SDP model they are currently using are the fast computation time, and the possibility to implement state-dependent restrictions. The disadvantage is that in a SDP model the watercourse has to be aggregated, and therefore might lose some details of the hydropower system or overestimate the flexibility in the system.

The SDDP model, on the other hand, does not aggregate the hydropower system, but solves the problem with representation of all reservoirs and plants. The computation time of the SDDP model is, however, somewhat higher. In addition, the SDDP model does not handle state-dependent restrictions as well as the SDP model.

This thesis answer the research question: “Which of the two methods SDP and SDDP for a medium-term hydropower scheduling problem provides the best usage of the water in Meråker hydropower system?”

Model/ measurements

To answer the research question two models using SDP and SDDP are made using the Python package PYOMO. The models aim to maximize income over the planning horizon while fulfilling the constraints in the water course. The SDP model is iterating over a backward loop until the convergence criteria is reached, while the SDDP model is iterating over both a forward and a backward loop until convergence is reached.

When convergence is reached the SDP model returns the aggregated water values which again is feed into a disaggregation algorithm to find the disaggregated water values and production plan. The SDDP returns the detailed production plan directly without the disaggregation algorithm.

Calculation

The results shows that the SDP and SDDP model fulfill the constraints in the water course equally. The results also shows that the SDDP model has lower spillage and higher production and income compared to the SDP model.

Conclusion

The results shows that the SDDP model gives the best usage of the water for the test case, meaning that the production and the income are higher for the SDDP model, compared to the SDP model. Since both models also equally fulfill the constraints in the water course, it can be concluded that the SDDP model gives the best results.

Investigating the Potential Integration of Alva Industries Technology in Axial Flux Motor Design

Student: **Hysing, Hans Dreyer**
Supervisor: **Nilssen, Robert**

Sammendrag

Denne forskningen fokuserte på å undersøke muligheten for å anvende Alva Industries viklingsteknologi til en aksial flux motor topologi, noe som ble vellykket demonstrert gjennom en bevis-konseptmotor. Utfordringer ble identifisert, spesielt behovet for å finne en løsning for å forhindre fremspring og komprimering av endeviklinger. Sammenligninger av ytelsen viste moderate resultater, hovedsakelig fordi stator materialet i utgangspunktet var designet for radial flux motorer. Rekonfigureringen av materialet resulterte i en betydelig reduksjon i statorstørrelse, noe som påvirket ytelsen på grunn av den aksiale konfigurasjonen.

Imidlertid fremhevet studien de iboende fordelene med aksiale flux motorer, spesielt med økende diameter, noe som indikerer et potensielt utviklingsområde. Hvis Alva Industries kan adressere de identifiserte utfordringene og fokusere på å optimalisere designet for aksiale flux motorer, er det lovende potensial for forbedringer i motorprestasjon. Fremtidig arbeid er foreslått å konsentrere seg om å optimalisere stator-materiale for aksial flux bruk, raffinere produksjonsmetodene for et bedre endeviklingsdesign og utnytte fordelene med økt motordiameter.

Design of Superconducting Propulsion Motor for Hydrogen-Powered Zero-Emission Aviation

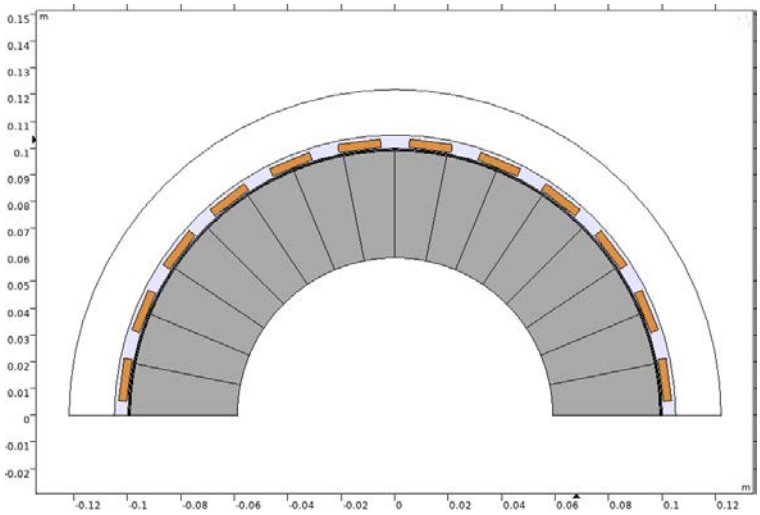
Student: **Ruben Vilnes Iden**
Supervisors: **Jonas Kristiansen Nøland**
Runar Mellerud

Problem description

This study aims to design and analyze a slotless PMSM that meets the performance requirements for aviation industry applications. More specifically, the power ratings of 2.5 MW and 3500 rpm. An analytical model will be developed and then implemented in COMSOL to achieve this goal, done. This model will serve as the basis for the optimization process. The optimization process will determine the electrical and geometrical parameters of the machine. Given its significant impact on machine performance in the aviation industry, the focus was primarily on the power density parameter.
Additionally, the study considered how implementing superconductors affects machine performance. The TA formulation was utilized to estimate the AC losses in the superconducting material. With these simulations, a better understanding of the behavior of the machine at different operating temperatures will be obtained. Further considerations of geometrical and electrical parameters were made based on these results, before a finished model was presented.

Model/ measurements

The analysis that was conducted in COMSOL investigated the air gap radius, magnet length, stator yoke, and winding layout. The results were presented, and the best-performing values were implemented into the design. TA formulation was also implemented to access the AC losses in the SC.



Results

After simulating the model with the TA formulation, the distribution of the current density was plotted, see Figure 1. It showed that the highest current density occurred on the sides. Due to the high magnetic field in the air gap, the critical current density was lower on the sides, see Figure 2. These two results combineddemonstrates the biggest problem with this design.

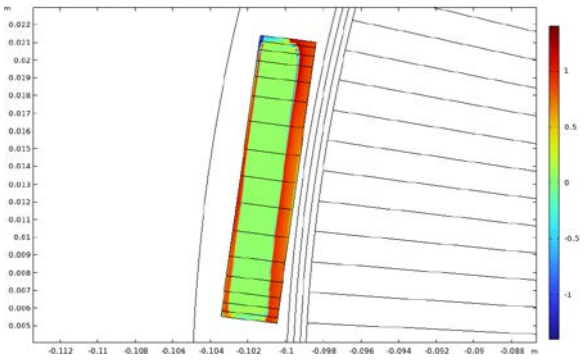


Figure 1

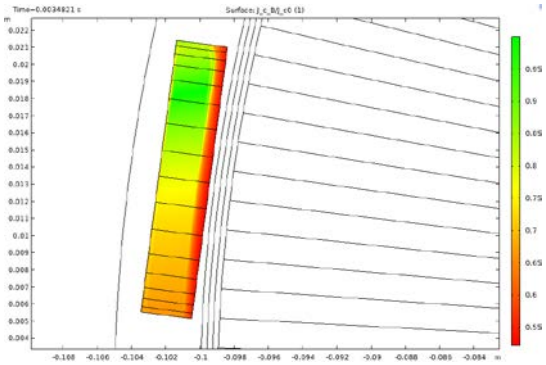


Figure 2

Conclusion

The study has presented a finalized design of a mega-watt scaled superconducting slotless PMSM for aviation applications. Using electromagnetic analysis in COMSOL, optimal geometrical parameters were deduced. In slotless machines, coil size and distance play a significant role in power density, with greater reach along the circumference leading to efficient current utilization. Surprisingly, increasing the air gap radius resulted in decreased torque production, contrary to theoretical expectations. A lower air gap radius demonstrated excellent power density. Winding layouts with higher slot numbers outperformed those with fewer slots. Implementation of a Halbach array reduced weight by eliminating the rotor yoke. The introduction of TA formulation allowed access to AC losses in superconductors. The performance of superconductors was heavily influenced by the flux density field in the air gap. Regions closest to the magnets experienced lower critical current density, resulting in increased losses. The sides of the superconducting tapes exhibited the highest current densities. Operating temperature and current loading played a crucial role in loss generation. By setting the current loading to 20% and operating temperature to 60 K, acceptable loss levels were maintained at 78 W for each coil.

The designed motor achieved a power density of 24.7 kW/kg, surpassing the industry's goal of 20 kW/kg. These results show promise for integrating superconductors in aviation applications, but further analysis is necessary, considering the factors not addressed in this study.

Performance Efficiency and Reliability Analysis of Offshore Wind Power Plants: Case Study of Utsira Nord

Student: **Emil Aune Jakobsen**
Supervisor: **Vijay Venu Vadlamudi**
Contact: **41227186**
Collaboration with: **Zephyr AS**

Abstract

This Master's thesis aims to address questions raised during a specialisation project on grid architectures for O↵shore Wind, with a specific focus on the collection system and transmission to shore of an o↵shore wind power plant. The objective of this research is twofold.

Firstly, the performance eciency of an o↵shore wind power plant will be analyzed us- ing three identified relevant methodologies – a Newton Raphson-based power flow, a Backward/Forward Sweep methodology termed as Distribution System Analysis, and a combinatorial approach. This analysis includes evaluating di↵erent system configura- tions, such as the use of conventional AC-technology and LFAC-technology, while also investigating the impact of di↵erent collection system topologies. The analysis will also assess the reliability of these system configurations using the RELRAD methodology.

Secondly, this thesis aims to compare the usage and results obtained from these method- ologies in order to establish a basis for methodology comparisons. Furthermore, it seeks to reflect on the approach taken in analyzing o↵shore wind power plants.

By realizing these objectives, through a pertinent case study of Utsira Nord, this research seeks to contribute to a better understanding of the performance eciency and reliability aspects of o↵shore wind power plants, and provide helpful insights for future analyses in this field. Moreover, a key aspiration of this Master's Thesis is to provide founda- tional knowledge and theory that can serve as a basis for potential future research on performance eciency and reliability evaluations of o↵shore wind power plants.

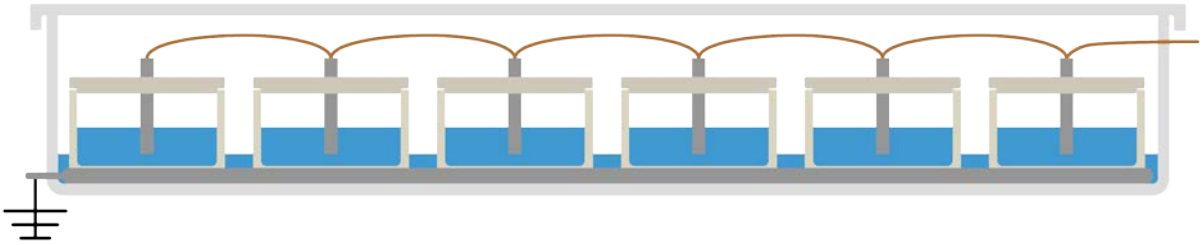
Future Design of Subsea High Voltage Cables for Offshore Renewables - Water tree growth from contaminants of oxidized polyethylene

Student: **Stian Jørgensen**
Supervisor: **Frank Mauseth**
Contact: **Sverre Hvidsten**
Collaboration with:

Problem description
High voltage subsea cables are key components of offshore floating renewables such as floating wind and solar farms. It is favorable to produce the inter-array cables of such installations without a water barrier of lead to reduce environmental impact, size, weight, price, and avoid fatigue the in lead sheathing. Removing the water barrier facilitate the possibility of water tree growth, as water will diffuse into cable insulation material. The main goal of this master's thesis is to determine whether water trees can originate from particles of oxidized polyethylene and determine the cause of initiation.

The task
This thesis investigates particles of oxidized polyethylene detected by an optical control system used in cable insulation manufacturing. The particles are molded into Rogowski-cups and electrically aged in a wet environment to facilitate the growth of water trees in a controlled manner. After aging the particles are inspected using a microscope and a scanning electron microscope to detect water trees and study the structure of the particles. The elemental composition of each particle is analyzed using energy dispersive X-ray spectroscopy in search of chemical content beyond the organic groups produced by the oxidation of polyethylene.

Model/ measurements
The cups were slightly submerged and filled with deionized water inside a box kept inside a heating cabinet.



With an electrode inside every cup, they were aged at 50 Hz and an electric field strength of 5 kV/mm. The electrode was connected to the secondary side of a transformer with a variable sinusoidal voltage source on the primary side. After aging the cups were inspected for treeing using a microscope and prepared for imagery in a scanning electron microscope and composition analysis using an energy dispersive X-ray spectroscope.

Calculation
Results show an occurrence of water trees from 2 out of 43 aged particles, which were among the most oxidized particles in the study. Both particles had the same porous structure when studied in a scanning electron microscope and there were no differences in elemental composition in the particles compared to the surrounding insulation. In other particles without

water trees, some contained grains visible through microscopy. Deposits of silicon were discovered using energy dispersive X-ray spectroscopy, which can be related to the grains.

Conclusion

The study showed that water threes can grow around particles of oxidized polyethylene encapsulated in polyethylene insulation. However, most of the particles did not show any visible signs of water tree growth. Characteristics of particles where water trees originated were:

- They were among the most oxidized particles in the study.
- They had a fine porous structure.
- There was no difference in chemical content compared to clean insulation.

Except for the general characteristics of these particles, it is difficult to exactly determine the cause or combination of features that initiated the trees, as accessing the point where the water trees originated was difficult.

To gain a better statistical basis, the study should be replicated and possibly aged for a longer time or accelerated by using a higher frequency. Energy dispersive X-ray spectroscopy findings indicated significant amounts of silicon in some particles without water trees. This should be investigated further to determine the origin of the silicon and rule out the possibility of water trees after further aging or in more oxidized particles with the same silicone contents.

Traveling Wave Fault Location on HVDC-MMC Transmission Lines

Student: **Anniken Eriksrud Karlsen**
Supervisor: **Hans Kristian Høidalen**

Problem description

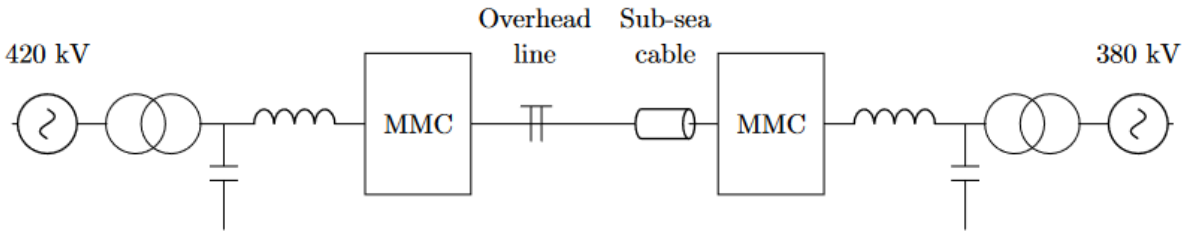
With an increasing need for electric energy, high voltage direct current (HVDC) systems have become more popular. These systems have several advantages compared to high voltage alternating current (HVAC) systems, being able to transfer more power with minimal losses. Traveling wave protection is a suitable choice for HVDC lines, which also gives the possibility of utilizing traveling wave fault location (TWFL). In this thesis, a TWFL algorithm has been developed to investigate the fault location of HVDC faults and power system incidents occurring in the HVDC system.

The purpose of the thesis is given below:

- Develop an HVDC-MMC model in PSCAD based on the NordLink interconnector and run simulations on HVDC overhead line faults and other power system incidents.
- Develop a TWFL algorithm using wavelet transformation in MATLAB for double-ended and single-ended fault location.
- Investigate how the TWFL accuracy is influenced by different system parameters and modeling approaches, and compare the proposed TWFL algorithms.

Model/ measurements

An HVDC system with modular multilevel converters (MMC) has been modeled using the PSCAD software. This model is a hybrid transmission line based on the NordLink interconnector. Faults such as pole-to-ground faults and lightning strikes have been applied on the overhead line. AC grid disconnection has also been simulated. Lastly, a DC voltage source model has been developed and pole-to-ground faults were applied, to compare this model to the original HVDC-MMC model.



Conclusion

To conclude this work, the double-ended TWFL algorithm obtained the best fault location results. It did locate almost all faults correctly, however, high-impedance faults and faults very close to the opposite terminal are challenging, as the fault responses are more damped. This algorithm also located lightning strikes within a reasonable error, which the single-ended algorithm did not manage. Even though the double-ended method requires time synchronization and has higher overall costs, this method is concluded to be the most reliable fault location method.

Optimization of Hybrid Power Plant

Student: **Vegard Kristiansen**
Supervisor: **Gro Klæbo**
Contact: **Hanne Nøvik**
Collaboration with: **Scatec**

Problem description
In recent years there has been a considerable acceleration in the development of renewable energy. Sustainable energy solutions such as solar, wind, and hydroelectric power have established themselves as clean alternatives that can offer abundant amounts of energy. Still, these technologies face some challenges which include site-specific requirements, intermittent traits and possible scalability concerns.

Hybrid power plants consisting of solar- and hydropower can help mitigate these challenges by combining intermittent energy sources with controllable generation. Meanwhile, there are few large-scale hybrid power plants in operation and it is still uncertain what conditions make hybrid power plants sustainable and economically viable. The scarcity of available studies related to hybrid power plants emphasizes a need for further research on this topic.

The task
An existing hydropower plant situated in the Central Province of Zambia, named Mulungushi power station, is reviewed to study the benefits of conserving water in periods with low demand and instead maximizing the generation in periods with higher demand and prices. Currently, the generated power is principally sold under firm power purchase agreements (PPA). However, the owners of the plant are initiating plans to enter the South African Power Pool and conduct trading on the Day-Ahead market (DAM). Moreover, they are also in the process of installing 10 MW of PV close to the existing hydropower plant. Hence, it is a suitable power plant to study when reviewing the potential benefits of transitioning into hybridized operation with hydro- and solar assets.

The main objectives of this thesis are to establish the following: Is it more advantageous for the Mulungushi plant to commence trading on the Day-Ahead market compared to selling the power under fixed contracts? Furthermore, is it better to operate the hydro and PV plant as two separate assets, or as one hybridized plant?

Model/ measurements
The analysis of the power plant is done using the Short-term Hydro Optimization Program (SHOP), which is principally a tool for hydropower scheduling. The scheduling period is one year with hourly resolution and the SHOP model includes an accurate representation of the reservoirs, hydrological data, and hydropower units, which are shown in Figure 1. Furthermore, authentic market prices from the Day-Ahead market and solar generation data are implemented in the model.

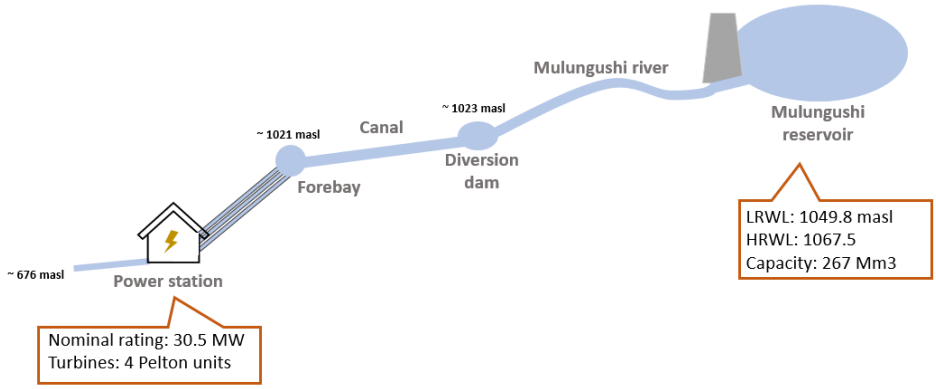


Figure 1: Overview of Mulungushi hydro power station.

Calculation

The most important results are the annual income the power plant achieves under different operational scenarios. Figure 2 describes the scenarios studied in this thesis and the amount of income generated by each scenario. From the analysis of the existing plant, there was no possibility of selling to DAM and thus all income is made from the firm PPA with a price of 100 USD/MWh. During scenarios 1, 2, and 3 it was possible to sell power to DAM, provided that a firm load of 14 MW was delivered under the PPA.

Current Power Station
↓
Possibility to trade on SAPP
↓
Scenario 1
↓
10 MW PV is added
↓
Scenario 2
↓
PV and hydropower is hybridized
↓
Scenario 3

	Income from load	Income from DAM	Total income
Existing plant	$20 290 000	0	$20 290 000
Scenario 1	$12 264 000	$8 454 000	$20 718 000
Scenario 2	$12 264 000	$9 833 000	$22 097 000
Scenario 3	$12 264 000	$9 925 000	$22 193 000

Value of each scenario	Additional income
Value of selling power on DAM	$428 000
Value of adding a 10 MW PV plant	$1 379 000
Value of hybridizing PV and hydropower	$96 000

Figure 2: Description of scenarios and the annual income achieved from each scenario. The additional income obtained between each scenario signifies the value of each scenario.

Conclusion

During the analysis of DAM participation, it is found that a load obligation of 14 MW with a firm rate of 100 USD/MWh, and with the excess power sold to DAM generates the maximum amount of income. In order to benefit from selling power to DAM, the excess power is sold during the morning and evening price peaks.

The second objective is to study if hybridized operation of PV and hydropower is more profitable than operating the two assets separately. During separate operations of the assets, the hourly PV generation is sold to the associated DAM price during the same hour, and over a year this results in an annual income of $1 379 000.

As a hybrid power plant, the annual income increases by approximately $100 000. The additional income of a hybrid power plant is achieved due to two reasons. Firstly, the share of PV that contributes to the load obligation experiences an increase in value because the load price of 100 USD/MWh is higher than the average midday rate that PV obtains on the DAM, which is 86.7 USD/MWh. Secondly, the amount of PV that assists in covering the load ensures that additional hydropower can be sold to the DAM at price peaks. Summarized, it is economically advantageous to commence trading on DAM and hybridize the hydro- and solar assets.

Prediction of power, energy and hydrogen demand in a zero-emission port

Student: **Ingrid Rodahl Kvale**
Supervisor: **Magnus Korpås**
Co-supervisor: **Aurora Fosli Flataker and Jonatan Klemets**

Problem description
To facilitate the transition to zero-emission transport, sufficient and efficient charging infrastructure is needed. However, charging of vehicles and vessels represents large power demands, which may require grid reinforcements. Therefore, more knowledge about the power demands in ports is important for planning the charging infrastructure itself, as well as for estimating future capacity needs in the power system.

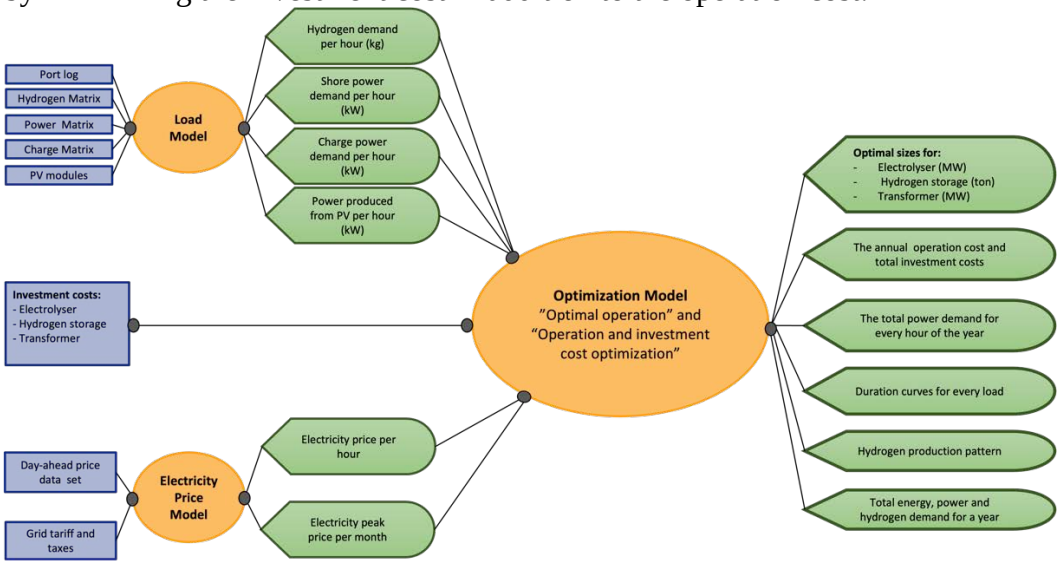
The task
The objective of this master's thesis can be divided into three main parts. Firstly, it aims to investigate and determine the load demand in a zero-emission port, considering diverse technology and fuel options such as shore power, charge power for full-electric and plug-in hybrids, and hydrogen for ships arriving at the port. This analysis is crucial for understanding the energy requirements and optimizing the usage of sustainable fuels.

The second objective involves utilizing the estimated loads and electricity prices to optimize the production of local green hydrogen, with the goal of minimizing operational costs in the port. This optimization process includes determining optimal electrolysis, transformers, and hydrogen storage sizes. The developed optimization model can be applied to all ports in Norway, providing a generalized approach for calculating future energy, power, and hydrogen demand in ports. Such analysis is valuable for transmission grid operators (TSO), distribution grid operators (DSO), or regulatory authorities, enabling them to forecast power requirements and enhance the grid infrastructure accordingly. Additionally, the evaluation of total hydrogen demand provides insights for companies involved in green hydrogen production or considering entering the market, helping them understand customer demand and identify market opportunities.

Moreover, the thesis explores the total operation and investment costs associated with different fuel mix scenarios. This assessment offers a comprehensive understanding of the economic feasibility of implementing various fuel options within the port, supporting decision-making processes. Finally, the developed models in this master thesis are applied to analyze the zero-emission port of Oslo, providing practical insights and recommendations specific to that port's context.

Model/ measurements
The developed model consists of three parts ”Load Model”, ”Electricity Price Model”, and ”Optimization Model” and is designed in a generalized manner so that it can be applied to all ports in Norway. The ”Load Model” determines the total loads included in a zero-emission port, considering hydrogen, shore power, and charge power to full-electric and plug-in hybrid ships per hour throughout the year. In addition, the energy production from local solar panels is included. The ”Optimization Model” consists of two optimization problems, which utilize the calculated loads, in addition to the electricity prices and grid tariffs to estimate an optimal production of hydrogen based on minimizing annual costs of operation. The ”Optimal operation” optimizes the operation cost in a port where the capacities of electrolysis,

transformer and hydrogen storage are limited, while ”Operation and investment optimization” includes finding the optimal sizes of electrolysis, transformer and hydrogen storage for a port by minimizing the investment cost in addition to the operation cost.



Calculation

In this master thesis, the port of Oslo is utilized as a case study to analyze the future power, energy and hydrogen demand for six different fuel mix scenarios. Furthermore, a sensitivity analysis is conducted to test the impact of the different system parameters. Summarizing the results, the implementation of shore power for all ships is estimated to require approximately 7 GWh for a year with a power peak reaching 3 MW. This implementation has the potential to reduce CO2 emissions in ports by approximately 4505 tons per year. Furthermore, in a scenario where all ships are either ”Green hybrids” or fueled with hydrogen, the total hydrogen demand for a year is calculated to be 18260 tons with a total energy demand of 923 GWh and a power peak reaching 170 MW. This implementation has the potential to reduce CO2 emissions in ports by approximately 215422 tons of CO2 per year. However, the predicted power demand is 4.7 times greater than the existing transformer capacity in the port of Oslo. This indicates that the capacity in both the transformers and cables needs to be renewed to handle a higher power demand in the future. Furthermore, the sensitivity analysis of this master thesis presents that the day-ahead prices of former years as well as a higher investment cost of electrolysis can reduce the simulated power peaks. In addition, the sensitivity analysis indicates that the operational costs can vary by a factor of 3.5 depending on the day-ahead prices from a former average year with 459 MNOK (2018) and an extreme year with 1646 MNOK (2022). Therefore, predicting the actual operational cost during the implementation of Step 3, which involves the fuel demand in the future, proves challenging.

Conclusion

The results obtained from this study contribute to providing an overview of the approximate total energy, power, and hydrogen demand that may emerge in the future. The primary purpose of this study is to raise awareness among stakeholders and industry participants regarding the projected demand, enabling them to plan and adapt their infrastructure and capacities accordingly. By doing so, they can better prepare for the anticipated changes and requirements in the maritime sector.

Enhancing Long-Term Hydropower Scheduling Through Scenario Reduction Using Shape-Based Clustering

Student: **Per Christian Lappen**
Supervisor: **Hossein Farahmand**

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

Optimal performance of a housing cooperative with PV and smart use of electric water heaters

Student: **Vemund Hjertvik Lenes**
Supervisor: **Karen Byskov Lindberg**

Abstract

Norway is projected to experience a substantial increase in electricity consumption by 2050, along with a potential peak power capacity deficit in the near future. The building sector is identified to have significant potential for reducing the peak power by using electricity flexibly. In addition, solar power presents an opportunity to meet future electricity demands while aligning with Norway's emission reduction goals. One promising solution involves combining solar power with water heaters to optimize energy consumption, reducing the operating cost as well as the stress on the grid. This study investigates the technical viability and profitability of this solution within the Norwegian power market context.

To quantify and assess the benefit of optimal electric water heater (EWH) control and solar panels, a linear optimization model was developed to analyze the heating strategy of hot water and evaluate its profitability. The model considered scenarios with and without local solar power production to evaluate the benefits of integrating these technologies. The model considers electricity consumption data gathered in the GreenCharge project, as well as simulated hot water consumption and solar panel power generation profiles.
The results indicate that smart control of EWHs can effectively reduce operational costs and peak power imports. The optimization analysis reveals potential cost savings of 6.7% through operational optimization and 26.4% by lowering the hot water temperature. Furthermore, the incorporation of solar power generation enhances the flexibility of the water heaters, leading to additional cost savings of 12.5% to 38%, depending on the hot water temperature and the presence of a fixed load. These savings primarily arise from reduced peak power tariffs rather than operational costs. However, it should be noted that the model assumes perfect information, which may not be attainable in practice, affecting the achievable savings.

