Masteroppgaver 2025

NTNU
Norges teknisk-naturvitenskapelige universitet
Institutt for elektrisk energi

NTNU
Norwegian University of Science and Technology

# Summary of Master's Theses 2025

Department of Electric Energy


Foto: Per Henning/NTNU

NTNU
Norwegian University of Science and Technology

Fakultet for informasjonsteknologi og elektroteknikk
Institutt for elektrisk energi

# Summary of Master Theses 2025

June is an important month for us at Department of Electric Energy. This is the month where our Master students finalize their work and graduate after 5 years of studies. It is always a pleasure to take part in the graduation and know that the students 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 2025 MSc theses at the department. The set of theses gives 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 get inspired by reading 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 reading!

Anngjerd Pleym
Head of Department

| | | | |
|---|---|---|---|
| Rafuna, Albertin - Moan, Magnus Fjerdingen | Sjur Føyen | Modeling Harmonic Distortion and Resonance in an Offshore Wind Farm: Effects of Harmonic Phase-Angle Variation and Sensitivity Analysis | 103 |
| Rahman, Tanjida | Elisabetta Tedeschi | Model Predictive Control for Switching Power Converters in Hybrid AC/DC Microgrids | 120 |
| Ripon, S M Sakiul Islam | Elisabetta Tedeschi | Model Predictive Control with Adaptive Droop for Power Sharing in DC Microgrids | 121 |
| Rogndokken, Sander | Jayaprakash Rajasekharan | Optimal scheduling and operation of a BESS in the mFRR market | 123 |
| Safdari, Farhad - Almaani, Mohamed | Arne Nysveen | Dynamisk nettdrift med DLR og fleksibilitet i regionalnettet | 9 |
| Sandal, Karoline Løtvedt | Robert Kristoffer Nilssen | Induced canning losses in FRAMO´s SX1000 | 125 |
| Sanden, Tomine Lysaker | Jonas Kristiansen Nøland | Cost Modelling of Pink Hydrogen Production from Small Modular Reactors | 126 |
| Sculac, Luka | Frank Mauseth | Long-Term Partial Discharge Behavior of Protrusion and Free Metallic Particle Defects in Air-Insulated HVDC Gas-Insulated Substations | 128 |
| Skavlem, Aleksander Veum - By, Einar | Magnus Korpås | Investigating Different Energy Pathways: A Techno-Economic Analysis of the Nordic Power System | 30 |
| Skeide, Sigurd Nordby | Gilbert Joseph Bergna Diaz | Absolute Stability Analysis of a DC Networked-Controlled Microgrid | 129 |
| Skram, Andrea Marie - Arnesen, Ingrid Wiig | Sjur Føyen | Impedance-Based Eigenvalue Participation Analysis in Offshore Wind Farms | 18 |
| Spakmo, Jo Emil | Irina Oleinikova | Optimization of Export System for Offshore Wind Parks | 131 |
| Spalder, Sivert Røyset | Bjørn Alfred Gustavsen | Determination of External Thermal Resistance of Buried Power Cables by Interpolation of Lookup Tables Generated by FEA | 132 |
| Steilbu, Henrik | Alexey Matveev | Efficiency of Motor Drive Systems for Brunvolls Marine Propulsion | 133 |
| Sundberg, Sophie Lægland | Pål Stabel Keim | Design and Life Cycle Assessment of an Insulation System for a Marine PMSM | 134 |
| Sørhaug, Jørgen Kjøpstad - Lillelien, Nora Si Jia Beck | Kjetil Obstfelder Uhlen | Evaluating Frequency Stability Mitigation Strategies in a Low-Inertia Nordic Power System | 93 |
| Thorset, Jon Thore Mogen | Gro Klæboe | Restoring Hydropower Flexibility Under Environmental Constraints: A Local Medium-Term Perspective | 135 |
| Tibaldi, Kristian | Jonas Kristiansen Nøland | Learning by Doing in the Global Race for Clean Energy Dominance: Wright's Law Cost Modeling for Nuclear and Floating Offshore Wind from First Principles | 137 |
| Usland, Anders | Kaveh Niayesh | Current Commutating in a Mechanical DC Circuit Breaker | 139 |

| | | | |
|---|---|---|---|
| Vassmyr, Sigurd Sandvoll - Walnum, Sigve Næss | Kasper Emil Thorvaldsen | Value Stacking Battery Services Considering Reactive Power Compensation and Frequency Containment Reserves | 141 |
| Vik, Tiril Berge - Iversen, Elisabeth Ottesen | Karen Byskov Lindberg | Optimizing demand flexibility for cost reduction and mFRR participation: A Case Study of a Supermarket with centralized cooling machine, roof-top PV and battery | 75 |
| Walde, Eskil - Lang, Lars-Erik Wikheim | Steve Völler | Solar at Campus Gløshaugen: Examining the technical, economic, and architectural dimensions for the future energy roadmap | 84 |
| Walderhaug, Stian | Eilif Hugo Hansen | Jording av avløpssystemet i bolig | 143 |
| Waldum-Grevbo, Jonas | Umit Cali | Techno-economic study of wind energy investments in Europe | 145 |
| Walnum, Sigve Næss - Vassmyr, Sigurd Sandvoll | Kasper Emil Thorvaldsen | Value Stacking Battery Services Considering Reactive Power Compensation and Frequency Containment Reserves | 141 |
| Wilborn, Julie Kathrine - Norvik, Eline | Gro Klæboe | Assessing the Impact of Capacity Reserve Dimensioning Methods on a Future Hydro-Dominated Power System | 115 |
| Østby, Jan-Ivar Flagestad | Inge Nordsteien | Energy Storage dimensioning tool for Lithium-Ion batteries | 146 |
| Østvold, Gard Bjørnar | Eilif Hugo Hansen | Kortslutningsbeskyttelse i mikronett | 148 |
| Aaberg, Sondre Modalsli | Vijay Venu Vadlamudi | Development of Open-Source Software for Reliability Assessment of Distribution Systems using RELRAD Methodology | 149 |
| Aarnes, Mikkel August Stähr | Robert Kristoffer Nilssen | Non-invasive Condition Monitoring of Induction Motors Using Advanced Pattern Recognition | 151 |

# Modelling and Analysis of Voltage Surge Phenomenon in Modular HVDC Generator for Offshore Wind

Student: **Monib Ahmad**
Supervisor: **Dr. Pål Stabel Keim**

### Problem description

The global shift toward renewable energy has intensified the need for efficient, reliable, and compact power generation systems. Offshore wind energy, in particular, has seen rapid development. To improve system performance and reduce weight in offshore turbines, the Modular High Voltage Direct Current (ModHVDC) generator concept has emerged as a promising solution. These transformerless generators produce high voltage DC directly in the nacelle, eliminating bulky transformers and enabling more compact architectures (see Figure 1).

However, this configuration introduces a significant insulation challenge. The stator windings are directly exposed to fast-rising voltage surges from power electronic converters, particularly those using silicon carbide (SiC) or high speed IGBT switches. These surges can have very high dv/dt values, causing non-uniform voltage distribution across winding turns, leading to localized insulation overstress, partial discharges, and eventual dielectric failure. Despite the importance of this issue, insulation design principles for ModHVDC generators remain underexplored.

### The task

This thesis aims to investigate the voltage surge behaviour in the stator winding of a ModHVDC generator using an analytical lumped parameter model. The specific goals are:

- To develop a representative single slot winding model that captures turn level electrical behaviour.
- To simulate high dv/dt surge inputs and analyse voltage distribution across turns.
- To identify critical stress locations and evaluate insulation risks.
- To perform a sensitivity analysis by varying surge front time and amplitude, thereby examining their influence on voltage stress profiles.

### Model

The model focuses on a single slot of the generator, consisting of 60 turns of copper conductors layered within a stator core. The geometric parameters include a slot width of 41 mm, depth of 63 mm, and axial length of 1.7 m (see Figure 2). The materials used for conductors, slot liners, and insulation (e.g., mica) were selected based on industrial practice for high voltage rotating machines.

Each turn is modelled using a circuit-based representation including series resistance, inductance, inter turn capacitance, and turn to ground capacitance. The parameters are calculated analytically using standard formulas and geometric inputs. Figure 3 shows the complete LP model is implemented in MATLAB/Simulink. The surge excitation is modelled as a custom impulse waveform with controlled rise time and amplitude, injected into the first turn through a controlled voltage source. Voltage responses from each turn are captured using measurement blocks, and the resulting waveforms are exported to MATLAB for post-processing and visualization.