In addition to cost reduction, the study also examines the potential for reducing peak power im- ports. The peak power import reduction is a result of the cost-optimal solution which considers the peak power tariff. The results demonstrate a significant decrease in peak power imports, ranging from 15% to 64% when considering EWHs in isolation. Incorporating solar power generation and a fixed load further enhances the reduction potential. The water heater can be completely turned off during peak fixed power import hours, thus reducing its contribution to the peak by 100%. The analysis highlights the complexity of heating strategies, which are highly dependent on specific scenarios and access to accurate information. Naive strategies can lead to increased costs and peak power usage. Therefore, it is crucial to tailor the heating approach to the unique circumstances of each case.

When evaluating the profitability of the technologies, it becomes evident that there is greater potential for cost savings through solar power integration than through smart control of EWHs alone. The study shows maximum savings of 25,000 NOK per year (4.3% of the total power bill) through optimal control, including a reduction in hot water temperature. This revenue is also highly uncertain and relies on perfect information. Contrary, solar power investments can

yield savings of up to 36,000 NOK per year with higher certainty. The profitability of solar power investment is dependent on the ability to increase self-consumption rates by virtually sharing power. At low self-consumption rates, solar power investment may not be financially viable, considering the assumed spot prices, tariffs, and investment costs.

Overall, the findings emphasize the potential benefits of optimal control of EWHs and the integration of solar power in the Norwegian power market. The results underscore the importance of considering specific use cases and available information when designing heating strategies. Moreover, while cost reduction in operation is feasible, the majority of savings are derived from reduced peak power tariffs which depend on the perfect knowledge about the monthly peak load. This study provides insights into the technological and economic aspects of solar power and smart water heater control.

Effektivitetsanalyse av AC- og AC/DC-hybridsystem i boliger

Student: **Ben Liang Li**
Faglærer: **Eilif Hugo Hansen**

Oppgaven skal ikke publiseres, og sammendrag er ikke tilgjengelig.

Impact of Industrial Size Battery Storage Systems on Electricity Price Distribution

-In collaboration with Volue Insight-

Authors:
Ferdinand Lindal
Sander Haugen

Supervisors:
Gro Klæboe, NTNU, IEL
Sjur Westgaard, NTNU, IØT

Problem description

The global energy mix has seen an increased reliance on Variable Renewable Energy (VRE), due to international climate goals and plummeting VRE costs, making these technologies economically competitive without subsidies. However, VRE's intermittent nature presents supply security challenges in electric systems that require a steady production-consumption balance. The fast response time and high efficiency of Battery Storage Systems (BSS), is seen as a solution to store excess VRE production. With rising capacities, the aggregated battery fleet could significantly influence the electricity market, impacting price formation and distribution.

Thus, this paper explores BSS's impact on electricity price distribution in Germany's electricity market, which features a significant presence of both VRE and industrial-sized BSS. The primary target is to investigate the impact of BSS storage capacity on the electricity price distribution. A main focus is also dedicated to drawing a mathematical relationship to the dynamics between BSS, VRE, and electricity price quantiles.

Model

In this thesis, a deterministic optimization market model is formulated and demonstrated on a base case, replicating the German electricity market, and a case study including storage capacity from BSS. The main source of input is real and measured fundamental data from the Volue Insight API. The case study assesses how batteries can be utilized optimally to decrease the most extreme prices and the total cost of the given market. The market prices from the market model are analyzed using descriptive statistics and multi-variable quantile regressions.

Results & Conclusion

The results show that BSS lowers the most extreme prices and increases the low prices, making the price distribution denser and less variable around its central tendency. Studying the prices further, with a quantile regression, reveals a distinct linear relationship between BSS storage capacity and electricity price quantiles. Figure 1 show the slope coefficients of the different quantiles.

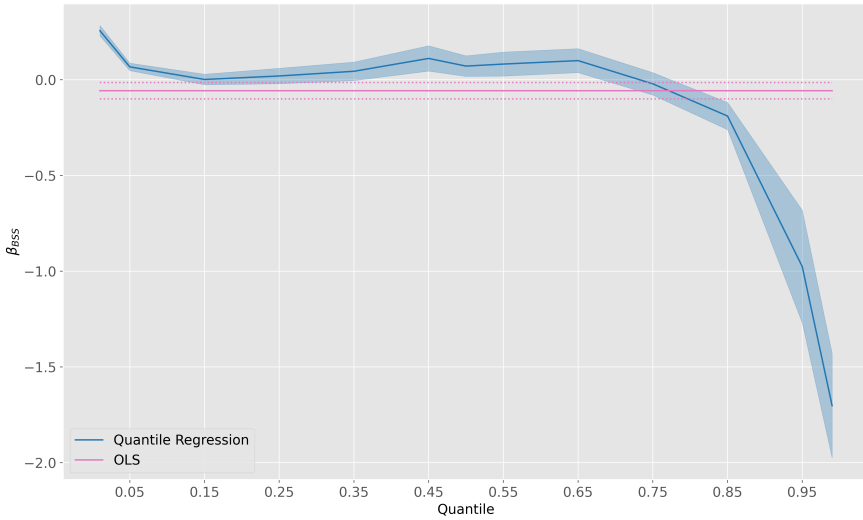


Figure 1: The effect of BSS on the market price - Beta coefficients across price quantiles

From Figure 1, the magnitude and sign of the slope coefficients vary, as the lower quantiles demonstrate a positive yet modest slope coefficient. However, the upper quantiles exhibit larger negative coefficients in comparison to the lower quantiles.

When investigating the dynamics between BSS and VRE, the VRE exhibits improved efficiency in reducing prices when paired with BSS in the system, particularly for upper price quantiles. This suggests that the presence of BSS enhances the system's ability to effectively utilize and store excess VRE generation, leading to lower electricity prices.

Potential of Hydrogen Technology for Coastal Electrification: Minimizing Distribution Grid Impacts through Flexibility

Student: **Sofie Lorentzen**
Supervisor: **Irina Oleinikova, Basanta Raj Pokhrel,**
Contact: **slorentz98@gmail.com**
Collaboration with: **SINTEF Energi, ZeroKyst**

Problem description
This thesis aims to investigate the impact electrifying coastal fishing fleets in Loftoen has on the local distribution network. Additionally, it explores potential flexibility solutions through the im- plementation of a water electrolysis system. The main objective is to analyze the feasibility of supplying hydrogen to the electrified fishing fleets while utilizing the electrolyser as a flexibility solution to ensure stable operation of the distribution network. To achieve this, a realistic model of the distribution network in Lofoten is developed, allowing for simulation of various scenarios to analyze network effects and flexibility solutions.

The task
To what extent does the electrification of a coastal fishing fleet in Lofoten affect the local distribution network, and how can the flexible operation of a water electrolyser be utilized to minimize these impacts efficiently?

Model/ measurements
Real network data obtained from the local distribution grid operator, Elmea, has been utilized to create a realistic network model in the simulation tool DIgSILENT Power Factory. Real load data from 2022 has been implemented in the software to enable simulations based on daily, weekly, and yearly cases, forming the basis for scenario creation. Furthermore, an electrolyser model has been developed to represent its characteristics and has been implemented at the end of the radial on the network section being analyzed.

Calculation
The analysis of the present network, considering 2022 loads, indicates that the electrification of the coastal fishing fleet in Lofoten has a relatively low impact on the local distribution network. However, when examining future scenarios, it becomes evident that the lines and cables operate close to their rated values, resulting in a more significant impact from electrification. The flexible operation of the electrolyser is demonstrated for these scenarios, proving not only its feasibility but also its necessity in the worst-case scenario.

Conclusion
Based on the results, the water electrolyser offers flexibility solutions such as voltage control to minimize voltage drops and load shifting to avoid network peaks. Additionally, the planned utilization of flexibility through hydrogen production and storage during periods of lower energy consumption is highlighted. The results confirm that the electrolyser is an effective resource for flexible operation, capable of rapid ramping up and down, thereby supporting stable network operation. The economic advantages of flexible electrolyser operation compared to grid reinforcement are yet to be explored in future research. Overall, this thesis not only provides evidence of the electrolyser's potential for flexible operation but also examines the impacts of electrification on the distribution grid.

Study on Rotary Transformers as Inertia Providers in Wind Energy Applications

Student: **Ane Emilie Løtveit**
Supervisor: **Olimpo Anaya-Lara**
Co-supervisor: **Raymundo Torres-Olguin**
Contact: **anelot@hotmail.com**

Problem description

Traditionally, power systems have been dominated by large conventional synchronous power plants, responsible for maintaining system stability and security of supply. However, given the accelerated increase in the penetration of converter-connected Renewable Energy Sources (RES), such as wind and solar PV energy systems, and their higher share in the energy mix, RES are now required to contribute and support system operation similar to conventional power plants. However, converter-connection introduces challenges such as lack of natural contribution to dynamic frequency control and to the total system inertia.

This master's thesis investigates the potential of a novel approach for natural inertia provision from a wind energy system based on rotary transformers. The induction machine based rotary transformers have been used in Variable Frequency Transformers (VFTs) to enable power flows between two asynchronous AC power grids. The VFT holds several beneficial capabilities, such as large inherent inertia, damping, simple and flexible control, and has generally shown to increase the power system stability and reliability. The transfer of these capabilities to the rotary transformer applied in the wind energy system is the aim of the master's thesis. The intended placement of the rotary transformer in the wind energy system is illustrated in Figure 1.

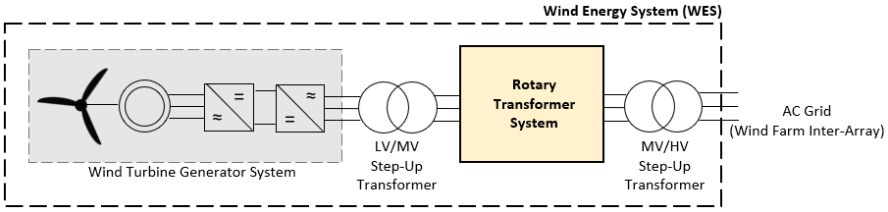


Figure 1: *Overview of the modified wind energy system*

The task

To achieve the thesis' purpose, the thesis work entails implementation of the rotary transformer in a wind energy system, development of appropriate controls, and subsequent tests of its inertia-providing capabilities. Investigation of the most important enablers to facilitate the introduction of the rotary transformer for this application is also particularly relevant. In order to build a strong theoretical foundation of the rotary transformer's capabilities, and for the model and control development, an extensive theoretical research and literature review was first conducted. The design, implementation, and testing of the appropriate rotary transformer controllers were conducted in Matlab/Simulink and compared to the state-of-the-art wind turbine kinetic energy extraction method.

Model/ measurements

A Matlab/Simulink model to represent a base test power system with four aggregated conventional power plants and one aggregated wind farm, was used and further developed to an appropriate base test system. Further, the state-of-the-art synthetic inertia provision solutions were implemented in one model, and the rotary transformer and Grid-Forming Converter control of the wind turbine grid-side converter, were implemented in another model

(Figure 2). Figure 3 shows the general coordination between the GFM unit and the rotary transformer to enhance the natural inertial response. The two models were verified, tested with a variety of test scenarios similar for both models, and finally model-specific sensitivity analyses were conducted to improve control performance. The two models were lastly used for the final comparisons.

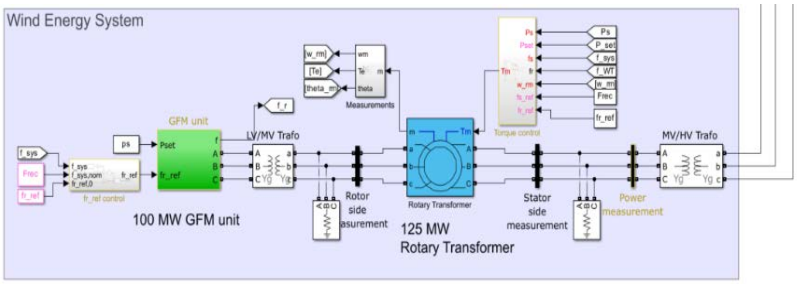


Figure 2: Overview of the modified wind energy system for implementation of the rotary transformer for inertia provision.

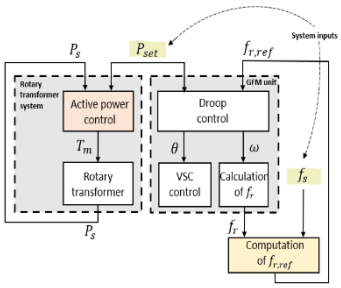


Figure 3: Simplified flowchart to show the general idea of the coordination of the rotary transformer control and the Grid-

Calculation

The results for the active power output from the wind energy system and the system frequency, both following a frequency event at t=5s, can be seen in Figures 4 and 5. The results show the comparison between the base model, the state-of-the-art inertia provision model, and the model with the implemented rotary transformer, all exposed to the same system conditions and the same frequency event. The rotary transformer model shows improved results for the initial few seconds, but is however not sustained for the rest of the simulation duration as for the state-of-the-art synthetic inertia provision.

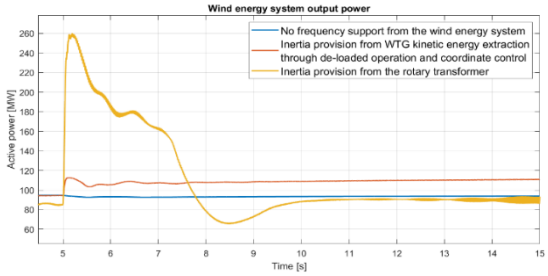


Figure 4: Active power output from the wind energy system following a frequency drop for the three systems.

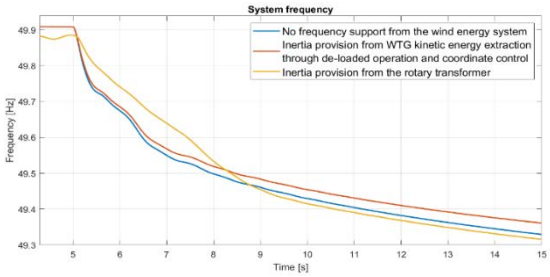


Figure 5: System frequency following a frequency drop for the three systems.

Conclusion

This thesis has shown that the implementation of the rotary transformer in the wind energy system significantly improves the initial RoCoF and the general frequency response in the system, compared to state-of-the-art approaches. It has also been shown how the implementation of the Grid-Forming (GFM) converter control of the grid-side converter of the wind turbine is an important enabler for integration and flexible control of the rotary transformer. The GFM enhances the natural response of the rotary transformer, improving the kinetic energy extraction capabilities of the device. A duality of frequency support mechanisms in the rotary transformer is established, both by natural inertia provision through kinetic energy extraction, and from externally provided power to the rotary transformer system. This also adds to the flexibility and improved operation range of frequency support. Compared to the state-of-the-art synthetic inertia provision via WTG kinetic energy extraction, is the rotary transformer approach more flexible and simpler with regards to control, more reliable because of independence of the wind conditions, and have a wider range of operation.

Intelligent Frequency Support for Offshore Wind

Student: **Øyvind Kvalheim Madsen**
Veileder: **Roy Nilsen**

Problemstilling

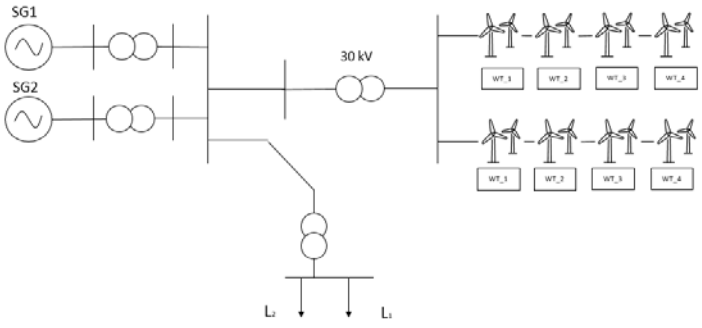
With the increasing demand for renewable energy sources, wind energy is becoming more and more utilized in modern energy grids, and as a result, wind turbines (WT)s are required to aid in frequency support. WTs in a wind farm (WF) are normally optimized individually in order to generate the highest amount of power available, but lack the ability to participate in frequency support as a result. Additionally, the wake interaction between WTs in a WF can be exploited in order to optimize the total generated power of the entire WF as well as the potential kinetic energy from the rotational blades. In this master thesis, different control strategies are proposed with the goal of optimizing generated power, maximizing kinetic energy available in the rotor and a de-loaded power strategy while maximizing the kinetic energy.

Oppgaven

The optimization strategy is based on regulating the rotor speed and the pitch angle variables of the turbine. A non-zero-pitch-angle-based control and a zero-pitch-angle-based control method is utilized, where each method can maximize the power and kinetic energy in the WF respectively by utilizing the pitch controller and exploiting the wake interaction between upstream and downstream WTs. In larger WFs, the amount of variables can be too large to optimize effectively and quick enough. In order to solve the problem, a method of clustering the WTs into groups based on the wind direction is proposed, where WTs in the same group are given the same rotor speed and pitch angle references. Each control method is described through a literature review and tested through simulation for an under/over-frequency event, and frequency response, active power and kinetic energy is measured.

Modell/målinger

A system consisting of several type IV WTs, a constant and sudden load increase/decrease and synchronous generators are established in MatLab Simulink, as expressed in the figure.



Different scenarios for different control strategies are explored and the measurements are compared.

Beregninger
The varying control strategies focus mainly on either maximizing kinetic energy to reduce RoCoF of the wind turbines during over/under-frequency events or maximizing power generation for either each individual WT or the entire WF.

When maximizing the power of the WTs, the wind turbine does not participate in frequency support and the frequency nadir is much larger compared to the strategies maximizing kinetic energy, and the time of recovery to steady state is larger for control strategies maximizing power. When maximizing kinetic energy of each individual WT, the frequency nadir and time of recovery is greatly improved, but comes at the cost of lowering the power generation for the WF, as the control strategies demand that power production is decreased.

Konklusjon
This Master's thesis focuses on optimizing power and kinetic energy in a wind farm (WF) using different strategies to enable wind turbines (WTs) to participate in frequency support while maintaining acceptable power levels. The control strategy involves storing optimized rotor speed and pitch angle variables in look-up tables for various optimization objectives. The study finds that adjusting pitch angles of upstream WTs allows downstream WTs to extract spilled power, increasing total power output but reducing kinetic energy storage, resulting in a trade-off between power generation and frequency response. The clustering strategy demonstrates significant impact on power optimization, particularly when wind direction is closer to 0 degrees and at lower wind speeds. Overall, the trade-off between frequency response and total power generated in the WF is challenging to objectively determine.

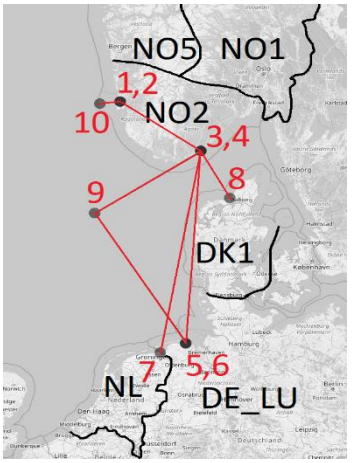
Optimizing hydrogen pathways using Norwegian energy resources dominated by offshore wind

Student: **Emilie Birgitte Marskar**
Supervisor: **Magnus Korpås**
Co-supervisor: **Espen Flo Bødal**
Contact: **emiliemarskar@gmail.com**

Problem description

The objective of this thesis is to investigate and optimize the role Norwegian energy resources constitute in current and future hydrogen production. The focus is to specifically investigate the conditions in which low and zero emission hydrogen production alternatives are phased in. The target is to cover a pre-specified hydrogen and electricity demand with minimal total costs through a minimization linear programming problem. A scenario analysis is conducted. Scenario 1 is the baseline scenario and is representing the year 2019. Scenario 2 and scenario 3 represents different variants of increased hydrogen demand.

The task



The modelled "North Sea system" geographically includes the South of Norway, Denmark, Netherlands and Germany, as shown in the figure to the right. The system is encompassing both offshore and onshore Norwegian power production and a demand for hydrogen and electricity in Norway and Germany. The hydrogen production methods are Polymer Electrolyte Membrane Electrolysis (PEMEL) and Steam Methane Reforming (SMR) with and without Carbon Capture and Storage (CCS).

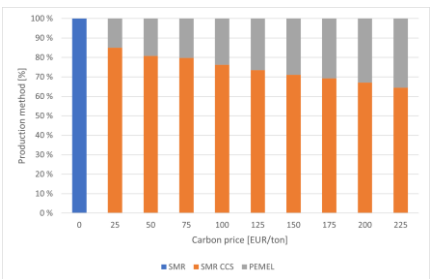
Model

The capacity expansion model “Hydrogen and Electricity system Integration Model” was utilized to solve the optimization problem, and NTNU's supercomputer Idun was used to run the simulations. The framework of the analysis is to investigate how the system responds to varying carbon prices and natural gas prices, in addition to increasing the offshore wind production. Each scenario consists of 10 simulations, where the carbon price or natural gas is varying within a range of fixed steps.

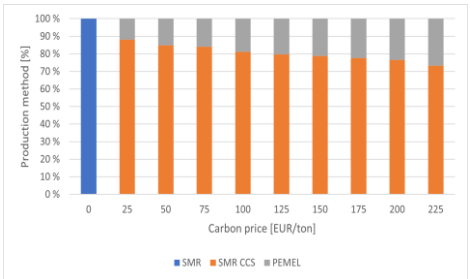
Results

Due to the comprehensive amount of results, only a share of them are presented in this summary. Within each scenario, it can be observed that the carbon price affects the choice of hydrogen production method. As the carbon price increases, so does the installation of low-emission hydrogen production alternatives, such as SMR with CCS and PEMEL. Traditional SMR without CCS is entirely phased out after the first simulation across scenarios.

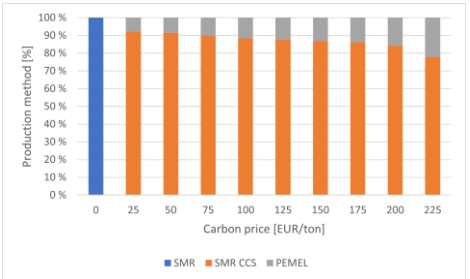
Scenario 1 (x1 H_2-demand):



Scenario 2 (x2 H_2-demand):

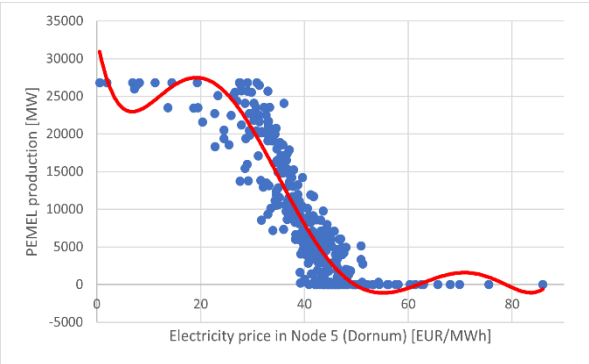


Scenario 3 (x4 H_2-demand):

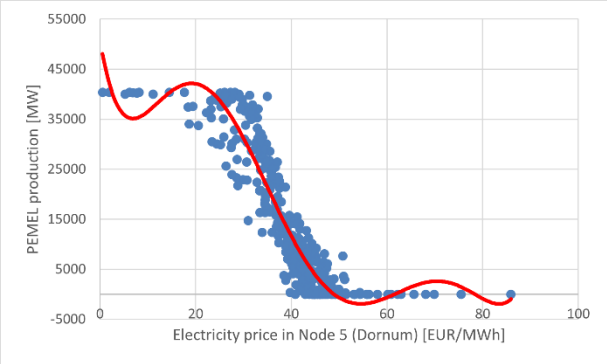


The operational costs of PEMEL is dependent on the electricity price. The scatter plots below depict PEMEL production and the average daily power price in Node 5, as PEMEL production is exclusively located there. The presented trend lines are showing the key take away of the figures, namely a high correlation between the electricity price and PEMEL production, with a correlation efficient of 84\% and 87%. The trend line is improved for high shares of offshore wind, which decreases the electricity prices and makes PEMEL more economically competitive.

Correlation between el. price and PEMEL:

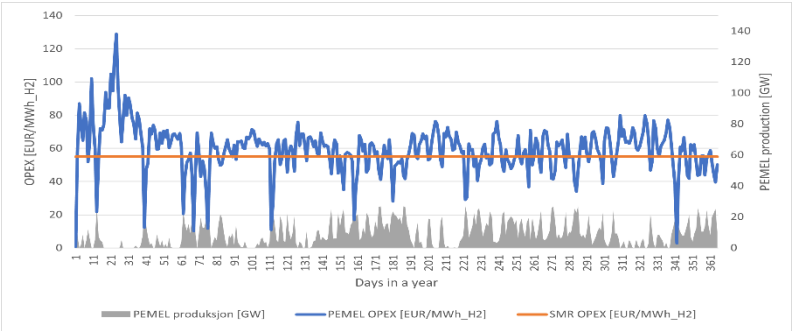


Correlation for high shares of offshore wind:



The figure below shows the operational expenditures (OPEX) of producing one MWh of hydrogen for PEMEL and SMR with CCS and illustrates that the cost of operating PEMEL is entirely dependent on the power price. The OPEX is constant for SMR with CCS, as it is only dependent on fixed costs, the cost of CCS, natural gas and emissions. When the electricity price drives the OPEX of PEMEL upwards, SMR is the most cost-efficient alternative. The production of PEMEL, illustrated by the grey graph, is respondent to this. However, it is not entirely responsive, which is supported by the correlation in the plots above to be "only" 84\%.

The daily OPEX of PEMEL and SMR and the production of PEMEL for a year.



Conclusion

The results show that without a carbon price, there are no incentives to reduce the greenhouse gas emissions, and hydrogen is produced through SMR. However, the results shows that a non-zero carbon price contributes to phase in low-emission hydrogen production methods. SMR with CCS is favourable for lower carbon prices, due to its lower capital costs and favourable operational cost, as the latter is not excessively penalized by emission costs. As the carbon price increases, the higher emission costs progressively phases out SMR with CCS for the benefit of PEMEL. The findings indicate that increasing electricity supply decreases the electricity prices, and lower electricity prices are beneficial for the cost-competitiveness of PEMEL. Sufficient electricity production to keep the electricity prices at a lower level is therefore crucial for the cost-competitiveness of PEMEL.

Analysing the Impact of 30 GW Offshore Wind Power in Norway using the Market Model FanSi

Student: **Kari Medhus**
Supervisor: **Magnus Korpås**
Co-supervisor: **Arild Helseth**
Collaboration with: **SINTEF Energy Research**

Problem description

In May 2022, the Norwegian government presented a plan to identify areas for 30 GW offshore wind power before 2040. The ambitious offshore wind initiative will significantly boost Norway's green energy production, resulting in a more robust energy balance and maintaining the country's position in the energy industry. However, the substantial increase in wind power production will have a significant impact on the Norwegian power system, which must be adequately prepared to accommodate this increased power production. A considerable challenge lies in managing the variable power generation caused by intermittent wind power. Flexible hydropower production is expected to play a key role in supporting the power system to cope with variability.

The task

This master's thesis aims to investigate the impact of 30 GW offshore wind power on the Norwegian power system. Additionally, the study examines three distinct wind power capacity allocations to examine the impact of the wind farm locations.

Model/measurements

The simulations are conducted using the long-term hydrothermal scheduling model FanSi, developed at SINTEF Energy Research. FanSi uses a method known as "Scenario Fan Simulator," which combines optimization and simulation.
The analysis utilizes a dataset that represents a scenario for the Northern European power system in 2030. The study investigates five offshore wind scenarios in Norway, described in Table 1. The offshore capacity is directly connected to the nearest onshore area without any corresponding modifications to the transmission system and demand. Two sets of wind series are employed in the simulations to analyze and compare the recently generated wind series by SINTEF Energy Research with the original wind series initially included in the dataset.