## Results

The simulation results revealed a highly non-uniform voltage distribution across the winding. The maximum node to ground voltage consistently occurred around turn 5 (see Figure 4), while the maximum turn to turn voltage difference was found between turns 1 and 2 (see Figure 5). These regions are therefore identified as high risk insulation zones. A sensitivity analysis was conducted using three surge cases with varying rise times and amplitudes. The findings revealed that the surge amplitude has the greatest impact on the magnitude of peak voltages and rise time (dv/dt) influences the timing and sharpness of wavefront arrival. The most severe insulation stress occurred under conditions of combined high amplitude and fast front time.

These patterns of surge propagation, voltage stacking, and reflection closely mimic traveling wave behaviour in RLC ladder networks, confirming the validity of the modelling approach.

## Conclusion

This thesis provides a detailed understanding of surge-induced voltage stress in ModHVDC generator windings using a lumped parameter modelling framework. The analysis identifies the front-end turns as the most vulnerable, with localized overvoltage that exceed the applied surge amplitude due to reflection and resonance effects. The results highlight the need for targeted insulation design, particularly in the initial winding layers.

Although the study focuses on a single slot model, it forms the foundation for broader insulation coordination strategies in modular HVDC machines. Future research should extend this work to multi slot configurations, include FEM based validation, and pursue experimental testing to support surge resilient insulation system development for offshore wind applications.

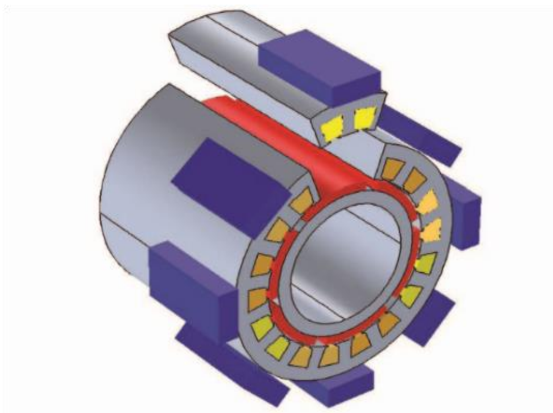
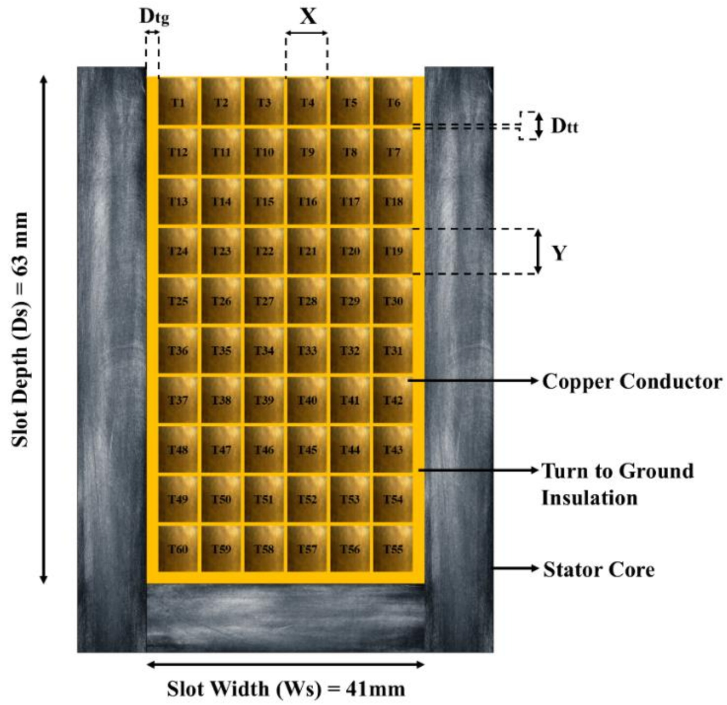