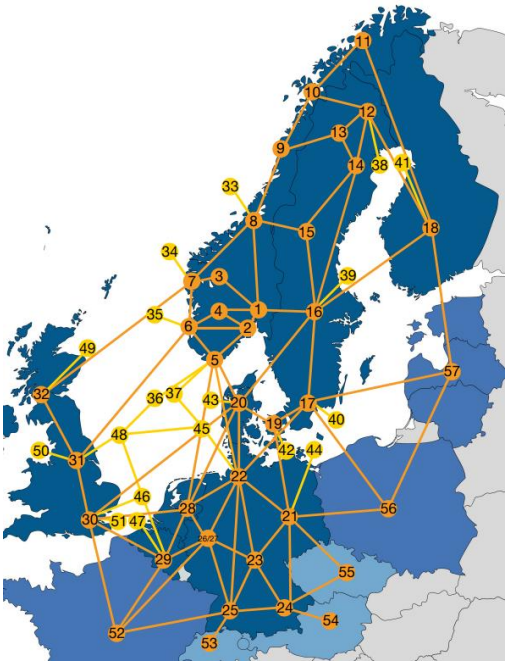


Fig.1: System structure in dataset

Tab.1: Overview of the scenarios simulated

Scenario	Offshore wind capacity	Location in Norway
Base	0 GW	
Sor4.5	4.5 GW	South
Sor30	30 GW	South
Mid30	30 GW	South- and mid
Nor30	30 GW	Along the entire coast

Results

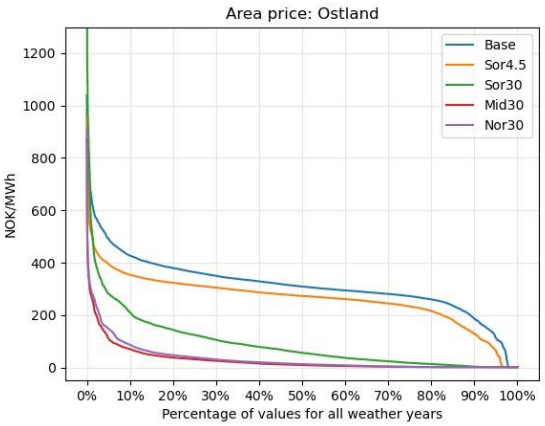


Fig.2: Area price in Ostland for all scenarios

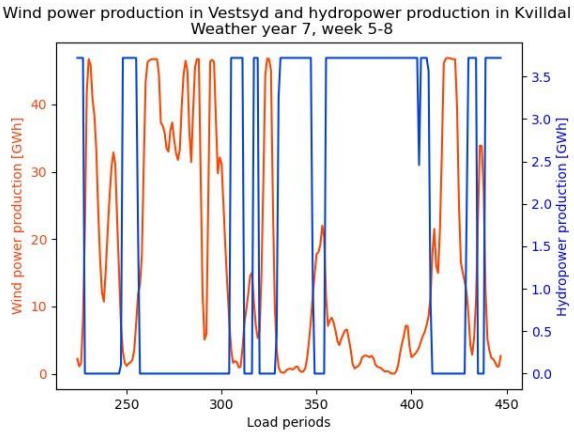


Fig.3: Wind power production in Vestsyd and hydropower production in Kvilldal power plant for Sor30

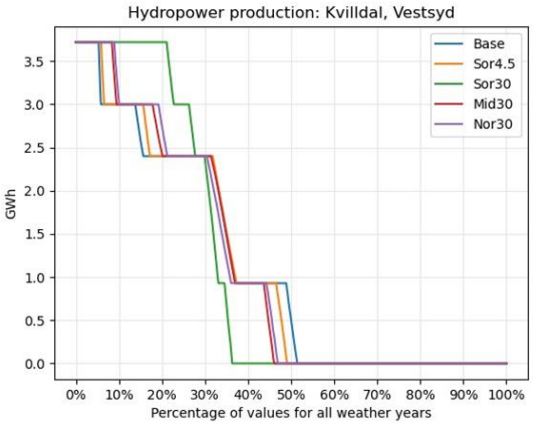


Fig.4: Hydropower production in Kvilldal power plant for all scenarios

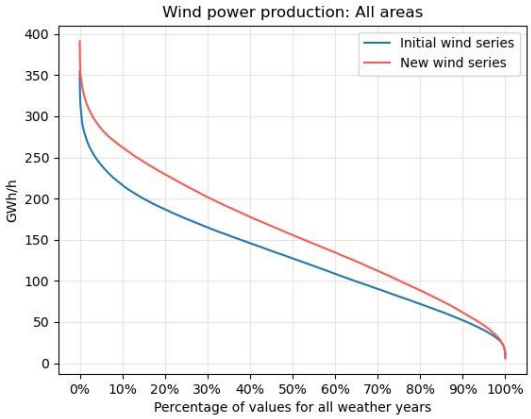


Fig.5: Total wind power production in the system for the wind series initially included in the dataset and the new wind series

Conclusion

- As wind power production increases, there is a decrease in area prices.
- The installation of 30 GW offshore wind capacity leads to a higher frequency of bottlenecks in the transmission system, highlighting the importance of aligning wind power developments with transmission capacity and power demand.
- The hydro production adapts to the increased wind power production by operating more frequently either at maximum capacity or with zero production. The value factor for hydropower plants increases with higher wind power production in the system.
- The concentration of wind power production in a smaller area causes notable fluctuations in wind production due to uniform wind conditions. Additionally, it results in higher area prices compared to distributing the capacity across a wider region, due to bottlenecks in the lines leading out of the production area.
- Increased wind power production positively impacts social welfare, primarily driven by increased consumer surplus and surplus of the TSO. Distributing the wind farms in a larger area leads to higher social welfare compared to concentrating them.
- The new wind series resulted in increased wind power production, impacting simulation results, and emphasizing the importance of accurate wind series in simulations involving large shares of wind power production.
- The EMPS model's water values, used in the end value setting in FanSi, were excessively high for high wind power production.

Design and analysis of a 2.5 MW Coreless Aero Generator for Hybrid-Electric Aircraft

Student: **Eirik Kvåle Mikkelsen**
Supervisor: **Jonas Kristiansen Nøland**
Co-supervisor: **Alexey Matveev**
Collaboration with: **Alva Industries AS**

Problem description

The aviation industry significantly contributes to global carbon dioxide (CO2) emissions, accounting for approximately 2.5 % of total emissions. One potential solution for reducing emissions from the aviation industry is electrifying the aviation industry. However, large all-electric aviation is still far from realization due to energy storage challenges, while hybrid-electric large-aircraft can be realized much sooner. Highly efficient and power-dense electrical machines and generators are crucial to a hybrid-electric propulsion system.

The task

This thesis presents the design and analysis of a 2.5 MW coreless generator for hybrid-electric aviation. The generator has a slotless topology based on Alva Industries FiberPrinting technology. The stator consists of four galvanically isolated winding rings, where each ring is connected to a separate power electronic converter. To meet the weight requirement in the aviation industry, the generator should operate at a power density of at least 20 kW/kg.

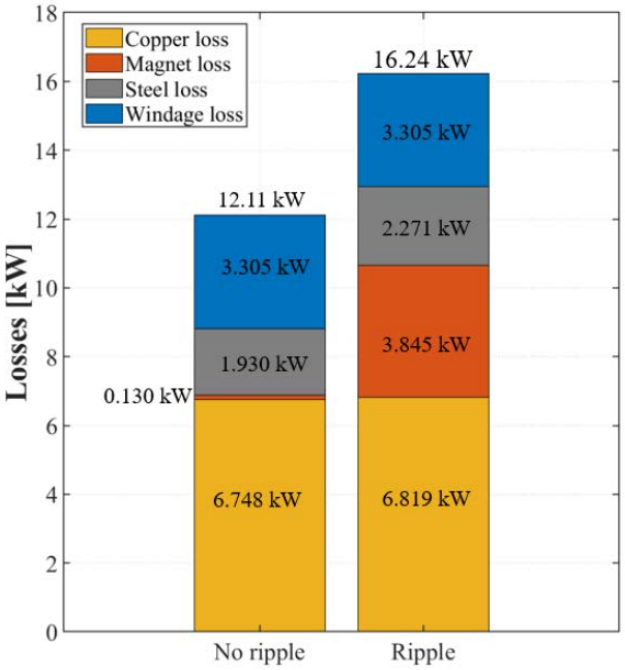
Model

The generator was modelled as a 2D model in COMSOL Multiphysics 6.0. The generator was modelled with 8-poles and a rotational speed of 15 000 rpm, generating an electrical power output of 2.5 MW. The loss analysis was performed through simulation in COMSOL, and analytical methods.

Calculation

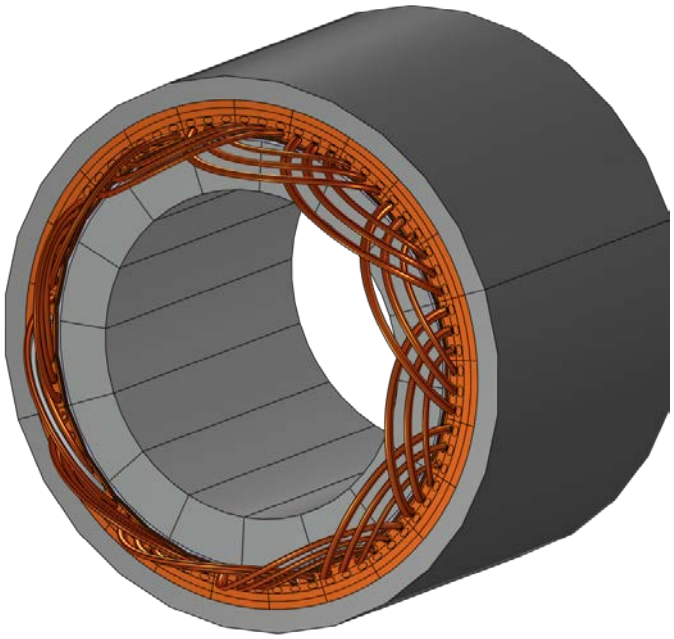
The total mass of the generator was 102.55 kg, which resulted in a power density of 24.38 kW/kg. The losses of the generator were evaluated for two cases, sinusoidal currents and with current harmonics. Sinusoidal currents resulted in an efficiency of 99.5 %, while the introduction of current harmonics reduced the efficiency to 99.35 %.

Material	Mass	Fraction of total mass
Magnet	44.96 kg	43.8 %
Carbon sleeve	0.726 kg	0.70 %
Copper winding	14.07 kg	13.7 %
Copper end-winding	9.80 kg	9.6 %
Insulation	3.80 kg	3.7 %
Iron	29.20 kg	28.5 %
Total	102.55 kg	100 %



Conclusion

The 2.5 MW coreless generator shows promising results regarding efficiency and power density. The generator achieves a higher efficiency than the E-fan X generator of Rolls Royce. An analysis of the hybrid-electric propulsion system demonstrated that no additional filtering components are necessary between the windings and the power electronic converters.



Physics informed neural networks in radial load flow calculations

Student: **Clemens Martin Müller**
Supervisor: **Olav Bjarte Fosso**
Contact: **clemensmuller@tuta.io**

Problem description
This thesis aims to gain insight in the performance and possible applications of neural networks, while using radial load flow calculations as a case. Further, it implements a physics informed neural network and compares its performance with regular neural network performance.

The task
Three differently sized neural networks are used to perform load flow calculations within a fictious 4 bus network and the radial IEEE33- and 69-bus systems. The different neural networks are implemented in python using TensorFlow. Physics informed loss functions are developed and added to the model. Finally, with the goal of optimizing neural network performance, different hyperparameter sets are tested on the two larger test networks.

Model/ measurements
The neural networks used in this thesis are fully connected feed-forward neural networks, as illustrated in figure 4.4. This figure illustrates the neural network architecture for the fictious test network. All network inputs are nodal power injections, excluding the slack bus. Network outputs are the complex voltages determining the system state. IEEE system states were predicted using identical system topologies, only changing the number of inputs and outputs. The physics informed loss functions, associate the average line flows connected to a bus to correct network outputs.

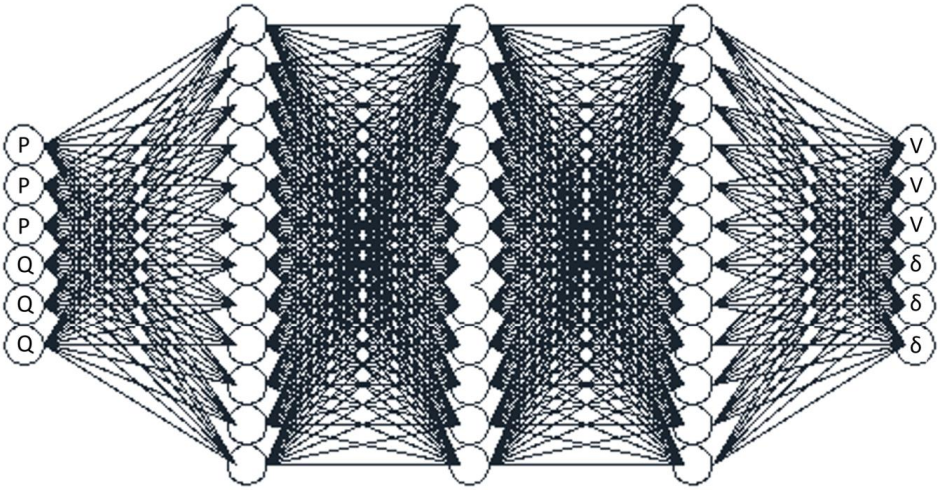


Figure 4.4: *Illustration of the small neural network architecture with inputs on the left and outputs on the right. Generated with and adapted from the eiffel2 python package.*

Calculation
Results show that the small neural network can predict the state of the fictious 4 bus system accurately with an acceptable worst-case performance. Medium neural network performance is less satisfying. Average voltage magnitude prediction accuracy is better than 0.2% in all cases, and voltage errors are found to be around 6%. Large neural network accuracy was typically around 50 to 70%, with one outlier at 160%. Angle predictions deviated up to 320% on average for the large neural network. No voltage prediction in this thesis was predicted with an error greater than 0.2%.

Conclusion
None of the developed neural network models predict the system states accurately enough for use in live power system analysis. Regardless of network size, the voltage magnitude predictions were more accurate than the voltage angle predictions. There is a marginal performance difference between the physics informed neural networks and their counterparts. The best performance was not found for the same set of parameters.

There is significant potential for improvement. Using a different neural network architecture with a closer relationship to power grid topology could improve model performance. Data processing could be improved to keep neural weights close to similar magnitudes and thus improve network stability and performance.

Further work should investigate other approaches to physics informed neural networks, such as different architectures and loss functions. Two separate networks for predicting voltage magnitudes and angles should also be considered. Finally, implementing collocation point training is likely to reduce neural network dependency on larger datasets.

Temperature Dependency and Active Gate Driver enabled Active Temperature Control of SiC Power MOSFETs

Student: **Mathias Fjeldberg Nerby**
Supervisor: **Dimosthenis Peftitsis**
Co-Supervisor: **Daniel Alexander Phillips**

Problem description

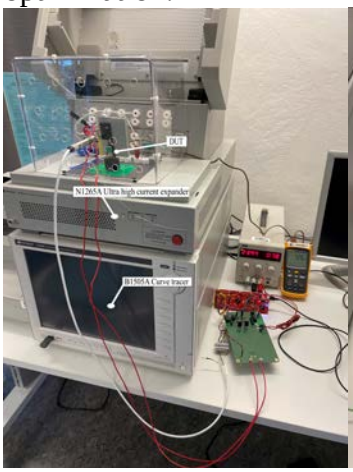
Knowledge of the SiC MOSFETs behaviour at varying temperatures is of critical importance. The objective of this master's thesis is twofold. Firstly, the thesis aims to carry out an electro-thermal characterization of a SiC MOSFET, specifically by examining the impact of temperature on the transfer and ID-VDS characteristics. Secondly, this thesis seeks to investigate the performance and feasibility of an active temperature control framework employing active gate driver for power-loss manipulation with the intent of reducing junction temperature fluctuation.

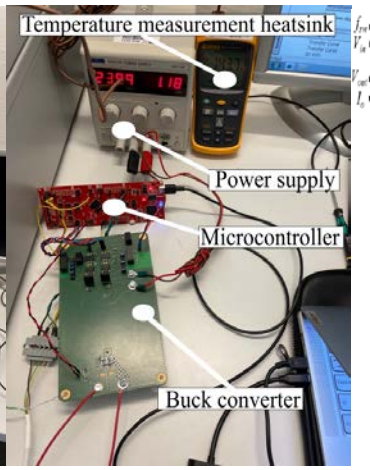
The task

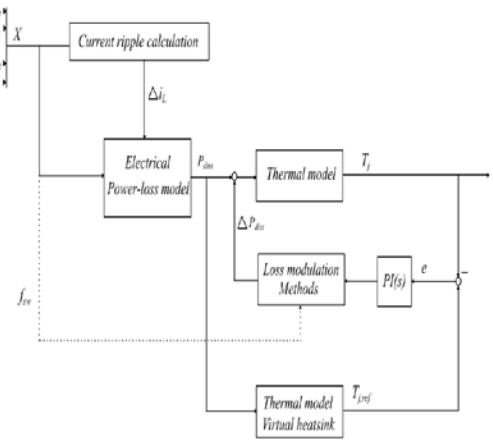
The outline of this methodology for accomplishing the first objective involves the design and implementation of a controllable synchronous buck converter for temperature regulation of a heatsink, to be used as a heating plate. In essence, a current-controller and a temperature controller are implemented for this purpose, employing a Texas Instrument developer board LAUNCHXL-F280049C, an infrared temperature sensor, and the C2000 embedded coder package in Simulink. The B1505A Keysight power device analyzer with the N1265A Keysight ultra-high current expander module is utilized for obtaining the experimental data. To examine a proposed active temperature control framework, the data obtained from the electro-thermal characterization is utilized to develop an accurate electrical power-loss model integrated into the active temperature control scheme, including the temperature dependencies.

Model/ measurements

The experimental setup for the electro-thermal characterization is shown in the two first pictures with the mentioned component. The second figure illustrates the general structure of the proposed active temperature control scheme for junction temperature swings reduction. It is based on a virtual heatsink concept for increasing the time constants of the thermal model for generating an improved reference. Two loss modulation methods were incorporated for selecting the appropriate active gate driver parameters for switching performance optimization.

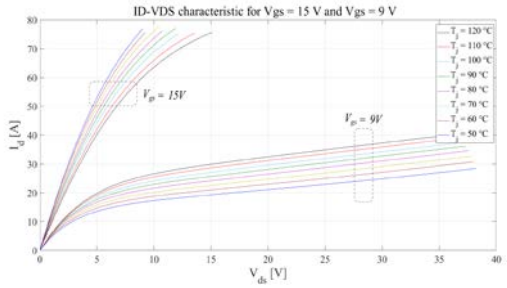


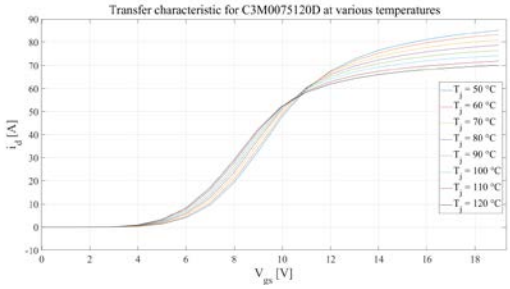




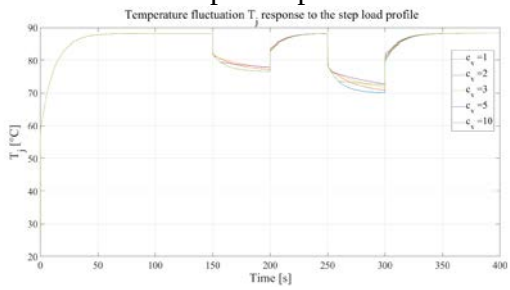
Calculation

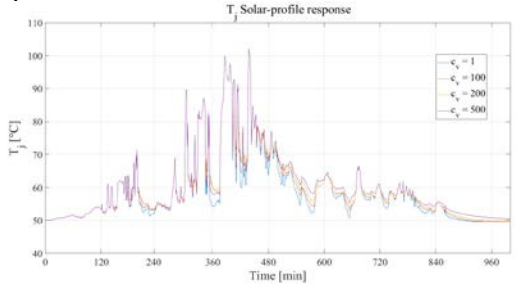
The results from the electro-thermal characterization of the SiC MOSFET are shown in the two first figures below. Visualizing the impact of the temperature on the ID-VDS characteristic and the transfer-characteristic.





Below are some of the junction temperature results from the active temperature control simulation for a step load profile and a solar load profile.





Conclusion

The electro-thermal characterisation was successful, and the effect of the temperature were aligned with the findings of other studies. Increased temperature indicates higher conduction losses at a gate-source voltage of 15V and lower threshold voltage with increased transconductance. The proposed active temperature control framework accomplished in simulations to reduce the temperature fluctuations for both the load profiles examined. The rapid temperature dynamics of the inner layers of the SiC MOSFET restricts the performance of the controller to a certain degree. For selecting the parameters for the active gate driver, both loss-modulator successfully chose parameters for reference tracking and switching performance, however with a significantly oscillating selection.

Detection and diagnosis of field-joint fault and static eccentricity in synchronous generators through analysis of the stray magnetic field.

Student: **Ingrid Nytun Nergård**
Faglærer: **Arne Nysveen**
Veileder: **Hossein Ehya**

Problem description
Synchronous generators are substantial in the production of hydroelectricity. Fault diagnosis may be costly and require significant downtime. A cheap and fast fault detection method is analysis of voltages recorded by magnetic sensors that are installed on the outside of the stator core. The voltages are induced by the machine's external magnetic field.

Hydroelectric generators may feature joints in the stator core, called field-joints. They are a product of core segmentation for transportation purposes. Another fault typical of synchronous generators is static eccentricity, which means that the rotor is not situated concentrically inside the stator. Neither field-joint fault nor static eccentricity alters the frequency spectrum of the stray magnetic field. This substantiates why these faults were investigated together in this thesis.

The task
Five pattern recognition methods were proposed and tested on the simulated generator models' recorded magnetic sensor voltages. Two methods involved basic visual comparison of voltages. One method involved vectorization of voltages from sensors at different locations. The patterns from these vectors were challenging to quantify. The last to methods described computation of the severity and angular position of a static eccentricity fault.

Models and measurements
Finite element modelling was used to model the electromagnetic fields in two generators, exhibiting various field-joints fault and static eccentricity conditions. The voltages simulated in the stray magnetic sensors were then analyzed.

Additionally, the findings were examined further on stray flux data from three real generators. One field test to a hydropower plant was carried out to collect measurements for the field-joints, while data from previous tests was employed for static eccentricity computation.

Calculation and conclusions
By comparing the induced voltages on sensors installed on each field-joints, faulty field-joints may be detected. The RMS values are identical for healthy field-joints, while they differ in faulty field-joints. A method was proposed to compute the severity of static eccentricity, also by means of RMS voltage comparison, from four sensors. A method was also proposed to compute the angular position of a static eccentricity fault, by means of time-series data mining.

Finally, a flow chart algorithm was proposed to identify faulty field-joints and static eccentricity, and to diagnose the static eccentricity.

Investments in Low-Carbon Power Generation and Energy Storage under Uncertainty

Student: **Nygaard, Lars Skjelbred**
Supervisor: **Korpås, Magnus**
Dimanchev, Emil
Contact:
Collaboration with: **firm or another university**

Problem description

This Master's Thesis examines the impact of uncertainty and risk aversion on the decarbonization of the power system and investigates the effect of different policy options on investments in Renewable Energy Sources. A deterministic, risk-neutral stochastic, and risk-averse stochastic optimization models for Generation Expansion Planning are made to conduct analysis of a multi-zonal grid in Northern Europe. The analysis examines the complex interplay between uncertainty, risk aversion, and climate policies and how it affects capacity expansion, carbon emissions, power prices, revenues, and Non-Served Energy. Moreover, this thesis investigates the investment point for nuclear capacity in the context of a CO2 Tax policy, and it explores how new profit taxes might affect the investment in renewable energy.

The task
The findings in the thesis aim to improve the understanding of the complex interplay between uncertainty, risk aversion, and sustainable planning of the power system. Ultimately providing valuable insights for policymakers, central planners, and investors involved in the development of the power system, aiming to achieve the climate goals set for 2050. Hence, the thesis strives to contribute to advancing knowledge in the field of Stochastic Optimization models for Generation Expansion Planning and energy politics, with the goal of facilitating informed decision-making.

Model/ measurements
The three models used in the study are the Deterministic optimization model, the Risk Neutral Stochastic optimization model, and the Risk Averse Stochastic optimization model.

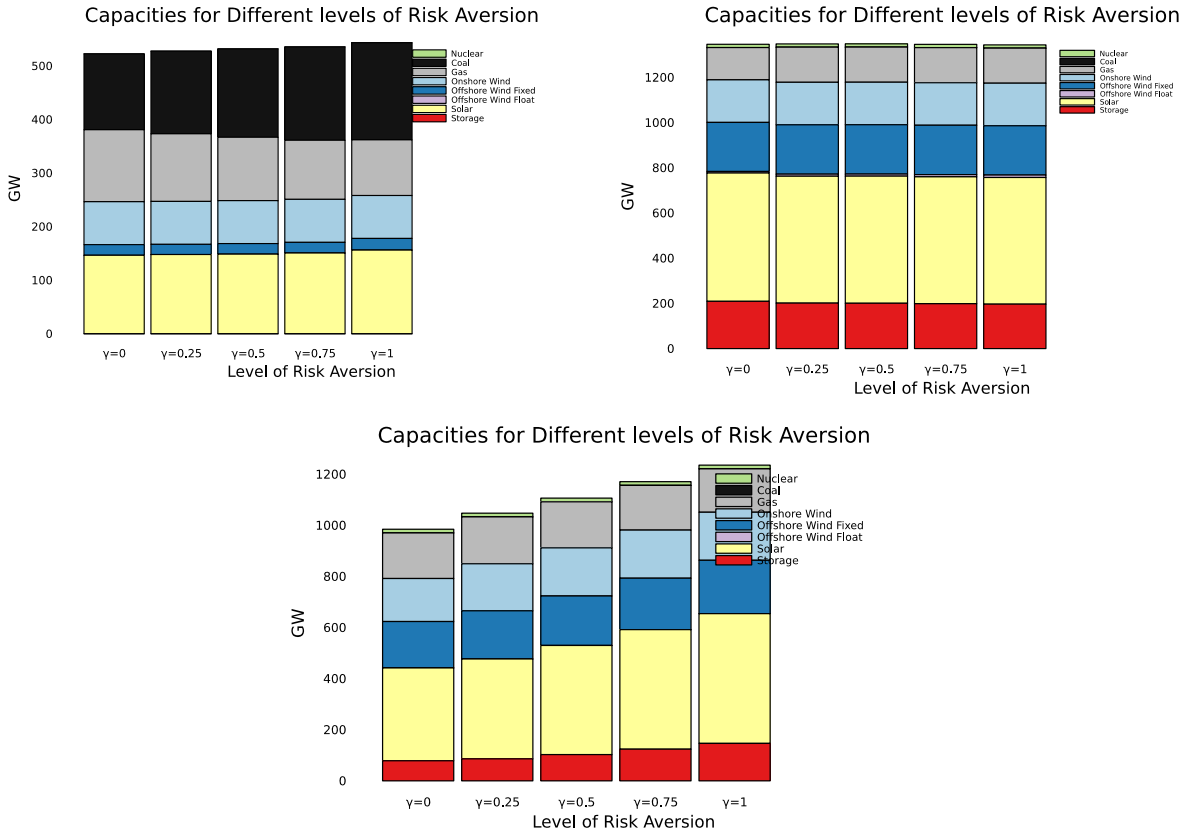
The Deterministic optimization model aims to minimize the Total System Cost (TSC) while meeting electricity demand. It considers investment costs, variable costs, and the cost of Non-served Energy (NSE). The model takes into account different price zones and with one corresponding demand time series and includes transmission capacity costs. It may also incorporate carbon emission taxes and ground rent taxes.

The Risk Neutral Stochastic optimization model extends the deterministic model to include multiple scenarios for each zone. Its objective is still to minimize the TSC and meet electricity demand, but it considers the variability of scenarios. The model sums over all scenarios, weighted by their probabilities, and includes investment costs for generation and transmission capacity, as well as variable costs for resources.

The Risk Averse Stochastic optimization model builds upon the risk-neutral model by introducing risk aversion. It incorporates parameters and variables to represent Conditional Value at Risk (CVaR). By considering risk aversion, the model aims to generate a more

robust capacity mix and minimize the expected cost of the most costly scenarios. It incorporates a risk aversion parameter, a CVaR threshold, and measures the trade-off between cost and risk. The model can also be interpreted as representing the equilibrium of a competitive market with different technologies as market participants.

Calculation



The capacity mix for different levels of risk aversion under no climate policy (top left), CO2 cap policy (top right), and CO2 Tax policy (bottom).

Conclusion

In conclusion, this Master's Thesis aims to illustrate some of the consequences of the complex interplay between uncertainty, risk aversion, and climate policy, providing valuable insights to policymakers, central planners, and investors. This thesis aims to facilitate well-informed decision-making by policymakers striving to find the best combination of climate policies and taxation and simultaneously enable incentives to invest in renewable energy capacity. The results achieved are consistent with anecdotal evidence and theory. Additionally, several findings have also been added to the existing knowledge on risk-averse stochastic optimization for Generation Expansion Planning models. Finally, the results of this Master's Thesis highlight that policymakers should include uncertainty and risk aversion in long-term Generation Expansion Planning models, as it is not possible to have a 100\% accurate foresight in long-term Generation Expansion Planning It has been shown that the models have a non-linear reaction to risk aversion for several outcomes. Thus, investigating these interactions before a climate or taxation policy is made is important to avoid unintended effects on the power system. By considering uncertainty and risk aversion, policymakers can effectively adapt to various scenarios, encouraging investments in Renewable Energy Sources and fostering the development of a sustainable power system.

Multimarket Services for Stationary Batteries – Considering Activation of Frequency Containment Normal Operation Reserves

Student: **Ingvild Eline Olsen**
Supervisor: **Magnus Korpås**
Co-Supervisor: **Venkatachalam Lakshmanan and Kasper Emil Thorvaldsen**
Collaboration with: **SINTEF Energy Research**

Problem description

The power system is changing from a centralised and unidirectional system to a decentralised and bi-directional system. This transformation is driven by the need to mitigate climate change and meet the growing electricity demand, which has increased the integration of renewable energy sources. However, incorporating renewable generation, such as wind and solar power, poses challenges related to their weather-dependent nature and the need for rotational inertia in the system. These challenges necessitate exploring new sources of flexibility to ensure stable grid operation. The objective of this master's thesis is to explore the viability of utilising stationary storage systems for delivering multiple services. Particular attention is given to markets for frequency reserves.

The task

The reserve markets involve participating at a capacity market, where one is paid for the capacity that could be provided for frequency reserves. In real-time time the reserves are activated according to the frequency deviation and a droop rate.

The task is done by formulating an optimisation model of a household with a photovoltaic (PV) generation and battery system connected to the grid. The battery is to cover the household demand, performing energy arbitrage and procuring and delivering frequency containment normal operation reserves (FCR-N). FCR-N is a symmetric service, delivered at frequency deviations of +-100 mHz A case study is created for a household in Hvaler, Norway.

Several papers have looked at using a flexible resource to deliver multiple services. Few account for the activation of the reserves since the effect of the activation is little since the frequency is near-normal distributed around 50 Hz. However, for a small battery with a limited energy reserve, the effect of activated energy can affect the battery operation. In the case of longer one-sided frequency deviations, the battery storage could reach its state of charge limits. Consequently, the battery could be unable to deliver the obligated services. Since a provider of FCR-N could be excluded form the market if the provider repeatedly fails to activate the reserve, it is undesirable to reach the SOC limits. It was attempted to reduce the number of hours the model fails to deliver reserves by accounting for the risk of reaching the SOC limits. The risk assessment was incorporated during the procurement of reserves in the first stage of the problem.

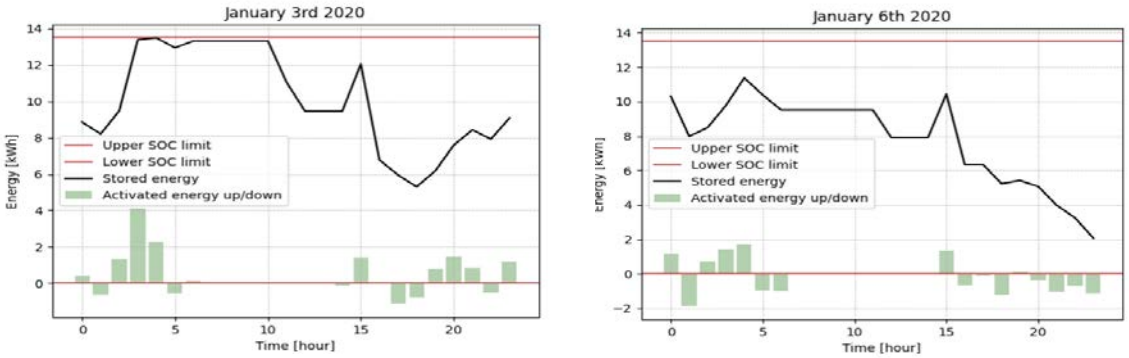


Figure 1: Example of an unsuccessful operation of the battery (Jan 3rd) and a successful operation (Jan 6th).

Model/ measurements

The optimisation model is formulated as a deterministic mixed-integer linear optimisation problem (MILP). It was formulated as a two-stage model using model predictive control with a rolling time horizon to ensure a close approximation to real-world conditions without including stochastic elements.

In the first stage, the decision to procure FCR-N reserves in the D1 and D2 market for FCR-N reserves are taken concerning the next day. Since frequency reserves are delivered as a deviation from a baseline scenario (i.e., the delivered or consumed power if no reserves are activated), a baseline consumption or production must be established. In accordance with the baseline, the number of reserves can be decided. This also applies to FCR-N reserves delivered by storage units or load entities. The first stage's battery charge and discharge decisions were used as a baseline for calculating the activated reserves. The baseline charge and discharge schedule are decided based on predictions of generation, consumption and prices in the spot and reserve markets.

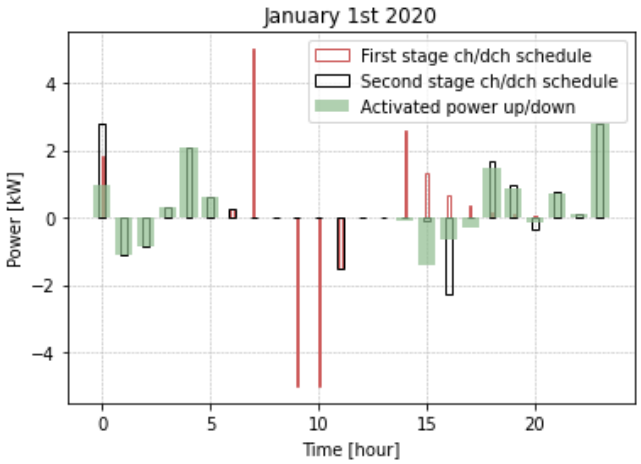


Figure 2: Charge and discharge schedule in the second stage as a change from the first stage schedule.

In the second stage, the activation of reserves is decided as a deviation from the baseline. Then, based on the PV generation, the household's demand for electricity, prices and activated reserves, the charge and discharge schedule and the import and export schedule are applied. The change in the second stage schedule also accounts for deviation from the prediction.

Calculation

Operating a stationary storage system in multiple markets (spot market and FCR-N markets) is associated with higher revenue. However, it is only the case if the battery owner is paid for both reservation and activation of the FCR-N reserves. Furthermore, the number of hours the SOC limits was exceeded was reduced for all tested alternatives and done by considering FCR-N procurement of several consecutive hours. However, the alternatives taking the least risk in the process of acquiring FCR-N reserves had double the annual expenses compared to the alternative with no restrictions. Nevertheless, the cases taking the most risk in the FCR-N procurement reduced the number of hours where the SOC limits were exceeded without increasing the annual expenses.

Conclusion

The case study results showed that providing FCR-N reserves in addition to other services resulted in declined annual expenses. Although the operational costs increased, the financial benefit of procuring FCR-N reserves resulted in overall decreased expenses. Further, the annual expenses decreased considerably after incorporating the compensation for activated energy accosted with FCR-N reserves. It it was a challenge keeping the SOC in the battery at an acceptable level. It was successfully achieved to reduce the number of hours the SOC limits were exceeded without increasing the annual expenses. However, the problem is still not completely removed. Therefore, this aspect should be a part of further work.

New Environmentally-friendly Insulation Gases: Breakdown Mechanisms along Insulating Cylinders when implementing Barriers and Triple Junction Gaskets

Student: **Helene Grimstad Osberg**
Supervisor: **Frank Mauseth**
Co-supervisor: **Hans Kristian Meyer**

Problem description

SF_6, used in gas insulated switchgear, has a high global warming potential of around 23000, and new environmentally friendly gasses should be investigated as possible replacements. Air is an option as an insulation gas with a low GWP. Air does not have a high enough breakdown strength on its own, and some improvements should be made. Solid insulation materials for supports, barriers and shafts need to be used along with air. These solid-gas interfaces are some of the weakest points in medium voltage switchgear. Understanding the breakdown mechanisms along these surfaces is important for implementing air.

The task

Two main research areas are introduced in the thesis:

- Investigate whether using a barrier around the insulating cylinder can increase the breakdown strength of the solid-gas interface.
- Investigates ways to increase the inception and breakdown voltage at the triple junctions, where the insulation material, gas and electrode meet, by adding gaskets.

Model/ measurements

3D-printed barriers as in Figure 1 are placed around a profiled insulating cylinder. Gaskets, either rubber as in Figure 2 or silicone as in Figure 3, were placed at the triple junction of a smooth cylinder. Rubber gaskets were placed in milled slots, while the silicone gaskets were cast between the cylinder and a sharp edge. The test object was connected to an impulse generator. Up-and-down tests were completed on the test object to find the 50% breakdown voltage for lightning impulses. To get an understanding of the breakdown mechanisms, pictures were taken of the breakdown channels.
COMSOL Multiphysics simulations were computed to supplement the breakdown voltage and get the inception voltage. The inception voltage was calculated using a Python script implementing streamer inception criteria. The average AC breakdown voltage was found using a continuous rising method for the silicone gaskets.

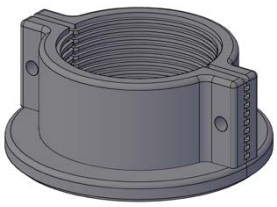


Figure 1: CAD model of 3D-printed barrier

Figure 2: Image of rubber gasket placed in the milled slot.

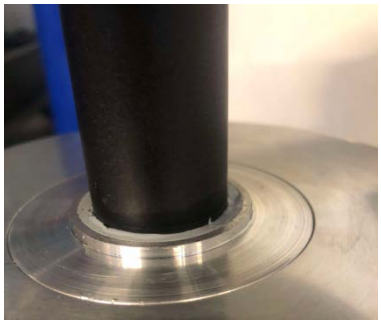


Figure 3: Image of silicone gasket.

Calculation

The breakdown channel with a 3D-printed PLA barrier, rubber gasket and silicone gasket can be seen in Figures 4, 5 and 6 respectively.

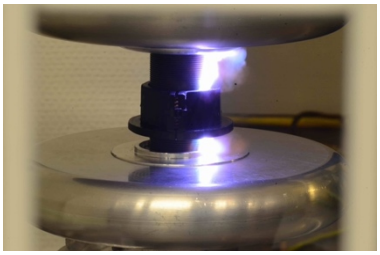


Figure 4: Breakdown channel with 3D printed barrier.

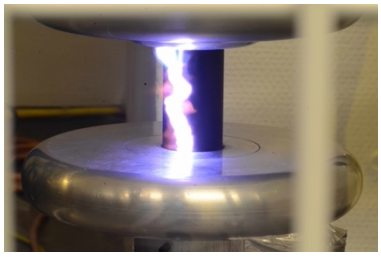


Figure 5: Breakdown channel with rubber gasket.

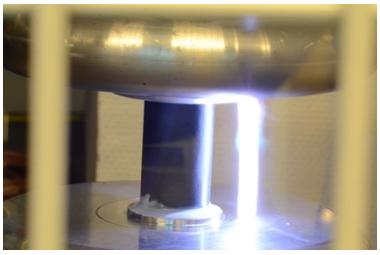


Figure 6: Breakdown channel with silicone gasket.

Conclusion

- Barriers around an insulating cylinder do not increase the breakdown strength of the gas-solid interface since the breakdown channel is lead between the insulating cylinder and the barrier.
- Rubber gaskets may improve the breakdown voltage of the air gap with an insulating cylinder if the gasket is big enough and placed precisely. The cylinder should also be centred.
- Silicone gaskets have a 20% increase in breakdown voltage compared to a reference setup for an air gap with a solid-gas interface. The increase in inception voltage around the triple junction is the main reason for this increase, eliminating the field enhancement at the triple junction. Two silicone gaskets are tested, one cut and one uncut. The increase in breakdown voltage is the same for both silicone gaskets.
- Testing the silicone gaskets in an AC-stressed situation, they have a slightly higher breakdown voltage and do not negatively affect the breakdown strength during regular operation.

Design of a laboratory setup to investigate stability criteria of series-connected synchronous machines

Student: **David Picazo Bou**
Supervisor: **Robert Nilssen**

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

Potential of Hydrogen Technology for Coastal Electrification: Minimizing Distribution Grid Impacts through Flexibility

Student: **Marius Rasmussen**
Supervisor: **Irina Oleinikova, Basanta Raj Pokhrel,**
Contact: **rasmuss1marius@gmail.com**
Collaboration with: **SINTEF Energi, ZeroKyst**

Problem description
This thesis aims to investigate the impact electrifying coastal fishing fleets in Loftoen has on the local distribution network. Additionally, it explores potential flexibility solutions through the im- plementation of a water electrolysis system. The main objective is to analyze the feasibility of supplying hydrogen to the electrified fishing fleets while utilizing the electrolyser as a flexibility solution to ensure stable operation of the distribution network. To achieve this, a realistic model of the distribution network in Lofoten is developed, allowing for simulation of various scenarios to analyze network effects and flexibility solutions.

The task
To what extent does the electrification of a coastal fishing fleet in Lofoten affect the local distribution network, and how can the flexible operation of a water electrolyser be utilized to minimize these impacts efficiently?

Model/ measurements
Real network data obtained from the local distribution grid operator, Elmea, has been utilized to create a realistic network model in the simulation tool DIgSILENT Power Factory. Real load data from 2022 has been implemented in the software to enable simulations based on daily, weekly, and yearly cases, forming the basis for scenario creation. Furthermore, an electrolyser model has been developed to represent its characteristics and has been implemented at the end of the radial on the network section being analyzed.

Calculation
The analysis of the present network, considering 2022 loads, indicates that the electrification of the coastal fishing fleet in Lofoten has a relatively low impact on the local distribution network. However, when examining future scenarios, it becomes evident that the lines and cables operate close to their rated values, resulting in a more significant impact from electrification. The flexible operation of the electrolyser is demonstrated for these scenarios, proving not only its feasibility but also its necessity in the worst-case scenario.

Conclusion
Based on the results, the water electrolyser offers flexibility solutions such as voltage control to minimize voltage drops and load shifting to avoid network peaks. Additionally, the planned utilization of flexibility through hydrogen production and storage during periods of lower energy consumption is highlighted. The results confirm that the electrolyser is an effective resource for flexible operation, capable of rapid ramping up and down, thereby supporting stable network operation. The economic advantages of flexible electrolyser operation compared to grid reinforcement are yet to be explored in future research. Overall, this thesis not only provides evidence of the electrolyser's potential for flexible operation but also examines the impacts of electrification on the distribution grid.

Analysis of Demagnetization Faults in a Permanent Magnet Machine utilizing the Stray Magnetic Field

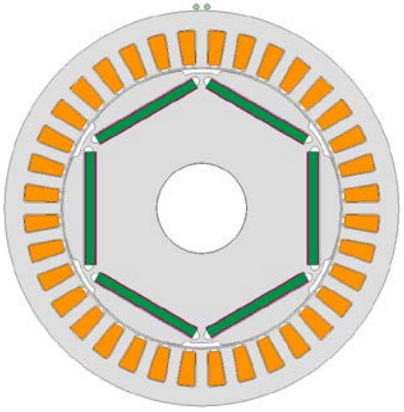
Student: **Sebastian Bruu Ringdal**
Supervisor: **Arne Nysveen**
Co-Supervisor: **Hossein Ehya**

Problem description
The PMSMs are very attractive as both motors and generators in industrial applications due to that they can supply reactive power to the system, produce bulk electrical energy, go from no load to full load at constant speed and operate with higher efficiency than other types of electrical machines. They have typically lower noise and are more robust, unfortunately they are still prone to faults and damages.

The task
The main objective of this thesis is to investigate if the stray magnetic field can detect three different demagnetization faults: uniform demagnetization, one pole demagnetization, trailing edge demagnetization in full load and 50% load thus preventing the faults going into further damage.

Model/ measurements
The analysis was conducted by using the FEM software Ansys Electronic Desktop where the module Maxwell is used.

The rotor consists of 3 pole pairs which is made up by 6 interior mounted permanent magnets. The stator is made up of 36 slots, stator yoke and stator teeth in between the slots. A sensor is mounted on top of the stator frame to detect the stray magnetic flux. The figure under shows the machine and the localization of the sensor used for extracting the stray magnetic field.



The fast Fourier transform (FFT) is used to transform the signal from the time domain to the frequency domain. The harmonic spectrum is further analysed and compared with healthy case.

Calculation

Some of the most interesting results are presented below. Fig.22 shows the stray magnetic field that radiates outside the machine frame in vector form. In Fig.26, the frequency spectrum of the comparison between healthy case and when one pole is demagnetized. It can be observed that an asymmetric fault has kicked in as the subharmonics marked with red circles following the equation $f_s(1 \pm \frac{k}{p})$ where k is an index increasing, f_s is the fundamental frequency and p is pole pairs. 16.67 Hz, 33.33 Hz, 66.67 Hz and 83.33 Hz have a percentage change of 75.5%, 86.5%, 87.9%, 83.5%. In Fig.29 the trailing edge demagnetization of ¼ magnet have some subharmonics following a pattern by the equation $f_s(1 \pm \frac{k}{4p})$.

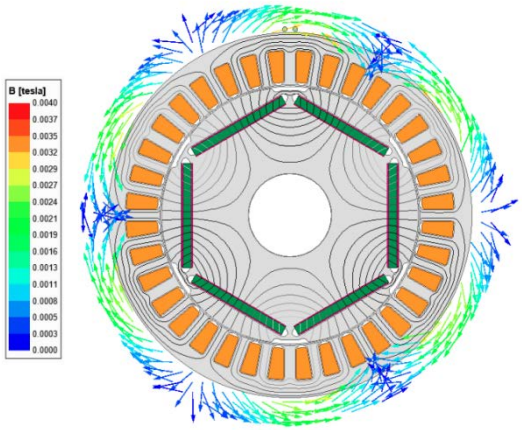


Fig. 22. Flux density of the stray flux in a full load healthy machine

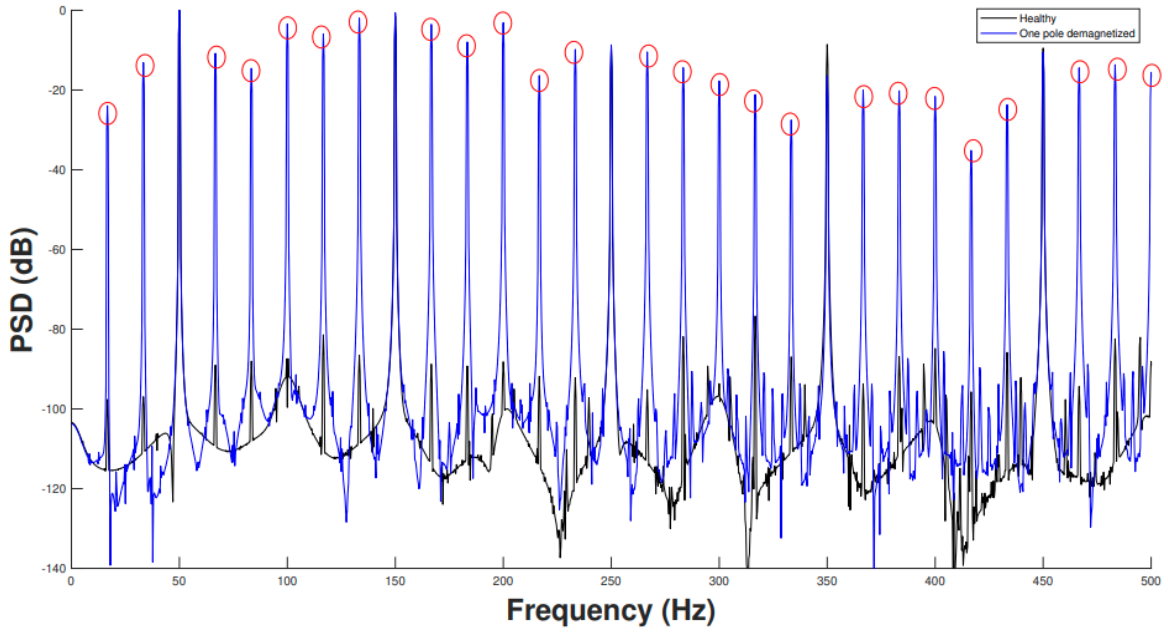


Fig. 26. One pole demagnetized, full load

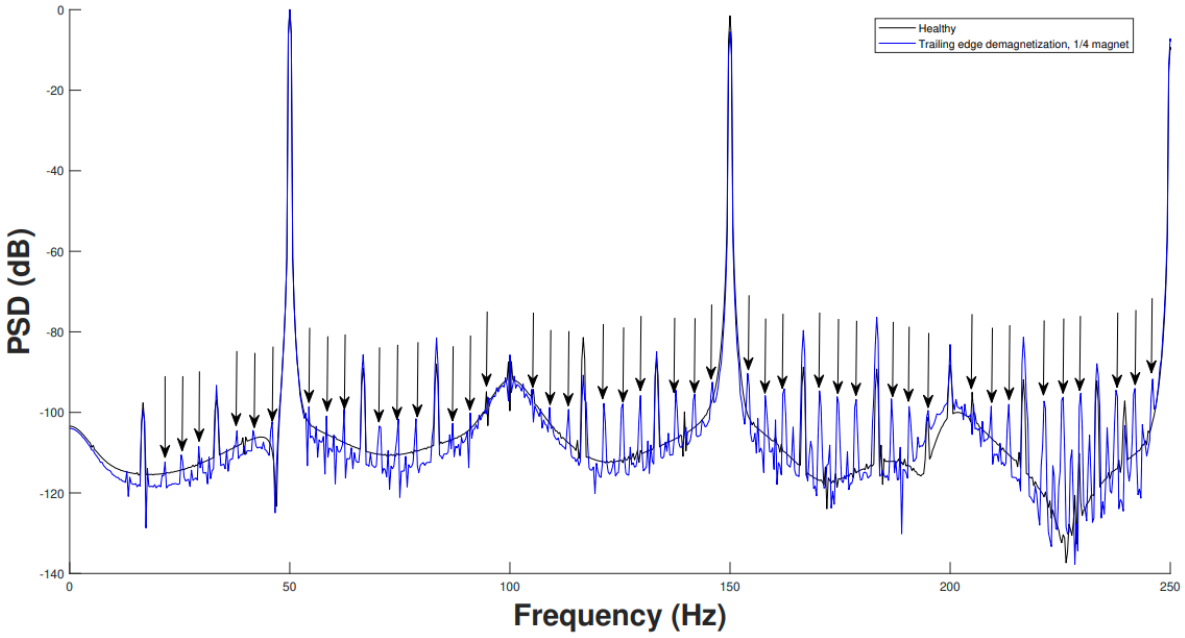


Fig. 29. Trailing edge demagnetization 1/4 magnet, full load

Conclusion

The FEM simulation and analysis revealed that the one pole demagnetization and trailing edge of ¼ of the magnet made subharmonics appear in the frequency spectrum in full load. The frequency spectrum was the same for one pole demagnetization but different for trailing edge with 50% load. The uniform demagnetization was detected by analysing waveform of the stray flux directly where spikes with an increase of 62.5% was observed compared to healthy case.

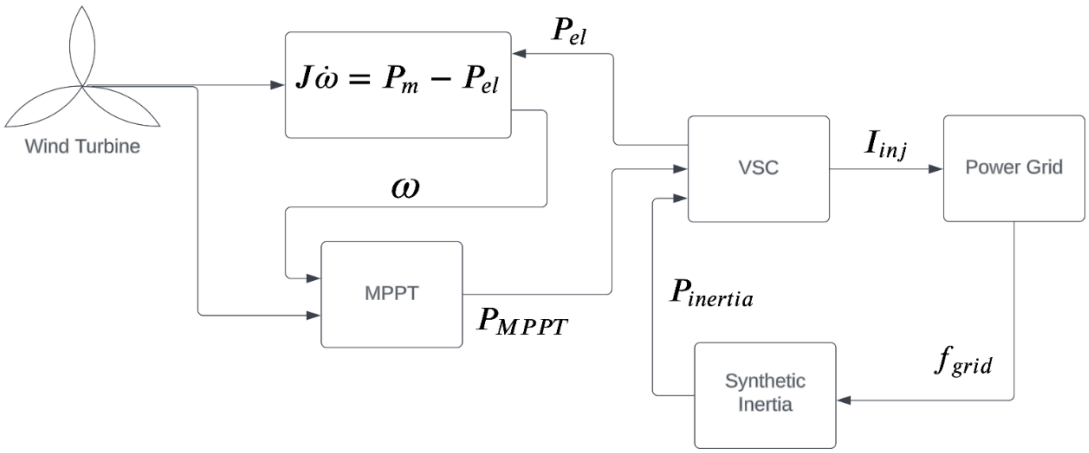
Frequency Control Evaluation for a Variable Speed Wind Power Plant in an Isolated Power System

Student: **Jonas Eidsvåg Rostad**
Supervisor: **Kjetil Uhlen**

Problem description
The growing proportion of renewable energy sources in the overall generation mix has significant implications for frequency regulation in modern power systems. Frequency control is essential for safe and stable operation of the power system. As renewable energy sources are unable to act as spinning reserves in the power system, the system's total inertia is reduced. However, due to the fast response capabilities of the electronic controllers, some renewable energy sources can provide frequency support during a transient event in the power system.
Wind energy is one of these sources, as it allows for the provision of synthetic inertia to the system. This is achieved by the implementation of variable speed wind turbines. The variable speed element of the turbines allow for faster and safer control as the turbines are decoupled from the power grid.

The task
The objective of this thesis is to develop a realistic model of a wind power plant and study the dynamics of both the power system and the connected wind farm. The specific focus of this research is to investigate the power system frequency during a transient event, such as a load deviation, and analyse the contribution of frequency support from the wind farm.

Model/ measurements
The model of the wind farm is established in the DynPSSimPy software, which is designed for performing dynamic simulations of small- to medium-sized power systems. To achieve desired behaviour of the wind farm, it is built like the block diagram in the figure below. During a load deviation in the system, the synthetic inertia regulator monitors the resulting deviation in frequency, and subsequently signals the wind farm to provide additional power to the grid in order to compensate for the deviation.



Initially, a base case is established using Kundur's Two Area System to examine the systems behaviour during a load deviation. Subsequently, the wind farm model is incorporated in the same power system configuration to examine the frequency support and impact of synthetic inertia provided by the wind farm.

Calculation
For the base case, the load increase of 180 MW initially produced a frequency drop of -0.25 Hz. Including the wind farm in the simulation, this frequency deviation was reduced to -0.20 Hz. The inclusion of the wind farm reduces the stress on the other generators in the system during the load deviation, making for a lower reduction in the generator frequency. Although the wind farm's frequency support, regarded as primary frequency control, reduces the initial impact of the load deviation, additional services must be provided to restore the system frequency to nominal value.

During the provision of synthetic inertia to the grid as a response to the load deviation, kinetic energy is extracted from the wind turbines. Consequently, the rotor speed of the turbine starts decelerating, leading to changes in the mechanical power. In order to keep the wind farm from stalling, control strategies for the rotor speed must be introduced in the absence of other frequency restoration reserves.

Conclusion
The integration of a variable speed wind farm shows promising results in enhancing the stability of the power system by providing frequency support. The wind farm plays a crucial role in reducing the initial drop in frequency caused by the load deviation. Additionally, it is important to note that the provision of frequency support from the wind farm is only temporary. During a sudden load increase, a portion of the kinetic energy stored in the system is released. The synthetic inertia regulator of the wind farm detects this and signals the wind farm to contribute power. As the load increase leads to a decrease in rotor speed decreases, the operating point on the power coefficient curve shifts. By initially operating on the right side of the curve, the wind farm is able to provide support for a significantly longer duration, as operating on the right side allows it to delay reaching the rotor speed limits, in contrast to operating on the left side. This positioning of the curve's operating point facilitates the prolonged support of the wind farm during transient events.

Experimental verification of control methods for series connected VSCs applied to a modular HVDC power train for offshore wind.

Student: **Vegard Yssen Rørstad**
Supervisor: **Pål Keim Olsen, Lorrana Faria da Rocha**
Contact: **Vegardyssenrorstad@gmail.com**

Problem description

This thesis discusses the ModHVDC power train concept. The ModHVDC proposes a high voltage generator which consists of isolated stator segments which are connected to separate voltage source converters. The voltage source converters are series connected on the DC-output. The problem this thesis investigates is DC-side voltage imbalance between the segments as a result of parameter variations in the isolated stator segments. PI based outer loop voltage balancing control is implemented, and three voltage balancing strategies are investigated.

The task

In this thesis, the control system for a two-module realization of the series-connected VSCs from the ModHVDC concept has been investigated through simulations and a laboratory small scale implementation. The lab implementation includes an embedded system carrying out the module-level control algorithms. The experimental setup is outlined in Figure 1 and emulates the ModHVDC system for a two-module implementation which is the minimal realization of the modular concept. Transformers were used to emulate the isolated stator segments. Lab results were compared to simulation results for verification.

Model

The lab setup used is illustrated in Figure 1. The simulations of the ModHVDC system were performed in Simulink. Additionally, simulation models of the lab setup itself were also developed to verify the lab results. The lab system is made to emulate the ModHVDC system at a module level, but does not include turbine-level control such as speed control.

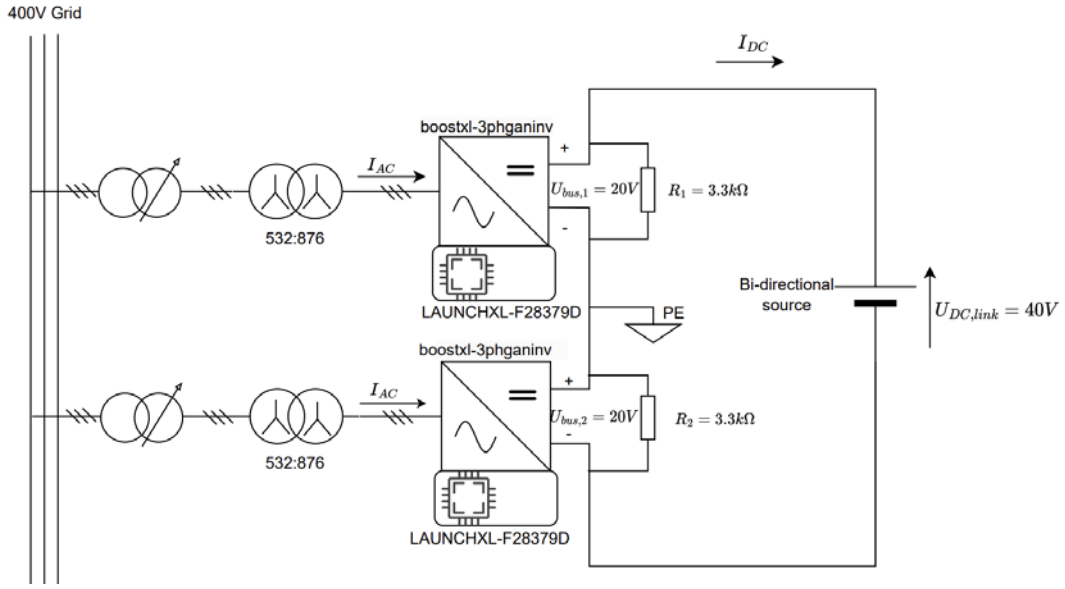


Figure 1: Lab setup of the two-module implementation.