**Figure 1: Modular stator configuration with separate converters per segment**




**X = Conductor Width = 5.7mm**
**Y = Conductor Height = 6.6 mm**
**** Turn to turn insulation thickness (Dtt) = Dt + Dt = 0.1 mm + 0.1 mm = 0.2 mm**
*****Turn to Ground Insulation (Dtg) = Dt + Main wall insulation = 1.1 mm**

**Figure 2: Winding layout in single stator slot**


**Figure 3: Implementation of LP model for single slot winding in MATLAB/Simulink.**

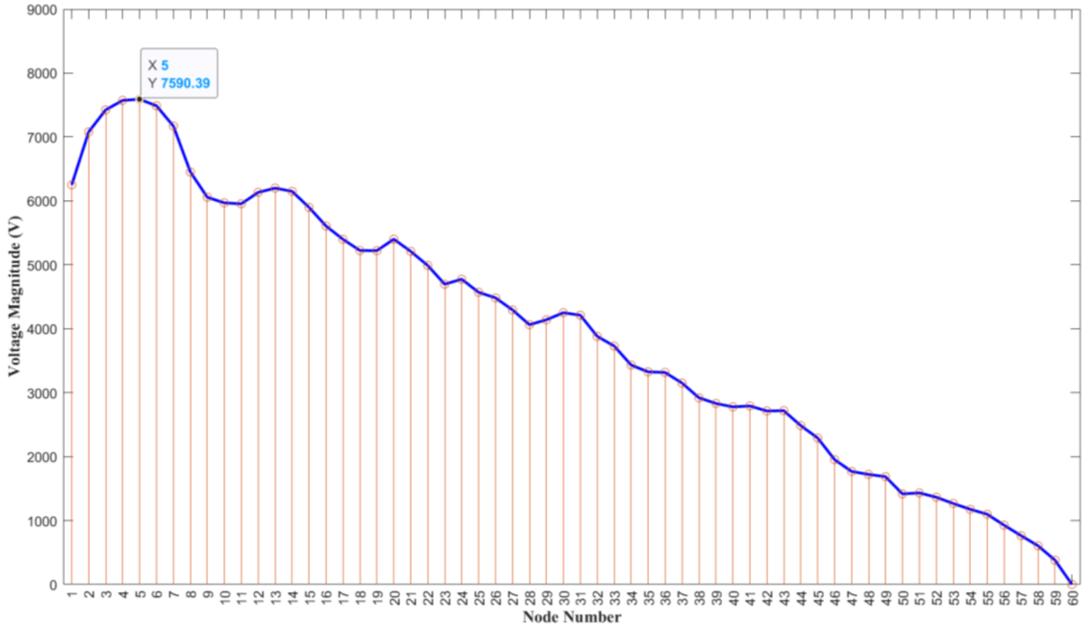



**Figure 4: Tun to ground voltage distribution along the length of winding.**

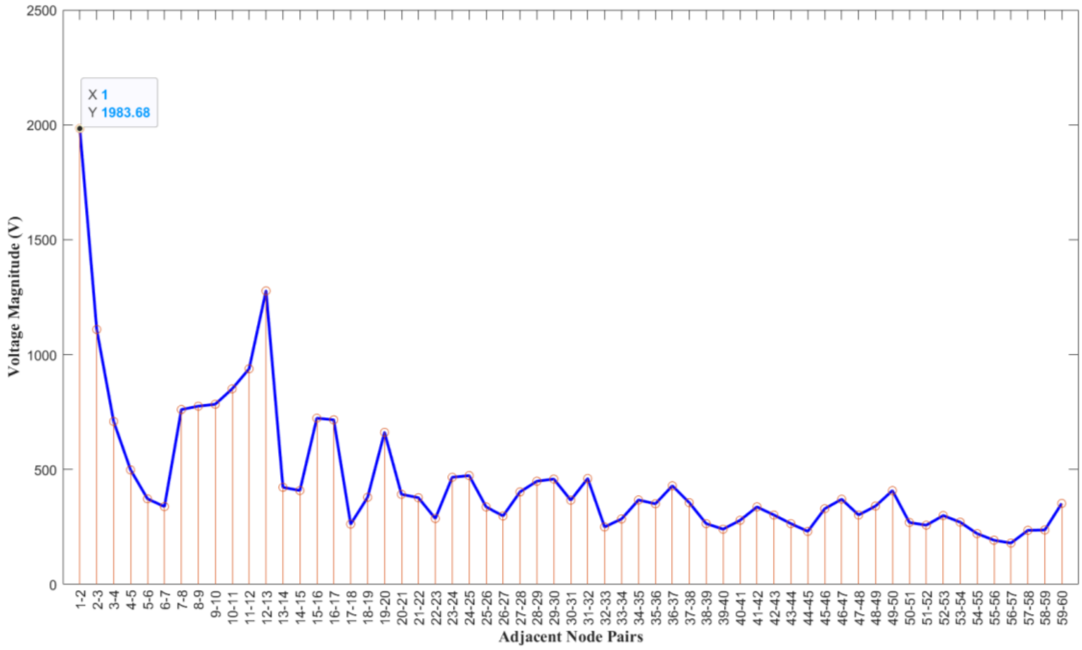



**Figure 5: Tun to ground voltage distribution along the length of winding.**

Techno-Economic Assessment of Cross-Border Hydrogen Trade and Offshore Wind Synergies in Europe

Student: **Felipe Stark de Alencar**
Supervisor: **Hossein Farahmand, Dana Reulein**
Contact: hossein.farahmand@ntnu.no, dana.reulein@ntnu.no
Collaboration with: **SINTEF**

**Problem description and Task**

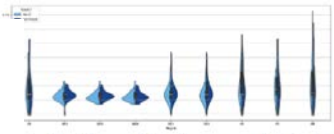
Decarbonizing Europe’s hard-to-abate sectors requires the coordinated expansion of variable renewable energy sources (VRES) and a continent-wide hydrogen backbone. We extend the open-source Global Energy System Model (GENeSYS-MOD) by endogenizing investment in proton-exchange-membrane electrolyzers, high-pressure pipelines, and liquid-hydrogen shipping while enforcing symmetric trade constraints for 30 European regions from 2018 to 2050. Relative to an electricity-only baseline, the optimal hydrogen grid raises discounted system costs by just 0.02 \% yet deploys 24.8 GW of cross-border pipeline capacity across 48 links, enabling annual flows of 99 TWh from Spain to France and 73 TWh from southern Sweden to Germany. Hydrogen production clusters in VRES-rich Spain, SE4 (Sweden) and Norway, whereas Germany and France