Results

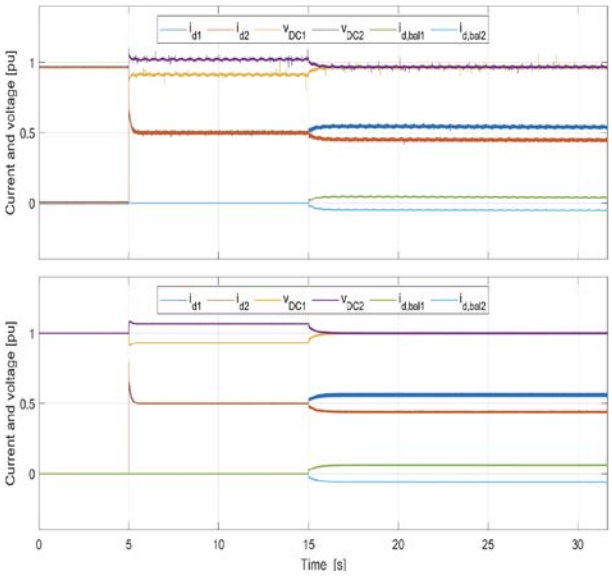


Figure 3: Voltage balancing results from the lab (top) and simulation (bottom).

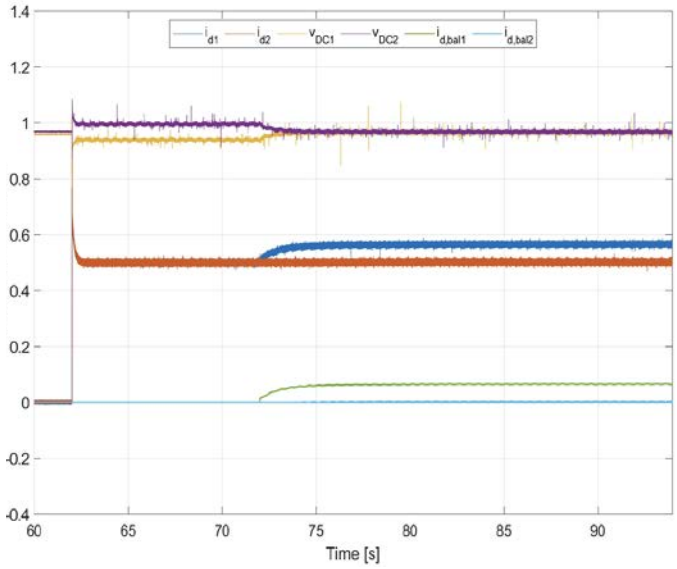


Figure 2: Voltage balancing results from the lab using the ”Lift to rated power” strategy.

Figure 2 and 3, show some key lab results illustrating the effectiveness of the voltage balancing control and that different control strategies can be implemented effectively. Figure 3 also shows simulation results from the Simulink model simulating the lab setup itself.

Conclusion

The experimental laboratory setup was found to emulate the ModHVDC concept proficiently, and the behaviour of the lab system relative to the simulations of the complete control system with a modelled PMSG showed reasonable correspondence. The implemented control algorithms in the lab setup, including the PLL, current control, and voltage balancing, all operated successfully, although with room for improvement.

Each of the voltage balancing strategies discussed in this thesis provides viable alternatives for balancing the bus voltages in the ModHVDC system. Each has specific implications regarding system performance, economic feasibility, and equipment rating requirements and further cost-benefit analysis is necessary to find the optimal strategy for implementing the ModHVDC system. However, it is demonstrated through experimental testing and simulations that all three strategies provide accurate DC voltage matching between the modules and provide a stable system response with the given tuning constants.

Valuation of energy storage technologies in the Nordic power systems and markets context with growing wind power penetration

Student: **Shirin Sadullaeva**
Supervisor: **Prof., Dr. Olimpo Anaya – Lara, Dr.Raymundo E.Torres-Olguin**
Contact: **4792062862, shirinsa@stud.ntnu.no**
Collaboration with: **N/A**

Problem description

Despite the Nordic region's extensive experience in operating power systems (PS) with high wind farm (WF) penetration, there are ongoing and emerging technical challenges. The signs of inflexibility in the Nordic markets include increasing demand for power ramping capacities, risk of frequency excursions, volatility of market prices, and cases of negative market prices. Energy storage systems (ESS) have garnered significant interest due to their ability to provide multiple grid-associated services and the declining cost of storage components. However, a property of storage systems to deliver a wide range of energy and power services, poses difficulties in quantifying their possible values and monetizing them.

The task

The main research question that framed this Master's Thesis is: "Is there a value and a niche for energy storage systems at the utility-scale to support the Nordic power system in the context of growing wind farms penetration?" The research evaluates the value of commercially mature and emerging storage technologies within the Nordic power systems and markets. Specifically, Battery Energy Storage Systems (BESS), Flywheel Energy Storage Systems (FESS), and Diabatic Compressed Air Energy Storage Systems (D-CAES) are examined across various Nordic ancillary and energy markets, including Frequency Containment Reserves for Normal Operation (FCR-N), Fast Frequency Reserves (FFR), manual Frequency Restoration Reserves (mFRR), and energy arbitrage in a Day-Ahead (DA) Elspot market. Listed frequency services are procured by the Nordic Transmission System Operators (TSOs) to maintain equilibrium and stable operation in the grid.

The contribution of this Master's thesis is the detailed assessment of the potential of mature and emerging storage technologies to address challenges in the Nordic power systems while benefiting storage project owners in the studied Nordic markets. This thesis attempts to enhance the understanding of storage value in Nordic systems by evaluating the feasibility and economic viability of these technologies through the establishment of a storage technology-Nordic market matching framework and simulation models.

Model/ measurements

A second-by-second and hourly annual simulations are implemented in Matlab de novo for frequency and energy services on real Nordic PS grid data and recent market prices from Nord Pool, Energinet, and Statnett to ensure the relevancy of the results. Where the optimization of operation based on the profit maximization is allowed by the Nordic market rules, the Convex (CVX) -tool in Matlab is used to solve a linear deterministic optimization problem. Activation of other services (FCR-N, FFR, mFRR capacity market + EAM) is based on the grid frequency profile or orders from the Nordic system operator.

Calculation

The results are presented for 3 study cases, 11 scenarios, and 82 sub-scenarios covering selected storage technology types, Nordic market services, and different energy-to-power (E:P) ratios. Findings indicate that BESS, despite cycles-related lifetime limitations, can achieve positive profits in all analyzed markets if sized accordingly. At the same time, FESS is primarily suitable for FCR-N due to its low E:P ratio. CAES, although having high capital expenditure (CAPEX) costs and low efficiency, can be valuable for energy arbitrage and

mFRR services with optimized duration. Recommended sizes and ratios for each technology are determined based on revenue potential and economic viability. For automatic frequency service (FCR-N, FFR) E:P of 1 with the size 5MW/5MWh is recommended for the BESS. FESS, having the E:P ratio limit of 0.25, demonstrated the best market performance in FCR-N with the size of 5MW/1MWh. For energy arbitrage in Elspot markets, a longer storage duration is required. Economic value calculations suggest 1MW/4MWh for the BESS, and 5MW/25MWh for CAES. In mFRR market, which has shown to be the most energy-demanding, 5MW/ 75MWh CAES yielded the highest NPV. The value of BESS in FCR-N is evaluated to be about 610 USD/kW/year based on the revenue from recommended 5MW/5MWh BESS with NPV totalling at 3,247.73 at the end of a BESS lifetime (12 years). The thesis showed that it is possible to yield a revenue of above 300 USD/kW/year of installed BESS capacity in Elspot market. If storage is already participating in FFR market, then its value can be increased by combining it with FCR-N (estimated value is 399.13 USD/kW/year) or Elspot day-ahead market (249.88 USD/kW/year). In the case of FESS technology, only FCR-N market has the potential of providing a positive business case according to the thesis conclusions. FFR requires 100% FFR committed capacity activation when the frequency is at its threshold, and therefore FESS is inherently bound to be penalized as maximum power output is less than installed power capacity due to energy constraints associated with low E:P. An alternative strategy was tested for FESS in FFR when only a fourth of the installed capacity is nominated at FFR market to match energy and power capacity limits, but an analysis demonstrated that with the current rules and prices in the Nordic FFR market, obtained revenue failed to offset high FESS' CAPEX costs, and negative NPV is yielded for the alternative strategy. The value of FESS that can be potentially obtained from FCR-N market, is evaluated to be 599.5 USD/kW/year based on the revenue values from 5MW/1MWh FESS with NPV totaling at 2,897.74 USD/kW at the end of a FESS lifetime (20 years). For CAES, all studied markets also allowed yielding positive cases. The analysis has shown that it is possible to yield a revenue of above 300 USD/kW/year of installed CAES capacity in Elspot market. The highest revenue contributor in mFRR market is energy payment EP which CAES receives for the activated capacity in EUR/MWh. mFRR is procured throughout the year. It is stated to be a symmetrical service. However, historical data indicates that Nordic TSOs mostly procure up-ward regulation. Therefore, CAES operators should adopt a certain strategy for recharging CAES. In the thesis, this was done by recharging the CAES from the grid and compensating at up-ward energy regulation prices. The highest value of CAES can be obtained from mFRR service when CAES is bidding into both capacity and energy markets, and evaluated to be 950.73 USD/kW per year based on the revenue from 5MW/75MWh CAES with NPV totaling at 4,774.61 USD/ kW at the end of a CAES lifetime (30 years). If CAES operator for some reason wants to bid in an Elspot market then combining it with mFRR EAM (estimated value is 536 USD/kW/year) can allow increasing the total revenue. This is because CAES would have a wider selection of prices to choose from and can optimize its operation accordingly. Participation of CAES in an Elspot only provides almost four times less revenue of mFRR generated.

Conclusion

(1) Nordic TSOs recognize the need for flexibility with increasing renewable energy, but wind farm operators lack incentives for storage. (2) Nordic markets face challenges of inflexibility, power ramping demands, frequency risks, and price volatility. (3) BESS shows positive profits in all markets, FESS has limitations, and CAES has high costs and requirements. BESS has potential in all markets, FESS in FCR-N, and CAES in all markets. (4) Combining storage technologies with different markets not necessarily increases their value and revenue.

Tree High Impedance Fault Modelling

Student: **Mercuzio Sassetto**
Supervisor: **Irina Oleinikova**
Co-supervisor: **Basanta Raj Pokhrel**

Abstract

Europe will be subject in the coming years to major changes in the energy sector, according to the plan called “REPowerEu” the goal is to reduce greenhouse gas emissions by 55% by 2030 and achieve climate neutrality by 2050. To meet these goals, it is essential to increase the adoption of renewable energy sources in the areas of power generation, industry, and transportation. This future scenario foresees an increasingly complex power system, which makes it essential to invest in the modernization of the electrical grid infrastructure and its management to ensure proper, stable, and cost-effective operation.

This thesis work is placed under the topic of digitization of the electrical system with an emphasis on supporting the development of artificial intelligence-based methodologies for electrical fault detection. A specific type of fault affecting power distribution lines is studied, the high impedance fault caused by the contact of a live shaft with phase conductors. This fault poses numerous problems for local power distributors due to the difficulty in its detection by protective devices and because of its danger to human health and electrical infrastructure as it can also lead to serious forest fires. The development of these new fault detection methodologies often struggles with the lack of datasets: faults are not very frequent, and measurements are rarely made accessible; field experiments for generating data are very expensive. A way to bypass these difficulties is to create models that simulate the characteristics of faults, this is precisely what was done within this thesis.

A model for the single-phase fault caused by vegetation contact will be exposed, it provides the fault current trend as a function of moisture content and line voltage, thus enabling fundamental data generation for the training phase of fault detection algorithms based on artificial intelligence. The model is shown and developed for a single vegetation species, but the same methodology can be applied to different types of trees.

Integration of Renewable Energy Sources into Electricity Markets via Optimized Wind Farm and Hydropower Scheduling

Student: **Kristin Serck-Hanssen & Hanna Birgitte Sletta**
Supervisor: **Umit Cali**
Contact: kristinserckhanss1@gmail.com , hannsletta@gmail.com
Collaboration with: **SINTEF Energy Research**

Problem description

The penetration of windpower has increased in the Norwegian power system traditionally dominated by hydropower. The goal of the thesis is to utilize SHOP, a short-term hydropower scheduling tool developed by SINTEF, to optimally schedule the operation of wind farms and hydropower plants on a short-term basis.

The task

A *Wind Optimization Model* is developed in the SHOP environment and its functionality tested on a case study at Geitfjellet Vindpark, located within the focus area price zone NO3. The analysis investigates the impact of a volatile up-regulation price on the day-ahead market power bid and total profit of a windpower producer. Historical data from the case study was inserted as scenarios into a scenario reduction algorithm. Stochasticity was utilized to assess the variations that arise from incorporating a varying number of scenarios. The long-term goal is that can be *Wind Optimization Model* further developed to become a joint Wind-Hydro Optimization Program (WHOP) through integration with SHOP.

Model

The *Wind Optimization Model* is developed in several stages. A scenario reduction algorithm is incorporated to help reduce the input data into the *Wind Optimization Model*. Figure 1 depicts the process of generating the input scenarios using the scenario reduction algorithm through data collection from Nord Pool and windpower production data. The input data is taken from the year of 2019, the only year with available windpower production data in hourly increments. The number of scenarios generated is 25, 50 and 365 for three distinct hours of the day. The *Wind Optimization Model* is developed by manipulating the hydropower specific attributes in SHOP to model the wind farm as a run-of-the-river plant without any means of storage. Figure 2 shows the physical system that was created in SHOP, clearly indicating the hydropower attributes. SHARM has been used to correctly include stochasticity in the market bids.

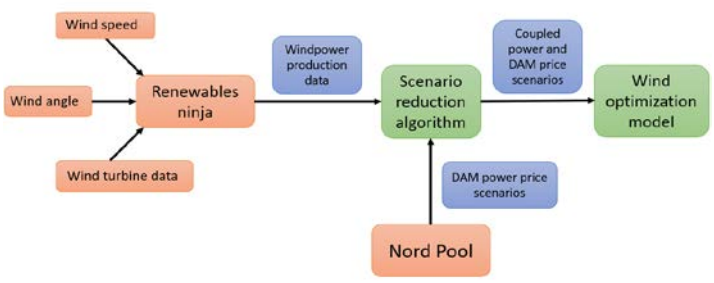


Figure 1: The process of generating input scenarios for the *Wind Optimization Model*.

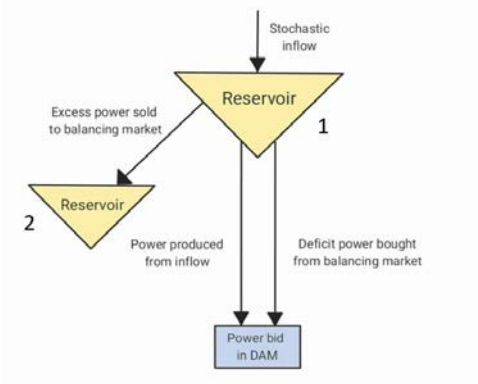


Figure 2: A representation of the physical system modelled in SHOPs hydropower environment.

Calculation

The functionality of the developed Wind Optimization Model was tested on a case study based at Geitfjellet Vindpark investigating the impact of volatile up-regulation prices on power bid and profit for the windpower producer. The case study was performed based on data from 8-9 AM, 12-1 PM and 4-5 PM, with input cases of 25 scenarios, 50 scenarios and 365 scenarios. The 4-5 PM cases had the most interesting results and were investigated closer by also doing a study using seasonal datapoints rather than yearly. The findings can be summarized as:

- The windpower producer consistently bid under expected production to avoid the high up-regulation penalty costs for balancing incorrect bids.
- Increase in scenarios gave a more detailed and accurate representation of the bids and profit.
- Using seasonal data points rather than yearly gave more realistic bidding strategies.
- For the seasonal cases the profit was relatively equal for both 25 and 50 scenarios, most likely caused by the reduced amount of input data points from 365 to 90.
- Winter season had an even probability distribution across the power produced and market price for both the 25 and 50 scenario cases compared to spring season, see Figure 3 and 4. The market price followed the expected seasonal variations, as can be seen in Figure 5.

Figure 3: Scatter plot showing input data for 50 scenarios at 4-5 PM for the winter months. Each point is a scenario, and the size of the plot indicates its probability.

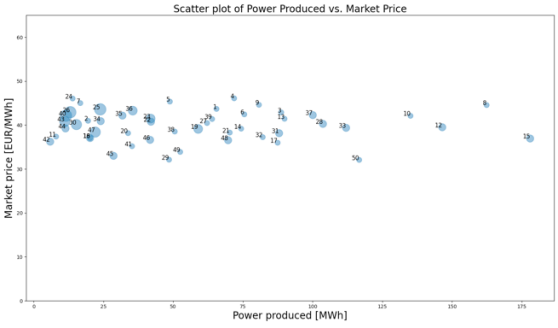


Figure 4: Scatter plot showing input data for 50 scenarios at 4-5 PM for the spring months. Each point is a scenario, and the size of the plot indicates its probability.

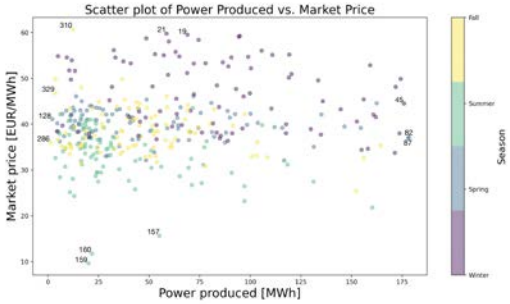


Figure 5: Scatter plot showing input data for 365 scenarios at 4-5 PM. Each point is a scenario, each with the same probability. The colors represent the four seasons and the scenarios within the respective season. Extreme points are numbered

Conclusion

The thesis have developed a *Wind Optimization Model* for short-term scheduling, and demonstrated functionality through a case study conducted at the Geitfjellet Vindpark. The way the market works today does not allow for the distinct variability and uncertainty a windpower producer encounters in their short-term scheduling. It could be beneficial for the wind producer to balance their bids through hydropower regulation rather than balancing through the up-regulation price, or through joint scheduling with hydropower using tools such as WHOP, which needs to be developed.

Off-Grid Microgrid Design Consideration for Rural Electrification

Student: **Shankar, Varshan Erik**
Supervisor: **Völler, Steve**

Abstract

This Master's thesis has made significant strides in advancing rural electrification efforts, mainly focusing on the design and implementation of microgrids. The primary contribution is developing a versatile Python-based tool tailored to the needs of GridVille NTNU, a technical student organization at the Norwegian University of Science and Technology, a project aiming to provide sustainable electricity to off-grid, rural areas.

The tool incorporates a multi-objective optimization approach that considers various variables and constraints, such as energy source selection, energy storage, load profiles, and applying the Multi-Tier Framework for energy access. It has been designed with a user-friendly structure that allows usage at various levels, from basic to advanced, depending on the user's technical expertise. This makes it a valuable resource for a broad user base, from students doing the technical sizing to board members involved in budget planning or similar tasks.

The tool's practicality and reliability were demonstrated through a case study and validated using real-world data. It was found to be accurate and capable of handling a variety of scenarios and conditions, which is critical in the rapidly evolving field of renewable energy and microgrids.

In addition to the tool's development, this thesis provides insights into microgrid design considerations based on field experiences from Kenya and Tanzania. These experiences underscore the importance of understanding the local context and highlight the crucial role of community engagement, the necessity of understanding local energy consumption habits, and user education about energy utilization.

The study also contributes to several Sustainable Development Goals (SDGs) set forth by the United Nations. It directly aids GridVille in achieving these goals by enabling the organization to size and implement off-grid microgrids optimally, thus improving living conditions in underserved communities.

Despite the significant contributions of this study, there are potential areas for improvement and future work. More extensive error handling and data validation steps could enhance the tool's user-friendliness. Furthermore, as the tool evolves and becomes more complex, significant restructuring might be needed to maintain its modularity and navigability.

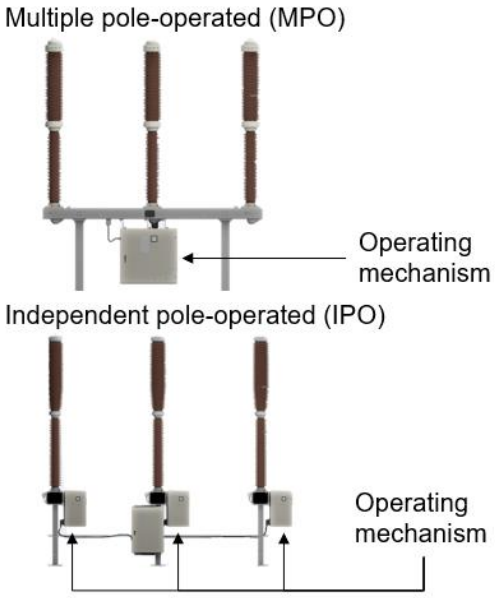
In summary, this Master's thesis presents a comprehensive study on rural electrification focusing on the design and implementation of microgrids. It provides a practical tool for microgrid sizing, offers insights into design choices, and shares first-hand field experiences. This work can greatly aid GridVille and similar projects in their mission to bring sustainable and reliable electricity to off-grid, rural communities. However, it is an ongoing journey that calls for continuous learning and adaptation to technological advancements and evolving field experiences.

Impact of Transformer Vector Group on Voltage Quality During IPO Breaker Operation in a Solidly Grounded Radial Systems

Student: **Johan Shields**
Supervisor: **Bjørn Gustavsen**

Problem description

Some of the regional distribution network owners in Norway are considering changing their 132 kV system from the commonly used Peterson-coil grounded system to a solid grounded. By doing so, they eliminate the need for constant updating of the coil when making changes or expanding the current power grid. They would, however, lose the built-in ability for self-clearing single-phase faults that the Peterson-coil grounded system possesses if a change is made. A possible solution to this problem is the implementation of circuit breaker systems with independent pole operating (IPO) capabilities in the solidly grounded system.

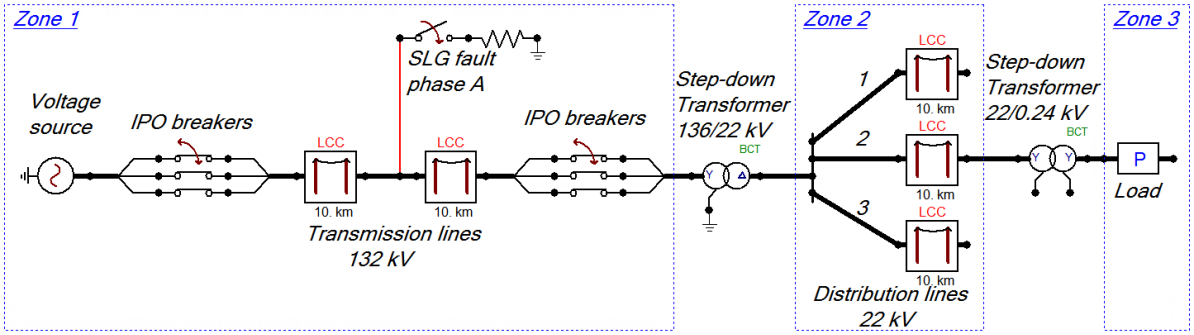


The task

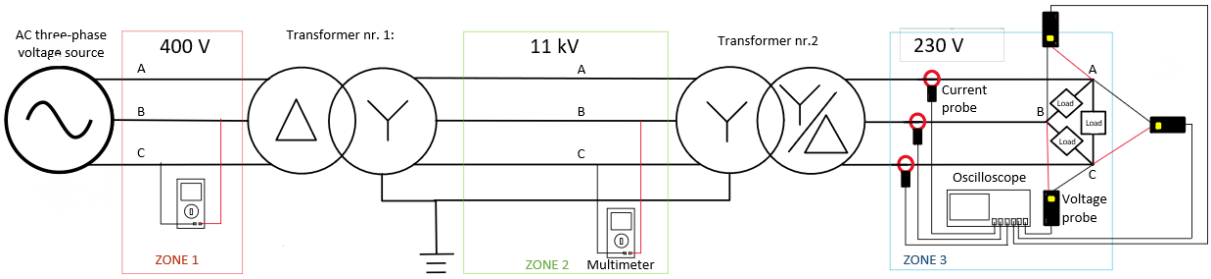
This project aims to investigate how the transformer vector group affects voltage quality when a single-line-to-ground fault (SLG) is removed by circuit breakers with IPO capabilities in a solidly grounded system.

Model/ measurements

Five separate BCTRAN transformer models with a different combination of vector groups and grounding of their neutrals were modeled in ATP. These five models were integrated independently in the previously developed test circuit, thereby forming five separate case studies. The effect the vector groups had on voltage quality could then be found by comparing the resulting voltage and current from each case.



A laboratory experiment was designed with the purpose of replicating the voltage and current trends seen from simulations during the IPO breaker operation.
This experiment was conducted with two different vector groups, wye-wye, and wye-delta. An open-phase condition (OPC) was generated by removing one of the supplying conductors on the high-voltage side of transformer nr. 2. The resulting line-line voltage on the secondary side was then monitored and compared with the simulated results.

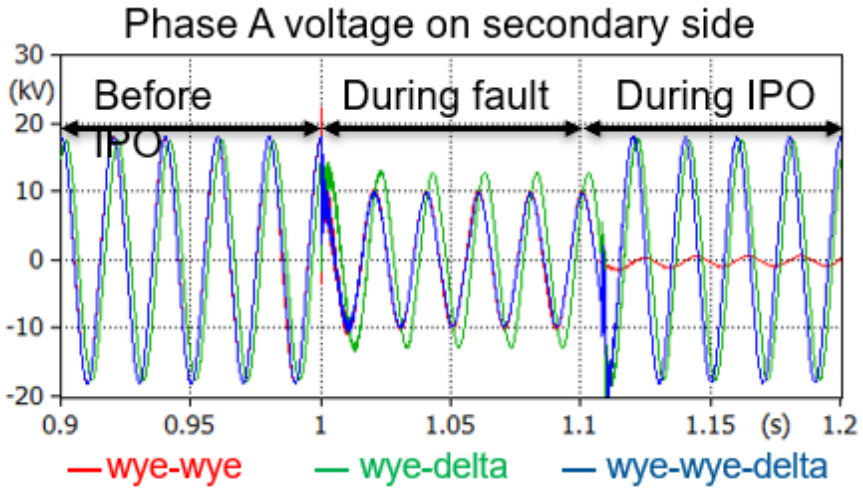


Calculation

The results from simulations and the laboratory experiment indicate that regeneration of voltage to pre-faulted values on the secondary side during IPO breaker operation is entirely dependent on the vector group, and grounding of available neutral points. The wye-wye transformer, where only the neutral point of the primary winding was grounded, experienced close to no voltage regeneration in the simulated results. The laboratory experiment, contrarily, showed full regeneration of line-line voltage with the same winding configuration. The contradictory results were because the three-legged core-type wye-wye transformers regenerate voltage magnetically through flux pathways in the core, which is heavily influenced by the size of the connected load. Voltage regeneration was, therefore, possible in the laboratory experiment because the load connected was minuscule compared to the size of the transformer. All situations involving wye-delta and wye-wye-delta transformers experienced full voltage regeneration when one of the supplying conductors was disconnected by IPO breakers in simulations or physically in the laboratory. This is always the case for wye-delta and wye-wye-delta transformers regardless of the core type or size of the connected load because it is a result of electrical interactions inside the delta winding.

Conclusion

Based on the theoretical analysis and presented results, it can be concluded that voltage quality is highly dependent on the transformer vector group, and grounding of the primary neutral when circuit breakers with IPO capabilities are operated in a solidly grounded radial system. Voltage regeneration during IPO breaker operation for all wye-wye coupled transformers is only possible for three-legged core types in low- or no-load conditions. A regeneration of voltage will always take place in wye-delta and wye-wye-delta transformers, when the neutral point of the primary side is grounded, regardless of core construction or loading.



Stability Analysis of a New Class of Inner Loops for Voltage Regulations in DC/DC converters

Student: **Astrid Sigurdsøn**
Supervisor: **Gilbert Bergna-Diaz**

Problem description

The production of energy from solar and wind power is anticipated to increase by 35 % in the next seven years. This growth will be facilitated by the incorporation of power electronics technology, which enables the integration of these variable renewable energy sources (RES) into the electrical power grid.

The master's thesis considers the closed-loop stability of a linear DC/DC converter using Lyapunov's method. A port-Hamiltonian (pH) representation is applied for the system equations, and the system controller is inspired by the widely-acknowledged passivity-based Proportional-Integral controller (PI-PBC). However, instead of only using the conventional passive output; i.e., inductor current error signal, the capacitor voltage error signal is also included. The controller was revised building upon the recommendations given in the preliminary work [1]; that is, if the voltage error signal is used as the only input to the PI controller, the system encounters significant stability challenges. Therefore, we propose to utilize the current error signal control in the proportional channel, and the voltage error signal appears in the integral channel of the PI controller.