emerge as import and storage hubs. Nine cost-sensitivity runs reveal that low pipeline and high electrolyzer CAPEX favour centralized export corridors, while the reverse promotes decentralized “produce-where-you-consume” architectures. Sectoral hydrogen demand remains modest but is led by synthetic methane production (up to 55 \%), followed by transport (20–35 \%) and industry (15–25 \%). These results show that relatively small pipeline investments can unlock substantial comparative advantages, offering guidance for the cost-effective planning of Europe’s emerging hydrogen infrastructure.

**Model/ measurements**

The optimisation process is governed by a comprehensive set of constraints. Capacity expansion is regulated by the interplay between new installations, retirements, and the existing residual fleet, all of which are determined by technical lifetimes, annual build limits, and predefined phase-in or phase-out trajectories. Renewable energy deployment is constrained by region-specific land availability and resource potential assessments. Inter-regional electricity trade is limited by existing transmission line capacities and optimized through endogenous expansion decisions within the power-trade module. Additionally, the model ensures operational flexibility through constraints on technology-specific ramp rates, energy balance requirements for storage systems, and reserve margin conditions. These collectively guarantee sufficient short-term flexibility, especially from technologies such as gas turbines and batteries, in each time slice.

**Calculation**

Fig. 1: Total Hydrogen Trade Capacity for the H2TRADE cas in 2050.



3: Electricity marginal prices across selected nodes ).

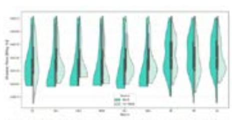
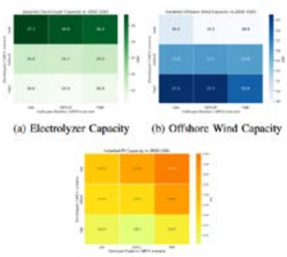


Fig. 4: Hydrogen marginal prices across selected nodes (2050).