The proposed PI controller rendered the system globally asymptotically stable (GAS) if a constant leakage term is included in the integral channel next to the system's output voltage error signal. Simulations for this control proposal with a constant leakage were carried out to quantify how much it affects the system's ability to reach its control objectives. Unfortunately, the amount of leakage required created voltage deviations that would not be considered acceptable in practice. Thus, we proceeded to remove the leakage and search for an alternative Lyapunov function to prove stability.

With the aim of proving GAS, a new Lyapunov function candidate (LFC) was proposed without it depending on the presence of a leakage term. The process consisted of populating the Lyapunov function candidate with a constant yet a priori unknown terms relating the physical and control states between them, following the procedure described in [1]. However, it was not possible for us to prove GAS by means of this LFC, as the required constant terms did not seem to exist for the proposed controller.

Nonetheless, because the system and the controller have linear dynamics, the eigenvalues of the closed-loop system could easily be calculated. For a given tuning, the system matrix could be made Hurwitz, and using the Lyapunov equation, a valid Lyapunov function was obtained. With this numerical Lyapunov function, the system was proven GAS. Interestingly, unlike the previous LFC, the new numerical one was fully populated. Subsequent to the acquisition of the stability certificate, simulations for the control proposal without the inclusion of the leakage term were carried out.

The populated LFC was utilized to render the system with the inclusion of the leakage term GAS, aiming to reduce the stabilizing leakage term and minimize the required voltage

deviations. We showed that increasing the conductance G enhanced the possibility of proving GAS with the populated LFC. Determining the unknown term in the LFC and adjusting the value of G, a new condition for the leakage term was established. Simulation results demonstrated a significant decrease in voltage deviations, effectively eliminating them. However, it is worth noting that the higher value of G resulted in spikes in the control signal and increased system losses.

In conclusion, the proposed PI controller gives closed-loop stability in the general, linear DC/DC converter in voltage-control mode directly in the inner-loop. By use of Lyapunov's method, Lyapunov functions exist and render the system GAS.

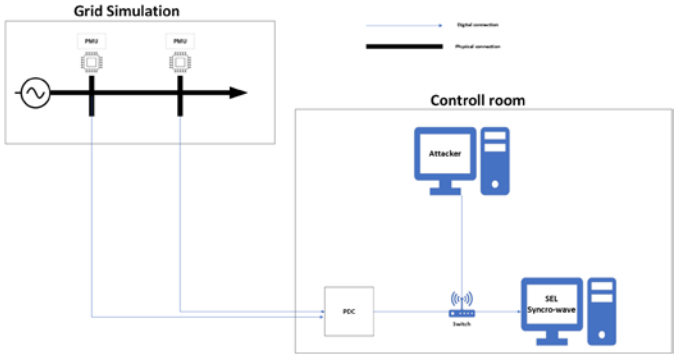
Assessment of cyber-security and communication protocols in smart grid

Student: **Jørgen André Skagemo**
Supervisor: **Irina Oleinikova, Laszlo Erdodi**

Problem description
New-generation digital substations will play a key role in the power system of the future. They will incorporate digital communications via fibre optic cables and wireless communication, replacing traditional copper connections using analogue signals. They will also enable available flexibility, connected to the grid, security of supply and safety while reducing cost, risk and environmental impact. Digital substations will also feature Intelligent Electronic Devices (IEDs) with integrated information and communication technology. Applying communication protocol IEEE C37.118 at substations we need to operate according to a zero-trust security model. Therefore, cyber resilience needs to be an integrated part of the substation and its components.

The task
- Compile a brief understanding of the changes in power systems and the need for cyber-security.
- Present recent and real attacks on the power system to breakdown the sequence of cyber-attacks on the power system.
- Prepare a lab set-up to observe and test the C37.118 communication protocol.
- Uncover viability for eavesdropping, parsing and creation of fake messages.

Model/ measurements
Using the analysis of real and recent cyber attacks on the power sector, a general attacks structure is made. From this understanding of attacks, a laboratory set-up to accurately represent grid operations are presented using the smart grid lab and Opal-RT.



To test this system a “infected” computer is placed, sharing s switch with the rest of the system. From here this computer is able to eavesdrop on the system, picking up all communication in the switch. From here the data is filtered and analysed to separate out the IEEE C37.118 messages. After obtaining the messages parsing to understand and translate the messages is preformed in order to understand and map out the system as well be able to plan out a larger-scale attack.

Following the understating from parsing the messages fake messages is crated. Most of the packet is easily replicated, but two blocks were harder to replicate. The SOC is a timestamp in seconds since 1/1/1970. Using the computer epoc time it is possible to calculate this, ad as the protocol only calls for whole seconds should be accurate enough. The second message is the 2-byte CHK. This is a CRC-CCITT 16-bit algorithm. By calculating the two bytes from the whole message i check value is made to verify that the given data is not corrupted.

Building the IEEE C37.118 messages a command frame would resemble this:

Sync	FrameSize	IDCODE	SOC	FRACSEC	CMD	CHK
aa41	0020	13ee	647092c0	00000000	0005	FE74

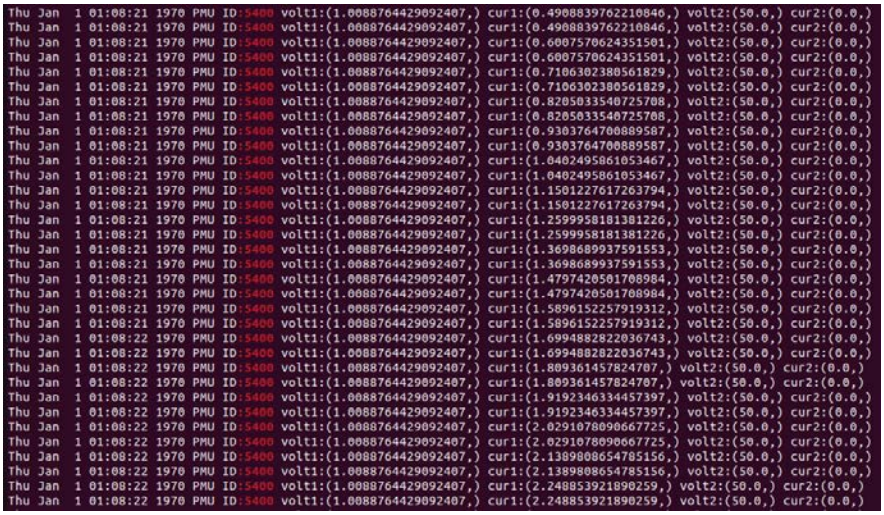
And a data frame would resemble this:

Sync	Frame Size	IDCODE	SOC	FRACSEC	Flags	Phasor data	ROCOF	CHK
aa01	0022	13ee	647092c0	00000000	0000	3f80e504bc8652c542480000	00000000	410E

Furthermore, a code to attack these massages with dynamic SOC and CHK values is made. Utilizing the Python library Scapy these massages can be custom made and attacked to a TCP/IP message and sent to the system as a legit message.

Results

Only from understanding the standard, parsing was possible. Access to configuration frames or equivalent would be useful but understanding of packets is still possible without. This work was consequently able to translate every packet accordingly and with correct values
when compared to data received in the visualisation software. It is also possible to translate live.



Running the code in appendix A the packet gets created and sent. Comparing the fake packet to a real packet, there are minimal differences and from a human eye indistinguishable without prior knowledge.

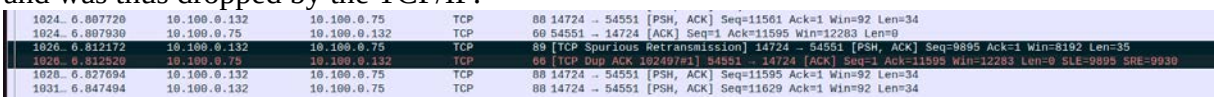
Real

a4 4c c8 5f 85 37 ac 1f 6b 60 5e d1 08 00 45 00
00 4a 9c a5 40 00 40 06 88 72 0a 64 00 84 0a 64
00 4b 39 84 d5 17 a5 3f 3e ad 45 d4 be a5 50 18
00 5c 22 a3 00 00 aa 01 00 22 0e 75 64 78 5f 1e
00 0b e6 e0 00 00 3f 81 df 9f 40 46 7e 44 42 48
00 00 00 00 00 00 fd 02

Fake

a4 4c c8 5f 85 37 c4 41 1e b4 79 ed 08 00 45 00
00 4b 00 01 00 00 40 06 65 16 0a 64 00 84 0a 64
00 4b 39 84 d5 17 a5 3f 5f 7f 45 d4 be a5 50 18
20 00 f2 ef 00 00 aa 01 00 22 0e 75 64 78 7b 19
00 00 00 00 00 00 40 40 00 00 40 40 00 00 22 42
48 00 00 00 00 00 60 ec

Unfortunately, the PMU data did not reach the software. Using the TCP_dump and Wireshark, it is possible to confirm that the packet was sent but flagged down as spurious retransmission. When observing the packet, the sequence number is 2770149307, while the previous sequence number was 2770150973. The sequence number should be 2770151007 and was thus dropped by the TCP/IP.



Conclusion

In conclusion cyber-security is a rising concern in power system. Crating a laboratory setup, it is proven that is a attacker gets access to the data flow, parsing and understanding is possible. It is then also possible to crate fake messages While some parts of the protocols were harder to fake, it was still proven possible even in a short time frame, meaning that is given enough time, this work believes that sending the message over TCP/IP will be possible.

Investigation of PD formation on AlN Ceramic Substrates: Impact of Square Voltage Pulses and Dielectric Liquids

Student: **Ingrid Smisethjell**
Supervisor: **Kaveh Niayesh**
Contact: **Torstein Grav Aakre**
Collaboration with: **SINTEF Energy Research**

Problem description

The electrical power industry is experiencing significant and complex expansion due to changes in consumer and supplier operation patterns, along with the integration of renewable energy sources. Insulated Gate Bipolar Transistors (IGBTs) are an essential component and are widely used. The frequent starts, outages and faster switching of the IGBTs may cause partial discharge (PD) formation, resulting in the degradation of the component. The ceramic substrate is one of the most PD-exposed parts of the IGBT.

The task

This thesis aimed to investigate the PD formation on an Aluminium Nitride (AlN) ceramic substrate under sinusoidal and square voltage pulses in two different insulation liquids, Silicone oil and Nytro 10XN. Additionally, the thesis aims to understand better the space charge phenomenon and how it varies in the two dielectric liquids.

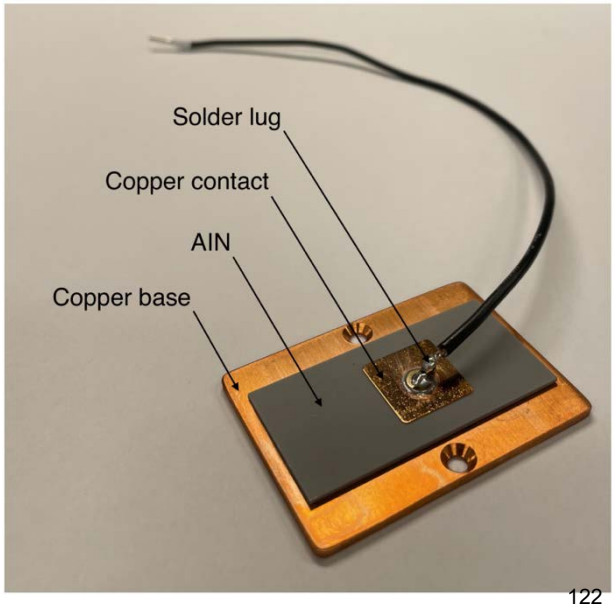
Model/ measurements

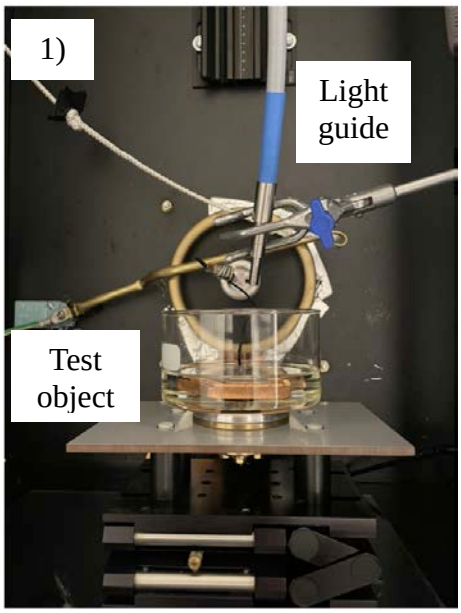
The PDs were detected using a photomultiplier tube (PMT). In some measurements, an ultra-fast gated intensified high-speed camera was included to take pictures of the PDs along the edge of the ceramic substrate. Three experimental setups were used:

1) Sinusoidal and Square voltage setup: Ramping up and down the voltage to determine the Partial Discharge Inception and Extinction Voltage (PDIV and PDEV) under sinusoidal, bipolar, positive, and negative unipolar voltage pulses.

2) Square voltage setup: High-speed camera was used to determine the location of PDs under bipolar voltage pulses.

3) Square voltage setup: Varied the duty cycles to 5% and 95% under negative unipolar voltage pulses. This was done to determine the impact of the duty cycle on PD formation.



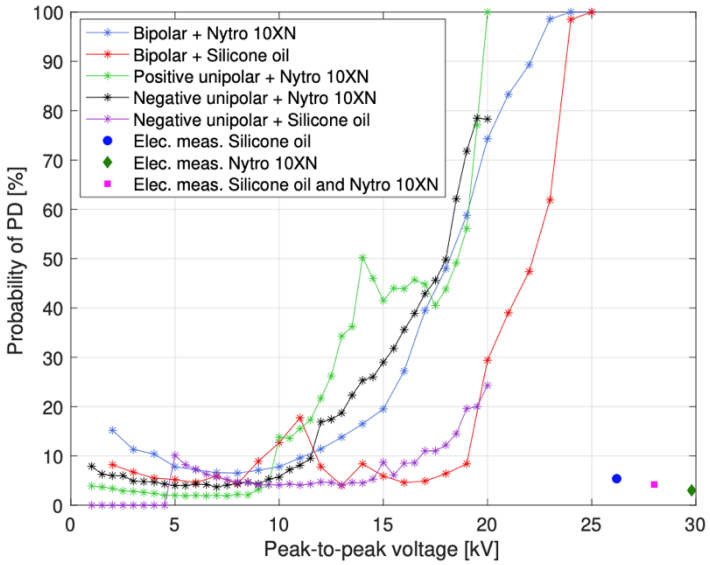


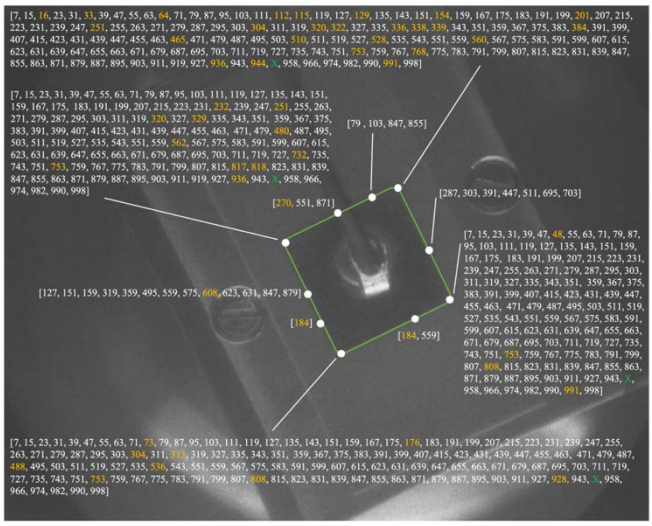
Results
Results from the three experimental setups:

1) The results indicate that the different voltage pulses significantly affect the PD and space charge formation on the substrate. The square voltage pulses are more critical for PD formation than sinusoidal voltages. Thus, the rise time of the voltage pulse is the critical factor for PD formation. Additionally, the results indicate that Nytro 10XN is more prone to PD formation than Silicone oil under square voltage pulses. However, this relation is reversed under sinusoidal voltage pulses.

2) The results indicate that rounded corners of the substrate are the most critical part and are more exposed to PD formation. In addition, the results reveal that PDs occur during voltage flanks, but space charges are also present, resulting in discharges during voltage plateau.

3) The results indicate that the majority of the PDs occur during voltage turn-on compared with voltage turn-off under negative unipolar voltage pulses. PDs occurring during voltage turn-on are the reason for the space charges at the voltage plateau, affecting PD formation during voltage turn-off. Nytro 10XN is more prone to PD formation than Silicone oil under negative unipolar voltage pulses.





Conclusion
The substrate's geometric shape significantly affects the PD formation, and the rounded corners of the ceramic substrate experience the most PD activity. Additionally, space charges along the substrate's edges play a crucial role in field strength distribution and PD probability. Square voltage pulses result in increased PD activity compared to sinusoidal voltage pulses, i.e., the rise time of voltage pulses is a critical factor. Moreover, Nytro 10XN exhibits higher PD activity and space charge accumulation than Silicone oil under square voltage pulses. However, it is reversed for sinusoidal voltage pulse. Therefore, it is crucial to carefully consider the suitable dielectric liquid for its application in the electrical power industry, considering the conditions it will be exposed to.

Thomson Coil Actuated DC Switch to Investigate Fast Elongating Arcs

Student: **Erlend Kummeneje Steinset**
Supervisor: **Kaveh Niayesh**
Co-Supervisor: **Paul Monceyron Røren**

Problem description

The replacement of sulfur hexafluoride (SF6) gas switches was an important reason for the research in this thesis. The global warming potential of SF6 is 23500, making it 23500 more influential on greenhouse emissions than carbon dioxide (CO2). A switch could resolve this issue. Using fast-opening switching contacts shows great potential for hybrid circuit breakers, hence a possible alternative to SF6.

The task

The objective of this thesis was to create a prototype of a TCA Switch to investigate fast elongating arcs by reconfiguration of an exiting TCA setup. The successful creation of a functioning prototype enabled the parametric study of the electrical arc elongation. The main focus of the parametric study was to investigate the effects of switching velocity and different applied arcing currents on Fast Elongating Arc (FEA)s of DC breakers.

Model/ measurements

The setup was separated into two circuits, a switching circuit responsible for the mechanical switching and an arc circuit feeding energy through the arcing contacts.

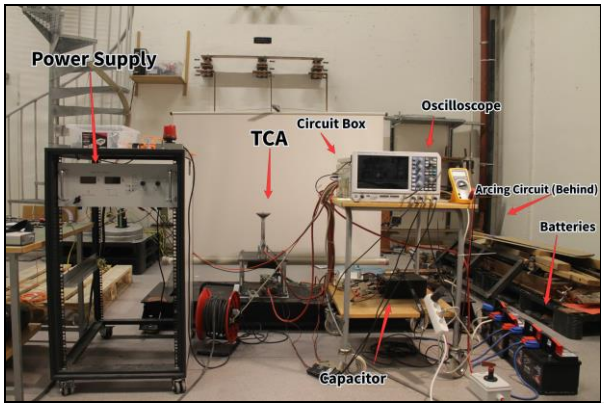


Figure 1: Experimental Setup

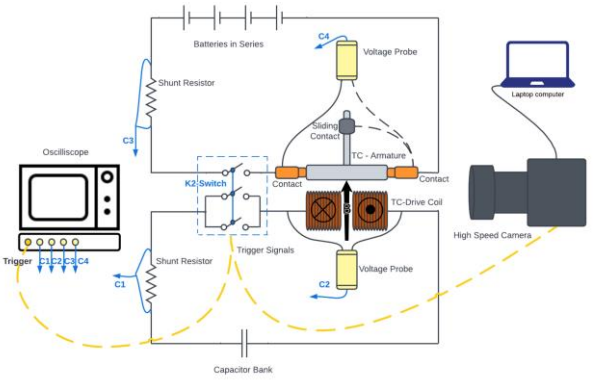


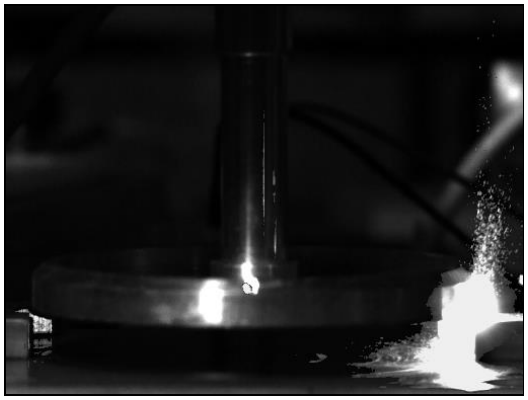
Figure 2: Measuring Setup Diagram

Figure 1 shows a total overview of the whole setup used for this study. On the left side of the figure, the energy supply for charging the capacitor of the actuator circuit was mounted. To the right of the energy supply, we have the Thomson Coil Actuator Switch itself and the test object.

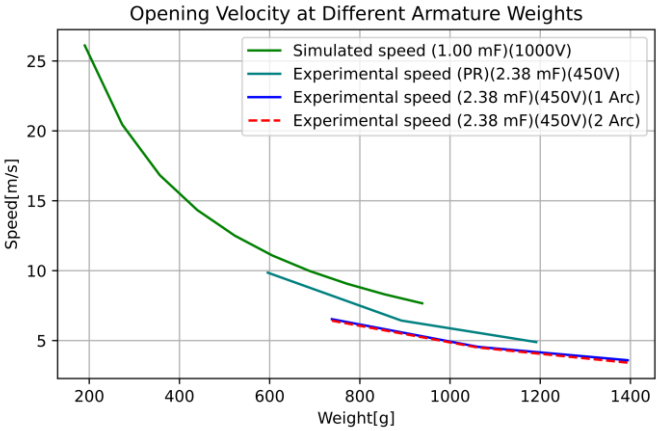
Figure 2 was the instrument setup used for the experimental study. The main switch, "K2-Switch" in the figure, initiates the TCA and triggers the oscilloscope and high-speed camera with fiber optic cables, the yellow dotted lines in the figure.

The setup was separated into two different circuits. One actuator circuit, that was responsible for initiation the actuation of the TCA Switch and the other, arcing circuit, for applying an arcing current through the contacts of the TCA Switch.

Calculation



Figur 3: Frame 164; t=0.9ms



Figur 4: Actuator Velocities

Figure 3: Selected frames from experimental trial video at 738 g and 400 A with 1 arcs, where t=0 is the start of arcing.

Figure 4: Velocities from the simulated results of a previous study, the experimental trials of the preliminary project report (PR), and the experimental trials of this thesis.

Weight\Current	200 [A]	300 [A]	400 [A]	400 [A] with 2 Arcs
738 [g]	1,025	1,283	0,626	0,659
1062 [g]	0,717	0,851	0,758	0,671
1394 [g]	1,735	2,724	2,098	0,755
2 Arcs at 1394 [g]	0,768	0,579	0,755	

Figur 5: The average arc duration of the different sets of the five experimental trials.

Weight\Current	200 [A]	300 [A]	400 [A]	400 [A] with 2 Arcs
738 [g]	54,40	57,99	61,49	64,64
1062 [g]	64,02	64,38	66,24	66,70
1394 [g]	51,98	51,49	50,64	61,49
2 Arcs at 1394 [g]	59,35	65,03	61,49	

Figur 6: The average maximum extinction peak voltage of the different sets of the five.

Conclusion

The contact design caused changes in airflow at different switching velocities. Turbulent airflow dominated at lower velocities, while laminar airflow was observed at the highest velocity. Different types of airflow strongly affected the cooling of the arcs. This caused arcs of the medium-velocity trials to cool faster, hence reaching a faster Current Zero (CZ). This study of different applied breaking currents showed that higher currents increased the arcing duration, except for the highest applied current. The highest applied current was forced to a CZ due to the higher arcing voltage getting restricted by the applied driving voltage, hence forcing a faster change of current and an earlier CZ. Quasi-static conditions of the arc were assumed, and the results showed some non-static relation of the different trials at the start of arcing, but as the arcs approached CZ, a more static relation was established.

The resulting TCA Switch prototype was a reliable setup, performing with high mechanical consistency and fully capable of producing FEAs

Sensorless control of PMSM with sinusoidal filter

Student: **Sudkamp, Maurice**
Supervisor: **Nilsen, Roy**

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

Flexibility in Distribution Systems through PyDSAL

Student: **Sundfør, Ingrid Maria**
Supervisor: **Fosso, Olav Bjarte**

Abstract

Distributed generation, local storage and electrification of transport and industrial processes give many new challenges for the distribution of electric energy. New consumption profiles combined with local generation where the available resources will show significant variation will give challenges for the distribution system. This thesis will address a number of these challenges by using an existing prototype tool on a reference system prepared by FME CINELDI. The purpose of this reference system is to have a well-defined case of a grid representative for a number of Norwegian distribution systems.

The analyses are done on the CINELDI 124 bus test system to find its optimal operation under different conditions using the object oriented tool PyDSAL (Python Distribution System Analysis Library). The Forward-Backward Sweep algorithm is used as the tool's engine. The tool has got extended functionality and a shell (Algorithm B.2) has been developed to facilitate the studies. Voltage control with a droop voltage approach is applied. The principles and strategies developed in this thesis will be applicable to other distribution systems with similar structure and characteristics.

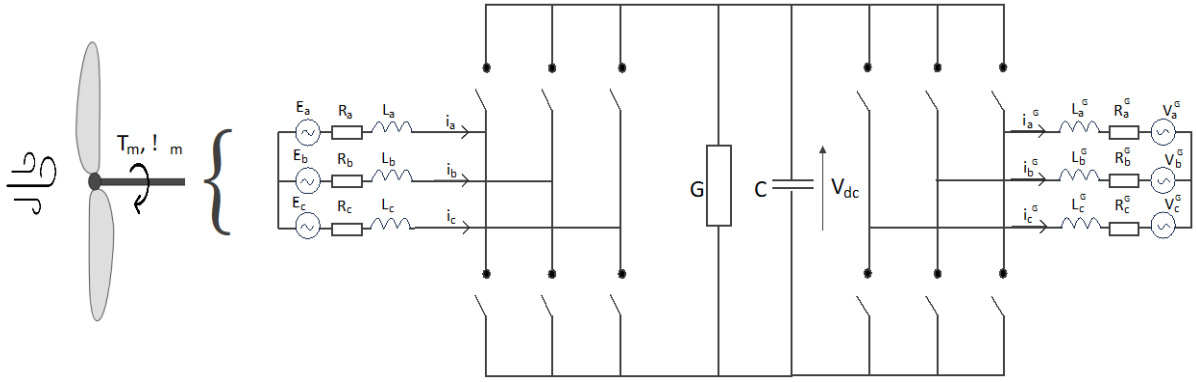
PyDSAL's outputs, which include profiles of voltage, line flow and sensitivities for voltage and loss due to changes in active and reactive injections, are useful for operational decisions. Its ability to solve alternative topology cases by splitting the grid and supplying sub-grids from backup sources or backup connections, makes the tool useful to investigate alternative strategies to improve the security of supply. The concept may involve both microgrid operation and in grid connected mode. Results are depicted graphically and discussed in detail in this report.

Robust Control of Nonlinear Wind Energy Conversion Systems:
A scalable and adaptive energy-based approach for cascaded interconnections

Student: **Emilie Bøe Surdal**
Supervisor: **Gilbert Bergna-Diaz**

Problem description

As our world urgently needs to transition to renewable energy, wind power has emerged as a critical player in achieving a more sustainable future. The integration of variable input renewable energies (VRE) poses several security of supply problems, and inverter-based sources - mainly wind and solar PV - are especially challenging due to the variable and uncertain power generation and the non-synchronous interface with the grid. One of the primary objectives in the evolution of wind energy conversion systems is the aim of obtaining plug-and-play solutions where wind energy can easily be integrated into the existing infrastructure. This requires control strategies that can respond to real-time changes in demand. The objective of this thesis is to provide a large-signal stability certificate for a wind energy conversion system consisting of a wind turbine (WT) connected to a permanent magnet synchronous generator (PMSG), followed by a full-scale back-to-back two-level voltage source converter (2L-VSC) connected to the grid. This will be done by taking into consideration the inaccurate knowledge of the equilibrium to be stabilized.



Method

A fundamental step towards our goal is to first force a cascaded structure in the dynamical system of interest, such that the overall system is decomposed as a cascade connection of two subsystems, with a leader-follower composition. Under this configuration, the leader subsystem is unaffected by the rest of the system, while the follower considers the leader as input or disturbance. In this way, the two subsystems can be considered almost separately, making the stability analysis and control design arguably less complex. Second, both subsystems are modeled using the port-Hamiltonian framework as a useful starting point for the control design while preserving the challenging nonlinearities in the generator dynamics, power converters, and between wind speed and mechanical torque. The leader subsystem, consisting of the wind turbine, PMSG, and a converter, must extract maximum power from the wind. Towards this end, the chosen controller for the closed loop is the proportional-integral current controller.

To address the issue of inaccurate wind speed knowledge, which affects the optimal operation of the conversion system, we design an adaptive control law based on Immersion and Invariance (I&I). We apply this methodology with three different degrees of model

complexity; i.e., we first utilize the I&I procedure to estimate the mechanical torque when considered as a constant, then by rewriting Tm = P/w and estimating the mechanical power, and finally to estimate the wind speed, accounting for all the non-linearities.

Similarly, perfect information of the equilibrium to be stabilized is not available for the follower system comprised of the grid-side converter and the grid. With the goal of practically regulating the dc voltage of the 2L-VSC to approximately a desired reference, a modified proportional-leaky- integrator (PLI) passivity-based controller (PBC) is implemented as the controller for the grid-side converter. The aim is to design the integral action in such a way that when having inaccuracies in the model, the leakage term acts similar to a droop controller, consequently limiting deviations while guaranteeing global asymptotic stability.

Simulations are first carried out for the leader system (WT, PMSG, machine side 2L-VSC) and follower (grid-side 2L-VSC, grid) system separately, before the two systems are combined, and simulating entire system to validate the theoretical results obtained.

Conclusion

The stability analysis and control design are made arguably less complex by forcing the system to behave as a cascade connection of two subsystems. The chosen controller for the leader system (WT, PMSG, machine side 2LVSC) is the proportional-integral current controller, which is shown to have prominent plug-and- play features, provided sufficient mechanical damping.

Three different I&I estimators were developed to estimate the mechanical torque, mechanical power, and finally, the wind speed. These estimators exhibited high convergence speed and accurate estimation, contributing to the optimal operation of the conversion system. When including all the nonlinearities regarding the wind speed, multiple equilibrium points for the rotor speed were observed, given a specific mechanical torque. To account for this, an outer loop was incorporated into the simulations. However, this additional loop introduces characteristics associated with a non-minimum-phase system, adding complexity to the overall system behaviour and compromising the stability analysis to a certain extent.

A PI controller with an additional leakage term in the integral channel was modified in the following two ways. First, the passive output is only included in the control input q-channel without any leakage action. Conversely, the control input d-channel had an important leakage term and did not utilize the passive output. These two changes resulted in indirectly controlling the voltage with one control input while regulating the q-axis current to zero with the other. This modification significantly improved the performance, complied with the control objectives while ensuring global asymptotic stability.

Taking all the challenging non-linearities in the generator dynamics, power converters, and between wind speed and mechanical torque, a viable Lyapunov candidate was obtained for both the leader and the follower subsystem. Finally, simulations were performed for the full system, which validated the theoretical results obtained throughout the study, and demonstrated the effectiveness of the method.

Dynamic Modelling of Twin Harmonic Counter-Rotating PMSM for Booster Pump in Pumped Storage Hydropower

Student: **Mathias Hagen Taksdal**
Supervisor: **Robert Nilssen**

Problem description

In the process of converting existing hydropower to pumped storage the existing runners will have to be replaced with reversible pump turbines (RPT). To overcome the friction losses in the existing water tunnels this runner must be considerably larger to provide sufficient lifting head. In addition, the RPT would need to be further submerged to avoid low pressure zones on the suction side of the turbine. The larger RPT diameter and further submergence would induce large costs of construction as existing powerhouse caverns and infrastructure could not be reused. The proposed solution is to install a counter rotating booster pump downstream of the main runner to provide the additional required lifting head while eliminating the need for further submergence. The counter rotation has the benefit of reducing swirl in the suction tube of the main runner thereby achieving a less turbulent flow at the inlet of the RPT. A novel PMSM design utilizing positive and negative sequence harmonic components of a concentrated three phase winding layout to drive counter-rotation in a single stator has been proposed to drive the pump. A small-scale prototype was built at NTNU in 2022.

The task

Limited testing has been done on the protype machine. This thesis aims to simulate the machine dynamics over a wide range of conditions through finite element analysis in COMSOL Multiphysics. Computational performance is drastically increased running simulations as distributed parametric sweeps on NTNU's high performance computing cluster IDUN.

Model/ measurements

The PMSM is modelled in 2D as two separate machines, with COMSOL's AC/DC module Rotating Machinery, Magnetic interface. Then the two machines are series connected with an Electrical Circuit physics. Dynamic load steps are performed with a rigid body rotating domain, moving mesh model. Simulations are set up as distributed parametric sweeps and solved in parallel on multiple processors on IDUN.

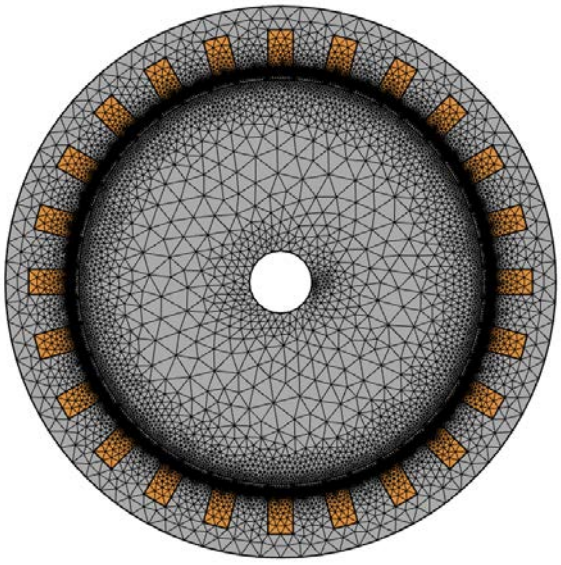


Figure 1: 2D cross section model of one rotor. Space discretization by mesh

Calculation

The 22 pole and 26 pole rotors manage to withstand a load step of 28.02 Nm and 30.98 Nm without a motor controller in the dynamic simulations. Efficiency maps exhibit 91.4 % efficiency of the 22-pole rotor and 89.27 % efficiency of the 26-pole rotor, along the intended torque-speed operational area of a booster pump. Distributed parametric sweeps give computational speedups of 92.67 % on the HPC, compared to a 64 GB RAM Intel Xeon W-2295 CPU workstation.

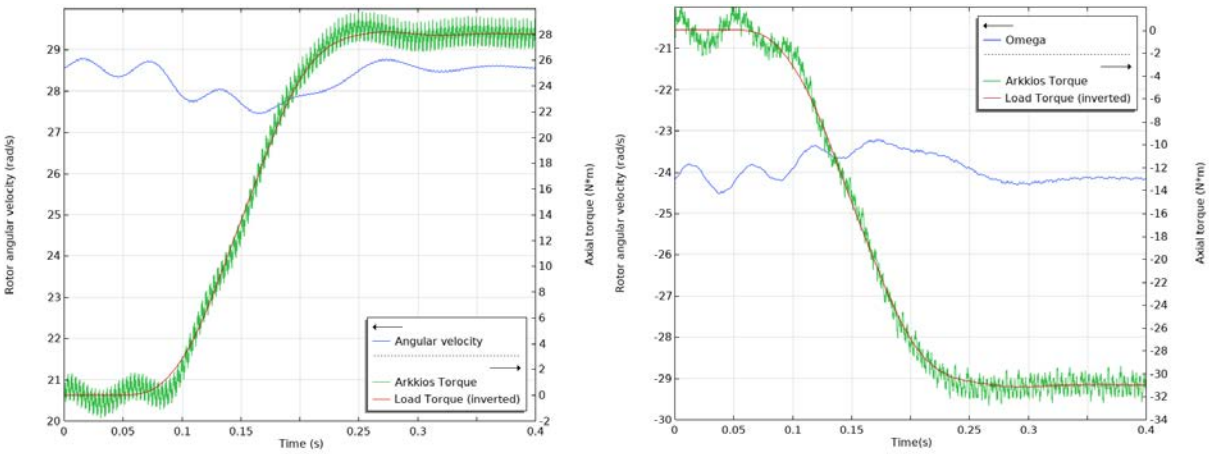


Figure 2: Maximum load steps on each rotor. 22- pole on the left, 26-pole on the right

Conclusion

The machine operates as intended with acceptable efficiency and torque ripple at high loads. The dynamic behavior is in line with the design requirements. Counter-rotation by twin harmonics is again confirmed through these results. However, the presented simulations only review the performance of the individual rotor models and two series connected machines. The performance of the actual twin harmonic design must be documented and compared with two separate counter-rotating PMSMs to find the best motor solution for the pump.

Provision of Primary Frequency Control from Electric Vehicles in the Nordic Power System

Student: **Martin Gulleik Teigenes**
Supervisor: **Kjetil Obstfelder Uhlen**

Problem description

In the coming years and decades, as the green transition moves forward, intermittent renewable energy sources (IRES) such as solar and wind will take over as the dominating source of energy in large parts of the world. These energy sources do not provide inertia to the electrical power system (EPS), making it more challenging to maintain a stable frequency in the EPS at the occurrence of faults or disturbances. Additionally, the green transition involves phasing out coal and gas-powered plants, which leads to a further deterioration of the power system's ability to maintain its frequency stability. However, with a total of 600,000 Electric Vehicles (EVs) in Norway as of December 2022 there is an enormous untapped potential of providing large amounts of frequency containment reserves (FCR) and fast frequency reserves (FFR) in the Nordic EPS. This thesis will therefore analyze the use of EVs for provision of frequency containment reserves for disturbances (FCR-D) and FFR in the Nordic power system.

Method

In order to lay some theoretical background for the simulations and results of the thesis, the most important theory regarding the provision of primary frequency control in an EPS is covered. Additionally, the current rules and regulations regarding the provision of FCR and FFR in the Nordic EPS are summarized, and some interesting findings from a project which analyzed the provision of FCR in the Nordic EPS are discussed.

An EV fleet is modeled both as a provider of FCR-D upwards and FFR, following the current rules and regulations for providers of such services. An updated and improved version of the Nordic 44 test model (N44) is constructed, called the Nordic 45 test model, which enables more precise simulations to be performed on the Nordic power system. 10 simulation cases are made, which are designed to highlight the different aspects of the performance of EVs as providers of frequency reserves in both the Kundur's two-area power system model (K2A) and the new Nordic 45 test model (N45).

Conclusion

The results of these cases are represented and discussed, and a conclusion is drawn as to whether or not EVs have sufficient performance as providers of frequency reserves in the Nordic power system as of today. It was concluded that using EVs as providers of FCR-D and FFR is currently not a viable option. The reason for this is the inherent time delay of the charging equipment and measurement devices associated with the use of EVs as providers of such services. However, it was found that if the time delay of charging equipment and measurement devices is sufficiently reduced, making it possible to activate the frequency response of the EVs almost instantaneously after the occurrence of a fault, the EVs could potentially perform just as well as the hydropowered generators which are currently used for these types of services, if not better.

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

Student: **Bjørnar Hætta Turi**
Supervisor: **Frank Mauseth**
Co-supervisors: **Sverre Hvidsten and Hans Kristian Hygen Meyer**
Contact: **bjornarturi@hotmail.com**
Collaboration with: **SINTEF, Statnett and Nexans**

Problem description

Partial discharges (PD) in a cable termination will lead to degradation of the insulation and, can in the long term cause a complete breakdown. As a result, PD sensors is an attractive option for on-line condition assessment with the purpose of giving a warning before something goes wrong. The inductive PD sensor consists of copper meshing wrapped around the cable and stress cone, and a High-Frequency Current Transformer (HFCT). During PDs, high-frequency current pulses will be capacitively coupled in the copper mesh, before being inductively coupled by the HFCT. The ferromagnetic core of a HFCT is what makes it suitable to measure current in the range of microseconds, however it also makes it susceptible to magnetic fields.

The task

The inductive PD sensor will be installed inside the housing of an oil-filled cable termination and will as a result be in close proximity to the cable and its emitted magnetic field. This laid the foundation for the scope of this thesis and the following subtitle was created:

"An experimental study on how transient magnetic fields affect an inductive partial discharge sensor"

Model/ measurements

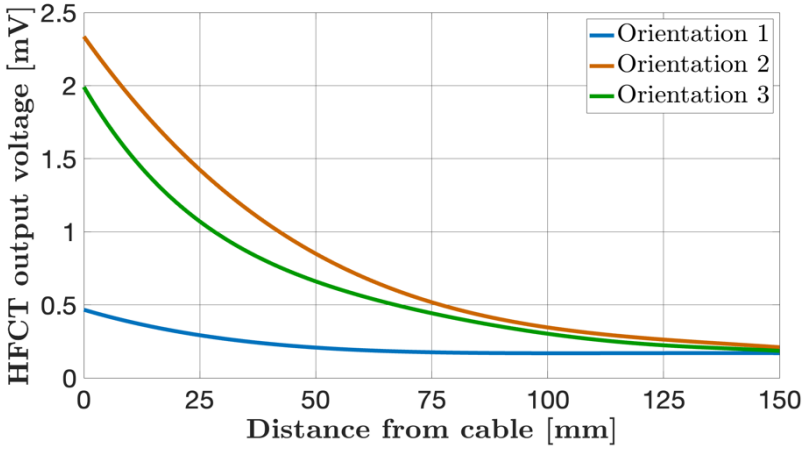
To evaluate the effect of transient magnetic field, three separate experiments were conducted. To begin with, experiment with high 50 Hz AC current was performed to evaluate the effect of HFCT orientation and distance from cable.

(a) Orientation 1 **(b)** Orientation 2 **(c)** Orientation 3

Switching transient experiments with short circuit current and current interruption was conducted. Current re-strike was attempted, however it remained unsuccessful. Following, lightning impulse tests was performed. Lastly, magnetic field simulations were performed in COMSOL for comparison of the obtained experimentally results.

Results

Results from the 50 Hz AC current experiment revealed that HFCT orientation poses as a significant factor in how much the sensor is affected by the magnetic field. Another important factor found was the distance between HFCT and cable, which decreases inversely proportionally with an increase in distance.



Results from the switching transient and lightning impulse experiments indicated that high HFCT output voltage amplitudes is likely to occur due to breaker activity and fast-acting transient currents. This does not pose a direct threat to the HFCT itself, but rather to the sensitive partial discharge measurement system it is connected to.

The magnetic field simulations performed generally aligned and conformed with the experimental result, however some deviations were observed. The deviations are assumed to be as a result of inaccurate HFCT modeling, unknown material proposition of the ferrite core and a low degree of model meshing.

Conclusion

- Through experiments and simulations, it has been discovered that the HFCT should be positioned in orientation 1, perpendicular to the cable, and at a distance as far away from the cable as possible.

- High HFCT output voltage amplitudes was observed which can cause damage to sensitive PD measuring systems. Therefore, protection schemes for overvoltage's should be implemented.

- Suggestions for further work is overvoltage protection, breakdown prediction and continue developing the magnetic field model in COMSOL.

Etablere en energidelingsmodell som simulerer lønnsomhet for energideling i et off-grid hyttefeltet.

Student: **Halgrim Ove Tørrisplass**
Veileder: **Ida Fuchs**
Utføres i samarbeid med: **NTNU**

Problemstilling

På bakgrunn av at dagens hyttelandsbyer begynner å ligne mer på små tettsted, er det pa tide å komme med nye bærekraftige løsninger gjeldende norske hytter. Denne masteroppgaven har som hensikt å undersøke forbedringspotensiale rundt å inkludere energideling i et offgrid hyttefelt, der hver hytte er utstyrt med hvert sitt solcelleanlegg.

Oppgaven

Input til modellen er forbruks- og produksjonsprofiler tilknyttet hyttene i hyttefeltet. Hyttene ble "dannet" gjennom arbeidet med fordypningsprosjektet høsten 2022. På bakgrunn av litteraturstudie og samtale med interessenter, ble det i fordypningsprosjektet satt opp en off-grid hyttekategorisering i form av effektforbruk. Dette resulterte i fire hytter. Solinnstrålingen på lokasjonen der hyttene står er hentet fra PVGIS. Videre er innstr˚alingsverdiene og tekniske data for hyttenes solcelleanlegg benyttet i Python-biblioteket PVlib for å estimere produksjon.

For å teste og demonstrere funksjonaliteten til modellen, simuleres det i masteroppgaven for tre energidelings-caser. Disse er PV-case, flex-case 1 og flex case 2. PV-case ser kun på energideling av produksjonsoverskudd, mens flex case 1 og 2 også inkluderer deling av energi lagret på batteri. Forskjellen på flex-case 1 og 2 er i hvor stor grad batteriet deltar i det lokale energimarkedet. Hver case simuleres videre for tre "bruksmønster-scenario". Med "bruksmønster" menes det hvor ofte hytta brukes, eksempelvis "feriebruk" og "hver helg". Simuleringsresultatene fra "bruksmønsterscenarioene" sammenlignes i resultatdelen. Målet med oppgaven er derfor å bruke modellen til å finne ut hvilke kombinasjoner av bruksmønster som er mest gunstig for energieling.

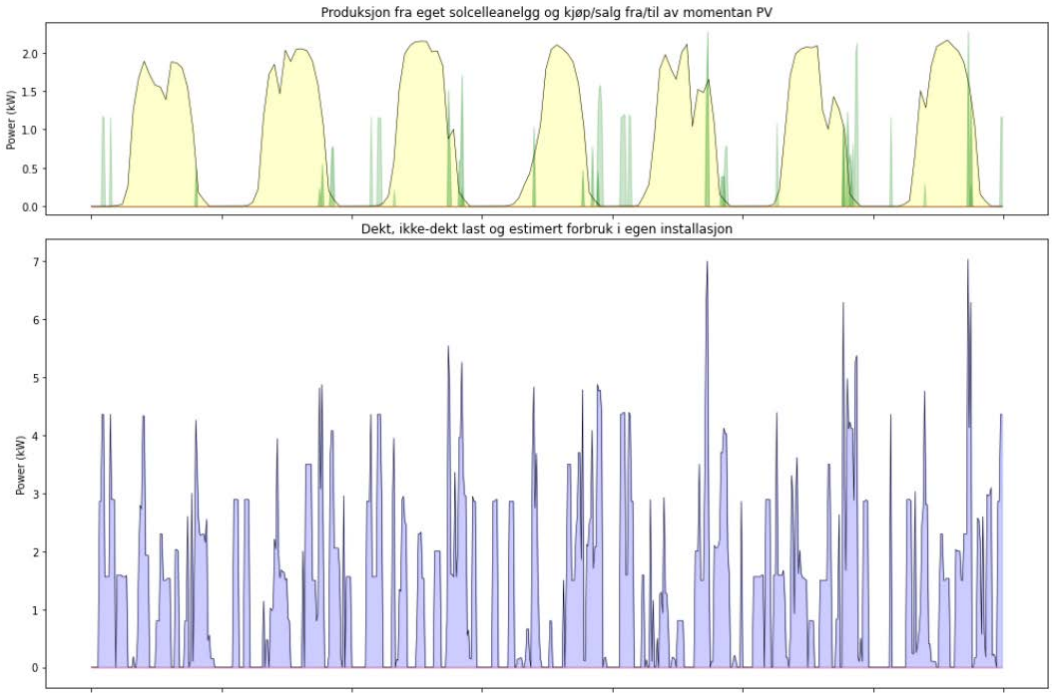
Modell/målinger

Oppaven har blitt løst gjennom å skreddersy en modell i Python som simulerer energiflyt mellom hytter i ett offgrid-scenario. Modellen er designet slik at den kan simulere for ulike delings-caser. I den enkleste casen inkluderer modellen kun deling av produksjonsoverskudd, mens i den mer kompliserte casen inkluderer modellen også deling av energi lagret på anleggenes batteri.

Beregninger

Den viktigste resultat-indikatoren som benyttes i masteroppgaven er "SF-rate". Denne størrelsen angir i hvor stor grad hytta er selvforsynt. For hvert bruksmønster-scenario, med tilhørende case, legges det frem resultater som viser til hvordan SF-raten endrer seg for hver hytte og hele hyttefelt samlet. En annen viktig del av resultatene er "simuleringsplots". Disse viser til "energistatus" for hyttene over bestemte tidsperioder, eksempelvis høstferien. Plottene viser til produsert solenergi, dekt last, tapt last, batteristatus og kjøpt/solgt energi.

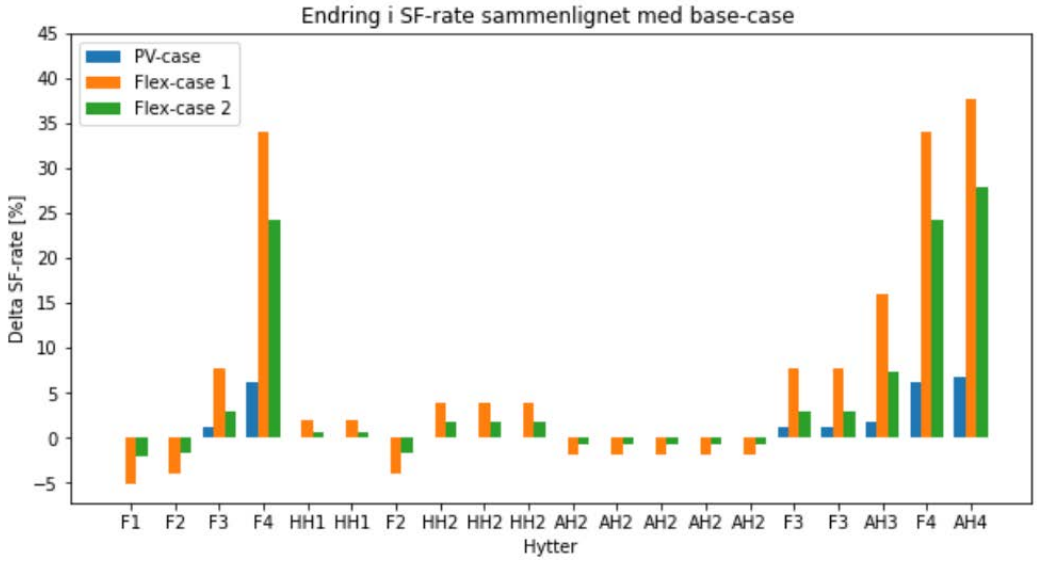
Figuren nedenfor viser til simluleringsresultatene for uke 29 gjeldende den mest elektrifiserte hytta i studien. Siden alt er blått i figuren er all last dekt.



Konklusjon

Simuleringene viser at forbedringspotensialet rundt energideling bedres med økende variasjon blant hyttenes bruksmønster. Resultatene viser også at det utgjør en betydelig forbedring å inkludere utveksling av energi lagret på batteri. En annen interessant observasjon er at hyttene som drar klart mest nytte av energidelingen er hyttene med høyest forbruk. I simuleringene der batteriene inkluderes i det lokale markedet opplever hyttene med lavest forbruk en nedgang i SF-rate sammenlignet med hva de opplever uten energideling.

Figuren nedenfor viser til forbedringspotensialet i SF-rate gjeldende bruksmønster-scenario 2 (som ga de beste resultatene).



Sensorless Control of Six-Phase Permanent Magnet Synchronous Machines

Student: Abdallah Ammar Hoseny Uosef
Supervisor: Roy Nilsen
Co-Supervisor: Robert Nilssen
Co-Supervisor: Thomas Huagan

Problem description

In Marine application usually Low Voltage 690 Vac systems are preferred. It is also of interest to investigate the use of such a solution in Offshore-Wind application. To increase the power ratings up to 10 MW and the system redundancy, a Dual Three Phase (DTP) Permanent Magnet Machine will be investigated. To be able to control PM drives without a position and speed-sensor, sensorless control shall be implemented. An important part of this is to have an accurate motor model. A PhD-candidate has worked on this topic, which will be the basis for this MSc-thesis. A mathematical model used for position estimation will be improved. This includes taking into account the magnetic cross-coupling between the d and q-axis of the motor.

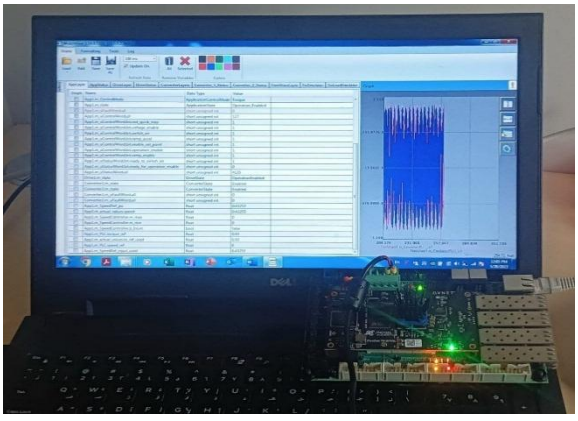
The task

This thesis proposes a complete study of cross-coupling effect between d- and -q axis for six-phase IPMSMs, and harnesses this study to develop a real-time FPGA-based emulator considering the nonlinearity of the system. The main aim of this work is to improve the performance of existed sensorless Dual Three-phase (DTP) interior Permanent Magnet Synchronous Machine (IPMSMs) Drives. This study and implementation will definitely help in improving the efficiency of the system to increase the power rating up to 10 MW and the system redundancy. Additionally, having complete and robust real-time emulator in the lab will drastically help in the educational process and in future researches as the cost and consumed-time in doing experiments using physical systems will reduce if it is replaced with the real-time emulator. The tasks to be executed are:

- Investigate a motor model in Simulink including cross-coupling.
- Develop and test an emulator in Simulink based on the System Generator library from Xilinx.
- Implement this on the FPGA
- Develop test-runs for parameter estimation
- Test and run the real time emulator

A control platform based pico-Zed board and a board developed at SINTEF will be used for implementation. By the end of this master thesis work, it is expected to get hands on experience with this control platforms.

Model/ measurements



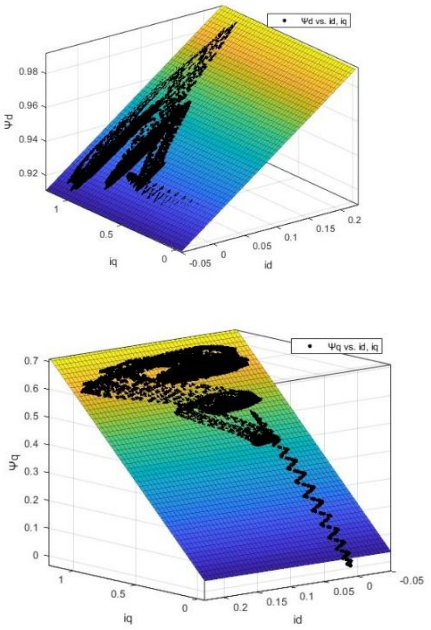
The current as state variable and flux as state variable methods will be used in investigating the effect of d- and -q axis currents on the flux linkages in q- and -d axis. Furthermore, a polynomial model will be developed and curve fitted to establish variables relationship between the currents and flux linkages of d-and -q axis. This model will help in calculating the currents as a function of flux linkages and vice versa. The next step after improving the model in Simulink is to modify the real-time emulator model, and this will be achieved by modifying the IP-Core emulator in Simulink and export it to IP-catalog in VIVADO. The new IP-Core block is added to the FPGA design for the purpose of synthesizing, implementation and bitstream file generation. The last

step is programming the nonlinear model in Xilinx SDK and upload the real time emulator's new files in pico-zed board.

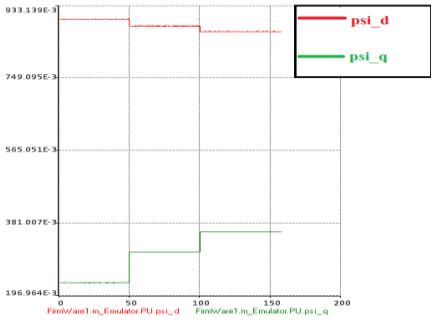
Calculation

The simulation results in Simulink justify the robustness of the system, where the values of alternating currents, d-q SSRF currents, z1-z2 axes currents, and DSRF currents are approximately the same in the two cases linear and non-linear model. while, in d-q flux linkages results are different due to the cross-coupling effect. It was noted that the flux linkage in q-axis was doubled in comparison the value in linear model, while the d-axis flux linkage was slightly affected by q-axis current. This result describes the saturation that q-axis suffered under the cross-coupling effects. Also, the electric torque was slightly decree-sed in non-linear model, this beside the oscillations and overshoots which appeared specially in torque plot, and q-axis current and fluxes. The last results in this specific section was the surface plots of self and mutual inductances which show the significant values of mutual inductances in non-linear model as their values was zero in ideal one.

The result of real-time emulators responses was the same as the Simulink results with slight difference in fluxes and current values. What distinguished the emulator models are their efficiency and accurate results, this for sure beside their low consumed time when executing the models. Table 1 show the complete results of linear and nonlinear models in Simulink and Real-Time emulator.



(a)



(b)

Figure 1: d-q axis flux linkages plots in simulink(a) and real-time emulator(b), respictevly.

Table 1: Results values for Simulink and emulators models

Motor parameter	Simulink Linear model	Simulink non- Linear model	Emulator Linear model	Emulator non-Linear model
	Direct id, iq control Iq1,iq2=1 pu- id1,id2=0		Torque control Te reference value=.93 pu	
i_d	0	0	-.124	-.126
i_q	1	1	.98	.96
ψ_d	.923	.902	.899	.87
ψ_q	.35	.62	.38	.59
T_e	.93	.85	.93	.89

Electric water heaters as flexible energy resources in the power grid

Student: Erlend Vabø
Supervisor: Jayaprakash Rajasekharan
Co-supervisor: Surya Venkatesh Pandiyan

Problem description

The intermittency of renewable power generation from wind and solar is challenging as it can cause severe issues for grid safety and reliability. Demand-side flexibility (DSF) from aggregated electric water heaters (EWHs) is a promising solution to mitigate this challenge, as the load of residential EWHs can be shifted to periods with a high share of renewable generation present to supply the load. However, as good business cases still need to be improved for aggregators with EWHs, this work investigates how aggregators can maximise flexibility from EWHs.