(a) Electrolyzer Capacity (b) Offshore Wind Capacity

(c) PV Capacity

Fig. 6: Installed capacities by technology across CAPEX sensitivity scenarios for 2050.

**Conclusion**

Using the open-source model GENeSYS-MOD, this study demonstrates that the addition of a pan-European, bidirectional hydrogen grid increases discounted system costs by only 0.02%, while significantly influencing infrastructure deployment patterns. By 2050, the model constructs 48 cross-border hydrogen pipelines (totalling 24.8 GW), with the Spain–France (5.2 GW) and SE4–Germany (2.8 GW) corridors transporting 98.7 TWh/year and 73.1 TWh/year, respectively. France emerges as a pivotal transit and distribution hub within the network.

Hydrogen production is concentrated in regions rich in renewable resources, notably Spain, southern Sweden, and Norway, while Germany and France function primarily as importers and storage centres. Photovoltaic energy dominates electrolyser operation, supported by Norwegian hydropower, whereas offshore wind plays a secondary role in the hydrogen supply chain.

The sensitivity analysis reveals a clear dynamic between infrastructure cost assumptions and supply configuration: low pipeline but high electrolyser capital expenditure (CAPEX) favours centralized production hubs, while the opposite scenario encourages more decentralized hydrogen supply. Although overall hydrogen demand remains moderate, it plays a key role in enabling synthetic methane production.

In conclusion, even a relatively modest investment in hydrogen pipeline infrastructure can yield significant comparative advantages. These findings highlight the strategic importance of aligning hydrogen infrastructure planning with regional renewable resource availability, cost conditions, and complementary energy technologies.

# A Non-Invasive Magnetic Signatures based Health Monitoring System for Bearings of Permanent Magnet Synchronous Machines using Adaptive Signal Processing

| | |
|---|---|
| Student: | **Syed Anas Ali** |
| Supervisor: | **Dr. Pål Stabel Keim** |
| Co-Supervisor: | **Dr. Hossein Ehya** |
| Contact: | **engr.syedanasali@gmail.com, pal.stabel.keim@ntnu.no** |

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

# Dynamisk nettdrift med DLR og fleksibilitet i regionalnettet

Student: **Farhad Safdari og Mohamed Almaani**
Faglærer: **Arne Nysveen**

## Sammendrag

Elektrifisering og økt effektbehov skaper kapasitetsutfordringer i det norske kraftnettet, spesielt i regionalnettet hvor etterspørselen etter tilknytning øker raskere enn utbyggingstakten. Samtidig baserer dagens nettforvaltning seg på konservative forutsetninger gjennom Statisk Line Rating (SLR), som ofte medfører underutnyttelse av linjekapasiteten. Denne masteroppgaven undersøker hvordan Dynamisk Line Rating (DLR), som benytter sanntidsdata om værforhold og ledertemperatur, kan gi mer presise og fleksible vurderinger av overføringskapasitet, og hvordan teknologien kan kombineres med aktivering av fleksibilitet for å møte fremtidige behov.

Casestudien tar utgangspunkt i et regionalnett i Indre Østfold. Ved hjelp av sanntidsdata fra Heimdall Power-sensorer og scenarioanalyser vurderes effekten av DLR sammenlignet med SLR under ulike driftsforhold. I normal drift viser resultatene at DLR gir betydelige kapasitetsgevinster, særlig i vinterhalvåret, hvor kjølende værforhold gir høyere strømføringsevne. For eksempel var medianverdiene for DLR 1324 A på Linje 1 og 1105 A på Linje 3, sammenlignet med SLR-nivåer på henholdsvis 884 A og 755 A – en økning på opptil 49 %. Feilanalyse viser at lastflyt etter bortfall av én linje styres av de relative impedansforholdene i nettet, noe som kan føre til overbelastning på én linje selv om det finnes tilstrekkelig termisk kapasitet på en parallell linje. Dette understreker at DLR må inngå i et bredere beslutningsgrunnlag som også vurderer lastfordeling og nettstruktur.

Videre vurderes to filtreringsstrategier – DLR Clipped og en autoregressiv modell – som jevner ut raske variasjoner og gir et mer stabilt beslutningsgrunnlag over tid. Dette reduserer risikoen for hyppige alarmer eller driftsendringer og gjør teknologien mer robust i praktisk bruk. Analysen viser også at teknisk gevinst alene ikke er tilstrekkelig dersom ikke driftsstrategiene tilpasses; for eksempel kan faste vernsinnstillinger begrense muligheten til å utnytte DLR, mens fleksible alarmgrenser på driftssentralen åpner for bedre styring. For Linje 1 ble det identifisert en stabil termisk margin på 102 A i 95 % av året – tilsvarende 8,3 MW ved 47 kV, mens Linje 3 hadde en margin på over 617 A i samme periode.

Til slutt utvikles et simuleringsverktøy i Python (MESA) som kombinerer DLR med fleksibilitetsaktivering gjennom LongFlex-markedet og tredjepartsvirksomheter (TPV). Resultatene viser at fleksibilitet kan dekke opp for kapasitetsmangel i perioder med høy belastning, og bidra til å utsette eller redusere behovet for nettforsterkning. DLR-grensen ble overskredet i 203 timer (18,4 % av året), hvorav 81,6 % ble dekket av TPV og 17 % av LongFlex, til en kostnad på 2,22 millioner NOK. Til tross for dette forble 74 timer udekket og 86,0 MWh ikke servert, noe som gir potensielle KILE-konsekvenser. En HCA-analyse viste samtidig at Linje 3 kunne håndtere 100 A ekstra last i over 90 % av året, mens Linje 1 kun klarte det i 60–70 % av tiden.

Samlet gir oppgaven ny innsikt i hvordan DLR og fleksibilitet kan integreres i driftsplanleggingen for å øke utnyttelsen av eksisterende nett. Teknologien representerer ikke bare en forbedring i målemetodikk, men et mulig skifte i hvordan kapasitet forvaltes – fra statisk og forsiktig til dynamisk og situasjonsbestemt.

# Påvirkning av klemtrykk ved fuktvandring mellom transformatorolje og presspan

Student: **William Aas Andreassen**
Veileder: **Kaveh Niayesh**
Medveileder: **Fahim Abid**

## Problemstilling

Det elektriske kraftsystemet utsettes for økende og varierende belastning, og dette stiller høye krav til mekanisk styrke i transformatorviklinger. Klemtrykket i transformatorviklinger reduseres over tid, hovedsakelig på grunn av termisk aldring og fukt som påvirker isolasjonsmaterialet presspan. Fukt gjør presspan mykere og gjør at den sveller, men hvordan dette påvirker klemtrykket direkte er lite dokumentert.

## Oppgaven

Motivasjonen bak dette arbeidet er å forbedre forståelsen av fuktvandring og svelling, og hvilken innvirkning dette har på klemtrykket i en transformatorvikling. Det vil bli gjennomført flere laboratorieforsøk med ulike oppsett. Det første oppsettet undersøker hvordan fuktighet vandrer mellom olje og presspan ved ulike fuktighetsnivåer. Det andre tar for seg svelling av presspan, mens det tredje ser på klemtrykk. Til slutt vil det bli undersøkt om det er noen sammenheng mellom fuktigheten i oljen, fuktvandringen, svellingen og klemtrykket.

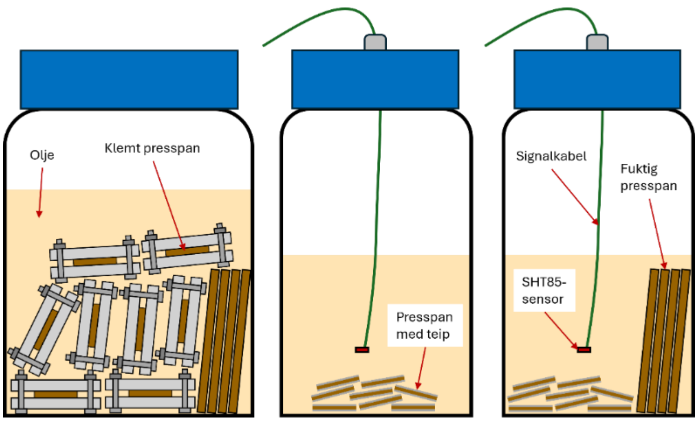
Det som skal undersøkes er med andre ord