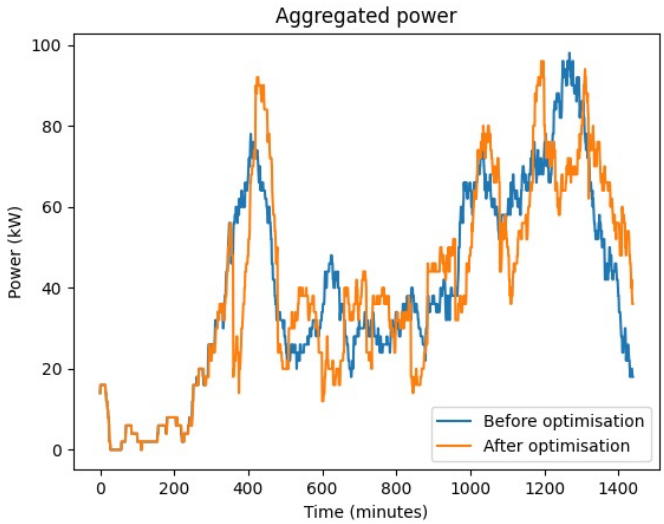
The task

This work investigates the research question of how aggregators can maximise flexibility from a group of residential EWHs using a non-linear accurate stratified temperature model. It is assumed that an aggregator applies flexibility as bids in an mFRR-market using a genetic algorithm (GA). In addition to flexibility maximisation, this work applies three reconnection strategies to avoid simultaneous reconnection and manage the peak load from the EWHs. At last, it is applied mFRR-prices, identifying potential market revenue from the flexible energy of EWHs.

Results

The results indicate that aggregators can provide up to 5.8 kWh of flexibility per EWH per day using the GA. This can translate to revenue of up to 1.5 EUR per day per EWH when applying prices from manual frequency restoration reserve (mFRR) markets of January 2023. The GA performs well for providing a high amount of flexibility, modelling accurately and being computationally manageable for a low number of EWHs. However, its simulation time scales poorly with many aggregated EWHs in the portfolio. In comparison, the simulation time of a simplified reference algorithm scales linearly with the number of EWHs and can therefore be useful for aggregators with a high number of EWHs in their portfolio.

The results also indicate that it is possible to apply the reconnection strategies without negatively affecting flexibility or peak load. All of the reconnection strategies implemented in the simulations resulted in higher or equal average flexibility than those without reconnection strategies. Additionally, two reconnection strategies significantly reduced peak load compared to the simulations without reconnection strategies.



Aggregated power before and after optimisation for one simulation of 24 hours with 100 EWHs

Conclusion

This thesis investigates the potential of EWHs as flexible energy resources for the power grid by maximising the aggregated flexibility of the EWHs. A comprehensive theoretical framework identifies the non-linear temperature behaviour of EWHs, technical challenges and barriers for aggregators, and relevant optimisation techniques for problems concerning EWHs. The literature review then reveals that most of the previous literature has aimed to control a single EWH or used inaccurate temperature modelling for groups of EWHs, thus establishing a research gap in the modelling of EWHs. By assessing three pillars for aggregators with EWHs, namely modelling, market participation and optimisation, this work highlights opportunities and challenges for market-participating aggregators with EWHs.

To accurately maximise the flexibility provided by the aggregator, this work uses a 10-layer stratified model with a one-minute resolution for up to 100 EWHs. The EWHs are assumed to be part of an aggregator's portfolio of flexible resources applied in an mFRR-market directly from the aggregator or through a third party. A genetic algorithm and a reference algorithm are created from scratch and employed to handle the non-linear behaviour of the EWHs, aiming to achieve a good trade-off between flexibility maximisation, accurate modelling, and computational efficiency. Furthermore, three different reconnection strategies are implemented to manage the simultaneous aggregated load from EWHs.

The results demonstrate that aggregators can provide up to 5.8 kWh of flexibility per EWH per day, translating to potential revenue of up to 1.5 EUR per day per EWH based on mFRR-prices in NO1 from January 2023. A genetic algorithm with a multi-layer temperature model provides the most flexibility of the methods in this work while simultaneously modelling the EWHs accurately. However, the simulation time of the GA scales poorly for many aggregated EWHs. In comparison, the simplified reference algorithm is fast for all numbers of EWHs and might therefore be more suitable for aggregators with many EWHs in their portfolio. Additionally, all implemented reconnection strategies yielded higher or equal average flexibility compared to simulations without reconnection strategies while addressing the issue of the simultaneous connection of EWHs, but with an increased risk of cold water for the consumers.

Several factors are essential for the optimisation results of this work and for the applicability of EWH flexibility in real life for aggregators. The flexibility per EWH decreased substantially with the number of EWHs in the portfolio, primarily based on how the minimum bid size constraint is formulated in the optimisation problem and due to the increased search space in the GA occurring when scaling the problem size. Moreover, the choice of values for parameters, thereunder the parameters in the GA, were not tuned for optimal performance. Therefore, this should be addressed in future research to maximise flexibility from EWHs using a GA. In practice, aggregators face additional challenges, like risk management and computational uncertainty, which must be adequately addressed to employ EWHs as flexible resources in the power grid.

Proposal and Evaluation of a New Short Circuit Protection Algorithm for Active Meshed Distribution Grids

Student: **Karl Fredrik Anker Wirgenes**
Supervisor: **Hans Kristian Høidalen**
Collaboration with: **SINTEF**

Problem description

Meshing the high voltage distribution network (DN) is a strategy to address future challenges related to voltage and overload issues caused by increased load and distributed generation (DG) in the DN. However, due to economic and algorithmic limitations, standard protection methods have reliability problems in an active meshed DN. Particularly in the case of islanded mode with only inverter-interfaced DG. Therefore, the thesis's primary objectives were to *propose* a phase-fault protection scheme for an active meshed distribution network, to *build* a Hardware In the Loop (HIL) test bench, and to *evaluate* the proposal using the test bench.

The task

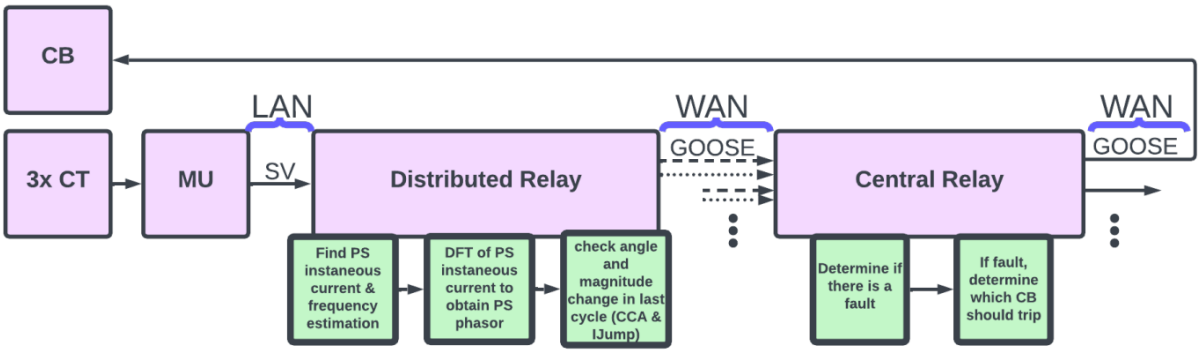
The proposed algorithm was to run the *existing* CCA and IJump schemes in parallel. Both schemes utilize changes in positive sequence (PS) current during fault to locate the fault. The distributed relay (DR), which are at all line interfaces, calculates the PS current. It sends a GOOSE message if either of these three equations returns true:

$$\left|\angle \mathbf{I_{PS}}(\mathrm{t}) - \angle \mathbf{I_{PS}}(\mathrm{t} - \mathrm{t_{cycle}})\right| \geq 90° \quad (CCA)$$

$$\frac{|\mathbf{I_{PS}}(\mathrm{t})|}{|\mathbf{I_{PS}}(\mathrm{t} - \mathrm{t_{cycle}})|} \geq 1.1 \quad (IJump)$$

$$\frac{|\mathbf{I_{PS}}(\mathrm{t})|}{|\mathbf{I_{PS}}(\mathrm{t} - \mathrm{t_{cycle}})|} \leq 0.9 \; (IJump)$$

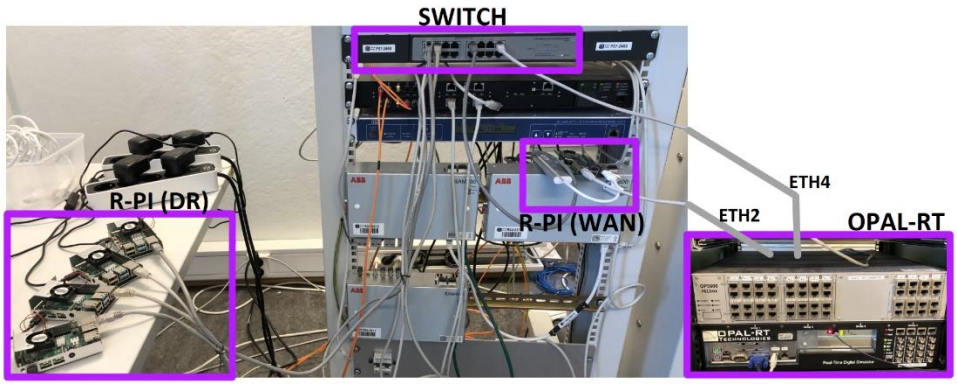
All GOOSE messages are collected by a single Central Relay (CR). The CR trips a particular line if: It receives CCA-GOOSE from only one line end. Or, one end has IJump-GOOSE due to the middle equation and the other end due to the bottom.



IJump was expected to locate faults in radial conditions, while CCA was expected to locate faults in meshed conditions. The thesis also proposed additional settings, a hierarchical structure of relays, and the use of a non-traditional PS phasor calculation method. The non-traditional method is: $\mathbf{I_{PS}} = \frac{1}{3} DFT\{i_a(t) + i_b\left(t - \frac{2}{3}t_{cycle}\right) + i_c(t - \frac{1}{3}t_{cycle})\}$

Measurements

The HIL test bench, depicted below, consists of an OPAL-RT and five credit card-sized computers called Raspberry Pi (R-PI). The OPAL simulates the DN with DG in real-time. From the OPAL, IEC61850 current samples goes out of ETH4 and to the switch and then arrives at the four R-PI to the left. These R-PIs emulate the DR through C-code. The R-PI/DR will communicate an IEC61850 GOOSE message back to the OPAL. ETH2 of the OPAL-RT is configured to subscribe to the GOOSE message. Before reaching ETH2, the GOOSE passes to the R-PI in the middle of the figure. This R-PI adds a communication delay to emulate the time-delay in a public mobile 4G/5G network. In the OPAL, the GOOSE message is passed to the CR. If the CR finds a fault, a circuit breaker opens in the simulation.



Calculation

Dependable = the scheme locates faulty line. Secure=No healthy line is seen as faulty. The figure based on 720 simulation shows that at nominal load the scheme is both dependable and secure. However, CCA only results in ≈80% dependability for meshed lines. Fortunately, IJump frequently and unexpectedly locates the fault, also when CCA does not.

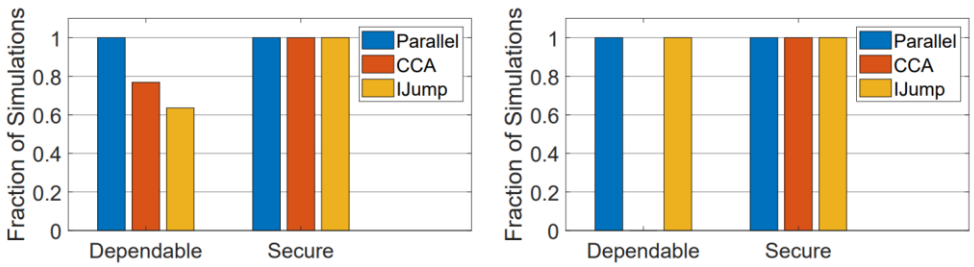


Figure 6.1: Reliability analysis with 0.1 Ω or 1 Ω fault Resistance. #720-sims.

Conclusion

The proposed algorithm is reliable during normal operating scenarios. The thesis's main finding is that running IJump in parallel to CCA on meshed lines increased the number of faults seen and reduced the time to trip. The performance improvement stemmed from IJump's unexpected ability to sometimes locate faults on meshed lines. The suggested additional settings and requirements for a crude frequency estimator also improved reliability. The non-traditional method of PS phasor calculation did not reduce reliability but was not recommended due to reduced speed and insignificant advantages. While the current public 4G/5G network has too large maximum delay, the future public 5G network is expected to be a feasible solution for long-distance GOOSE communication. Three operating scenarios were found to have decreased reliability: cross-country fault, pre-fault line flow with a power factor near zero, and when the pre-fault line current is less or comparable to the line charging current.

Grid planning with flexible measures

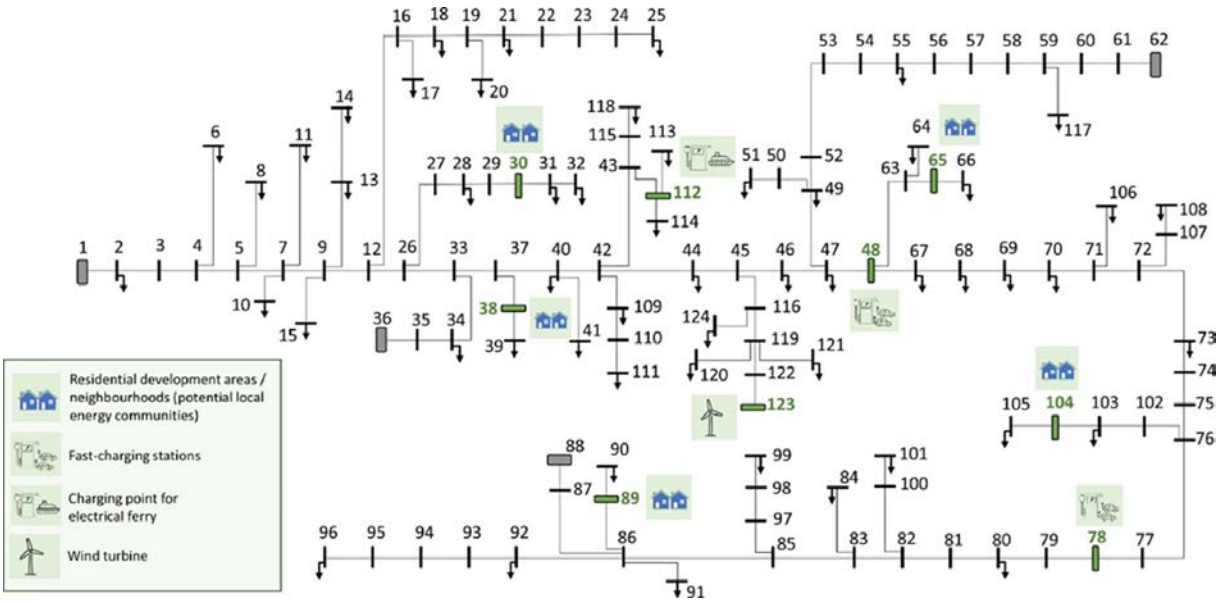
Student: **Erlend Waage**
Supervisor: **Olav B Fosso**
Collaboration with: Sintef

Problem description
This thesis has investigated flexible measures and how they can be included in grid planning. Flexible measures often include resources already available in the grid such as demand side management or can be based in technology adopted by the end users such as battery systems. These measures can be seen as an alternative to the traditional grid planning strategies which involves grid reinforcements such as building new lines. A new framework developed by CINELDI allows for inclusion of these flexible measures in the planning phase.

Research question
How can flexible measures contribute to postponing distribution grid reinforcements.

Model

The thesis includes a case study on a 124 bus distribution grid located in Norway. New loads such as Local energy communities, Electric vehicle charging stations and ferry charging stations. Flexible measures have been simulated on these new loads, such as Battery energy storage systems, reactive power compensation and demand side management. To account for the rapid increase in electricity demand a 4 % annual increase of the relevant loads has been simulated. Individual peak loads for each of the busses was used for the model, making the approach deterministic.



Results

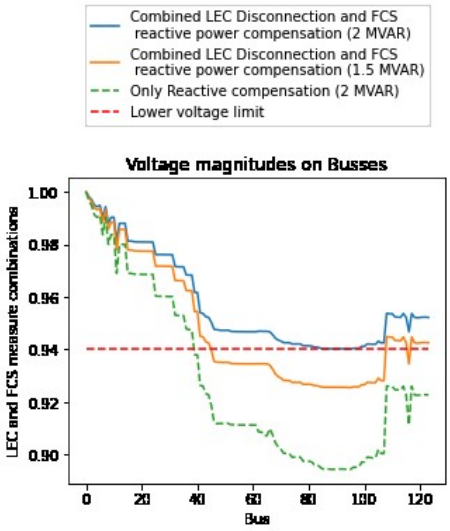


Figure 1 Combination of flexible measures

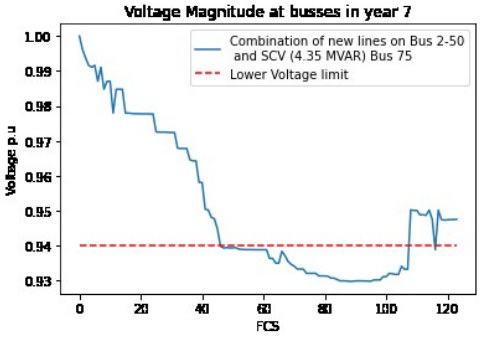


Figure 2 Combination of passive measures

Conclusion

The results showed that flexible measures can contribute to the postponement of grid reinforcements. A combination of disconnecting the LECs and providing reactive power compensation from the EV charging stations yields a sufficient voltage magnitude across the grid. The results also showed that the passive measures investigated did not provide a sufficient voltage magnitude across the grids indicating that substantial reinforcement are needed if flexible measures are not used, leading to large costs.

Addressing Reliability Challenges in Digital Substation Automation Systems

Student: **Kristoffer Ballantine Øverby**
Supervisor: **Hans Kristian Høidalen**

Abstract

This master's thesis investigates the reliability of digital substations utilizing the IEC 61850 process bus. The digital substation, characterized by enhanced interoperability and real-time performance, relies heavily on this process bus for effective communication and information exchange within the system. However, the transition from conventional to digital substations raises concerns about the reliability of power systems. This study investigates the reliability attributes of digital compared to a conventional substation along with an analysis of how different process bus architectures impact the system's reliability, with an examination of the High-availability Seamless Redundancy (HSR) and Parallel Redundancy Protocol (PRP) protocols. The study employs reliability block diagrams to conduct this reliability analysis and to also evaluate maintenance times, and resilience of non-repairable versus repairable systems. The research also identifies and analyzes potential failure modes in digital substations.

Findings from the study indicate that the reliability of a conventional substation surpasses that of a digital one due to fewer points of failure. Yet, the research reveals potential enhancement of the digital system's reliability where it was found that the incorporation of duplicate components, star Ethernet topology, and the PRP protocol is a good option. The failure modes analysis revealed that the Ethernet communication network introduced with the process bus is the greatest vulnerability in the digital substation. Although, an efficient network topology integrated with robust redundancy protocols could improve reliability. This study, therefore, suggests that a combination of PRP protocol with a star Ethernet topology could be a promising solution for enhancing the reliability of digital substations.

Production and development of HTS terminations for future HTS coil manufacturing

Student: Erling Andreas Aabrekk
Supervisor: Jonas Kristiansen Nøland
Co-Supervisors: Runar Mellerud
Co-Supervisors: Christian Magnus Hartmann

Problem Description:

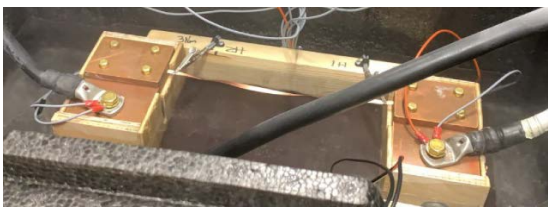
Termination methods for single and parallel coupled REBCO HTS tapes have been examined in laboratory experiments to gain handling knowledge for further experiments and production of HTS coils at the EME research group at NTNU in Trondheim. The literature review gathers and compounds factors that reduce the critical current of HTS tapes. Results obtained in the experiments could therefore be compared with more context. The effect of twisting was investigated, but it is suspected that the critical current reduction observed was not caused only by twisting, but also due to too high temperature during soldering. Non-twisted parallel coupled HTS tapes were also investigated, where the current measured before quench suggests that 5 of 6 HTS tapes functioned properly. The termination method for parallel coupling was found to have a better resistance area than the method that inspired it under similar conditions. The work performed in this thesis lays the groundwork for future lab experiments and the production of HTS coils, and many potential improvements for future lab experiments have been identified.

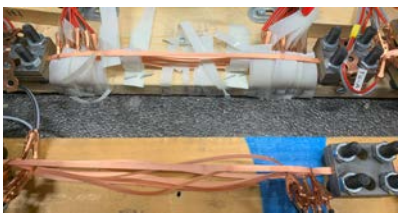
Method:

A total of 3 labs were conducted with high temperature superconductors (HTS) shaped like tapes. The tapes used in the experiments where 4 mm wide. Commonly electric cables are shaped like wires, and therefore handling and termination of the tapes are fundamentally different. The objective is to investigate a simple termination method that also makes the power supply system simple. As a bonus, it should also be easy to replace should it break.

Each lab consisted of 2 rigs, where HTS tapes were terminated and currents was sent through the rigs. Voltage measurements was taken over the termination sections, any joints, and over the HTS tapes spanning the gap between the terminations (in lab 1) and joints (in labs 2 and 3).

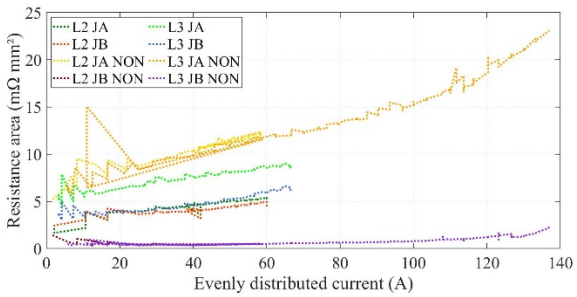
The first lab tested the effect of twisting a superconductor, while labs 2 and 3 focused on termination of parallel coupled HTS tapes.

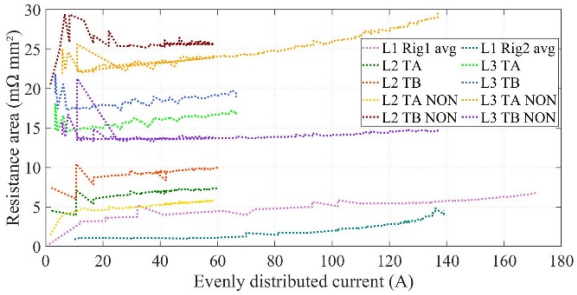




Results:

The resistance area found in the terminations and joints are shown in the pictures below, where L2 JA NON denotes “Lab 2, Joint A, Non-insulated”, and the result shown is the average over all the 6 HTS tapes in the joint. As can be observed where the labs not tested to the same currents. This is because the rigs in lab 1 was und to quench, the rigs in lab 2 where run to 350 A total for the entire rig, and the non-insulated rig in lab 3 was run to quench while the insulated one only to 400 A in order to preserve it for planned future testing by the supervisors. The highest current achieved for the non-insulated was 820-840A.





Conclusion:

From the 3 labs conducted in this thesis, it is evident that the handling of HTS tapes is of utmost importance. Handling can result in too high or uneven twist pitch, damages to the HTS due to too high temperature during soldering, or unintended bends which all reduce the current carrying capabilities of the tapes.

The results gained by the measurement equipment could have been more exact and useful if more insulation and more space had been allotted to it. Additionally, the analysis suffers from the lack of individual current measurements.

Acceptably low termination and joint resistances have been observed based on the voltage measurements and assumption of evenly distributed current, even outperforming a joint with higher clamping pressure but rougher sanding produced in the article that inspired the termination-section used in lab 2 and 3. Lower resistances is expected to be easy to achieve with higher pressure and solder, especially in the joints.

Integration of Fast-Charging Stations in the Distribution System

- Exploring the Potential of Alternative Grid Connection Agreements

Student: **Anna Liv Leikanger Aasen**
Supervisor: **Olav Bjarte Fosso, Iver Bakken Sperstad, Aurora Fosli Flataker**
Contact: **anna-liv@hotmail.com**
Collaboration with: **Sintef Energy Research**

Problem description

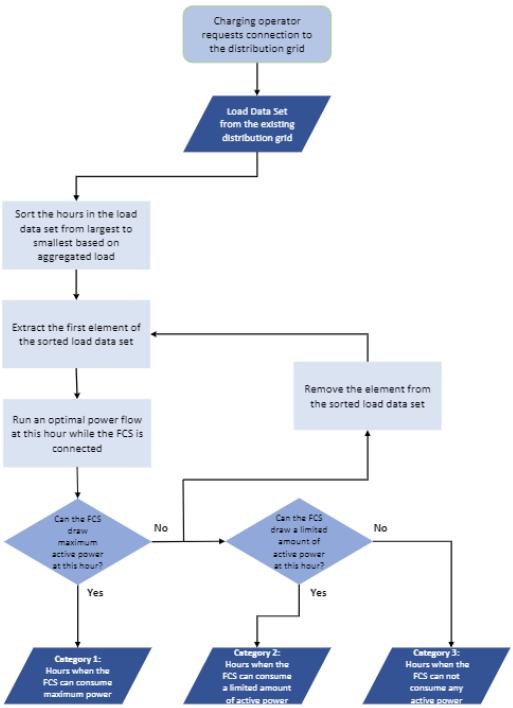
In order to reduce the Norwegian greenhouse gas emissions from the transport sector, which accounts for nearly 30 % of the emissions, adopting electric vehicles and phasing out fossil-fuelled cars will be essential. A significant increase in electric vehicles will require the charging infrastructure to develop at the same speed. Connecting fast-charging stations (FCSs) to a large extent in the distribution grid will lead to a need for upgrades in the existing distribution grid. As reinforcing and expanding the power grid both take time and are costly, it is interesting to investigate alternatives to the common practice.

The task

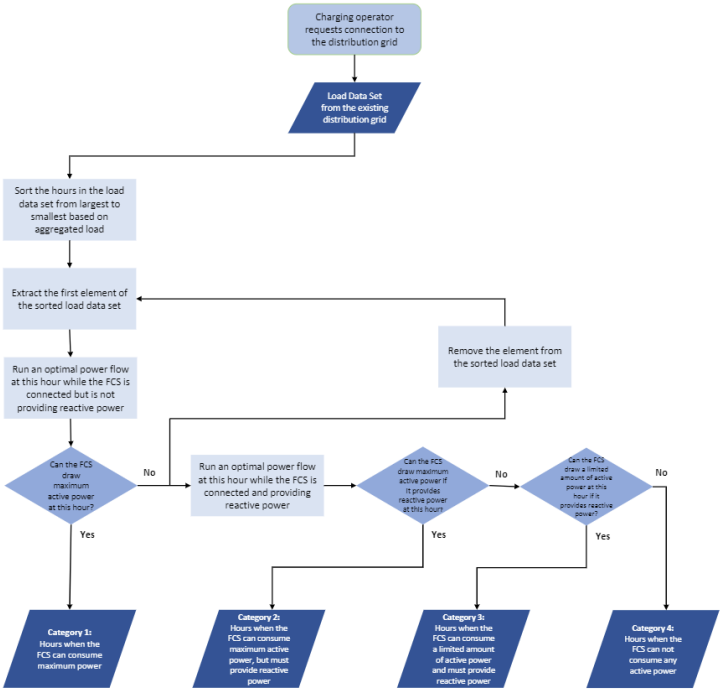
Two main issues with connecting FCSs to the distribution grid are overloading of components and voltage deviations. By utilizing measures such as active power curtailment and reactive power provision, or a combination, the need for grid upgrades may be postponed or reduced as the measures counteract voltage drops and reduce the loading of components. Grid connection agreements which utilize such measures were defined as *alternative grid connection agreements* in the thesis. The potential of alternative grid connection agreements was explored by developing a methodology for technical analysis that Distribution System Operators (DSOs) can perform to evaluate the feasibility of such agreements. The methodology was applied to a case study to provide insights and recommendations to both charging operators and DSOs.

Model/ measurements

A methodology was developed with the aim of exploring the potential of alternative grid connection agreements between Distribution System Operators (DSOs) and fast-charging operators. The methodology proposes a technical analysis for three alternative grid connection agreements: Alternative 3, Alternative 4 and Alternative 5. In Alternative 3, the active power the fast-charging station (FCS) has available is limited when the grid is suffering congestion or the voltage level in the grid is unacceptably low. In Alternative 4, the FCS provides reactive power while drawing active power in periods when the voltage level is unacceptable low or when the loading of the power lines is too high. Alternative 5 combines Alternative 3 and 4 and uses both active power curtailment and reactive power provision to enhance the voltage levels and prevent overloading of the lines.



Methodology for Alternative 3



Methodology for Alternative 4 and 5

Calculation

The case study showed that the voltage level on multiple buses in the system was unacceptable low when the FCS was connected to the system and consumed 2 MW during the aggregated peak load hour of the other loads in the system. Based on this, measures were needed to connect the FCS to the system. In all cases, measures were required during 392 hours of the year to enable a connection. The case study showed that the implementation of active power curtailment, reactive power provision and a combination of both enhanced the voltage level in the system in the 392 hours, enabling the FCS to be connected and draw power. This shows great potential for alternative grid connection agreements.

Conclusion

The most suitable grid connection agreement depends on the connection request and the needs of the charging operator. If the charging operator must be guaranteed to always have maximum capacity available, either Alternative 4 or upgrading the existing grid would be the most appropriate option. However, in Alternative 4, a more complex converter is needed, which triggers an extra investment. In the case of upgrading the grid, a connection charge payment is required. If the available capacity will be restricted in periods when the maximum capacity most likely is not necessitated, Alternative 3 would be the better option as it does not require expensive extra equipment.