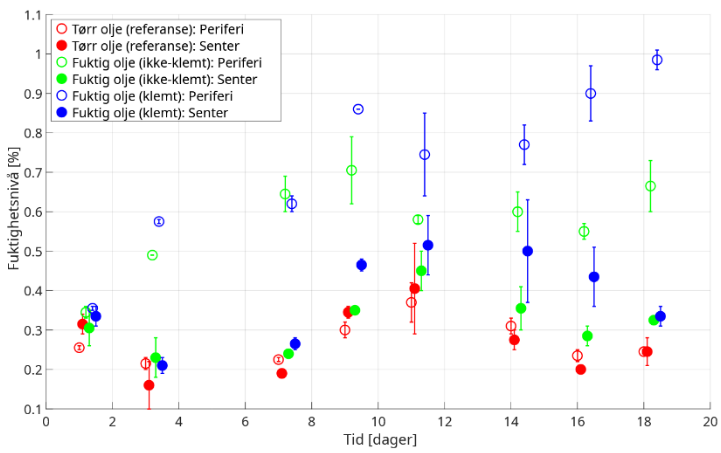
- effekten av fuktvandring inn og ut av presspan og dens effekt på svelling
- effekten av svelling og påfølgende utvikling av klemtrykk
- sammenhengen mellom klemtrykk og fuktigheten i oljen

## Laboratorieoppsett og målinger

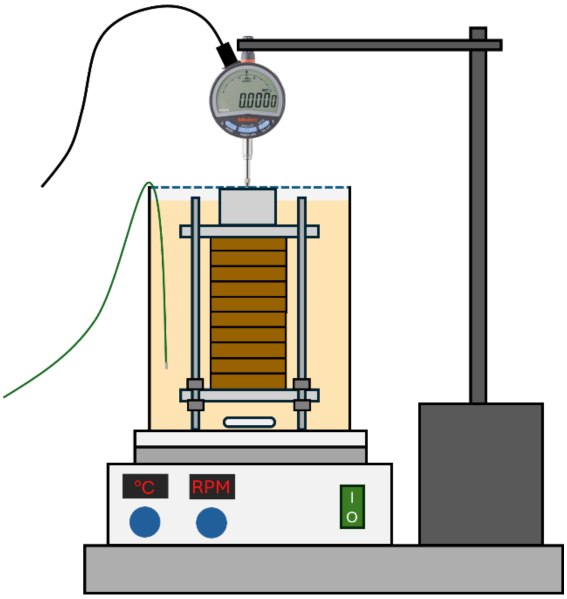
Det har blitt gjort flere forsøk med tre ulike oppsett. Disse og et utvalg resultater er vist under.

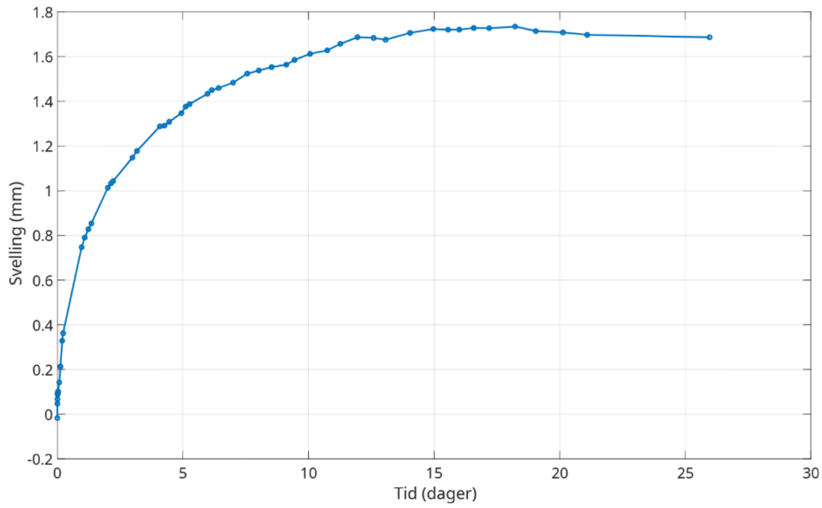
1. Fuktvandring mellom olje og presspan



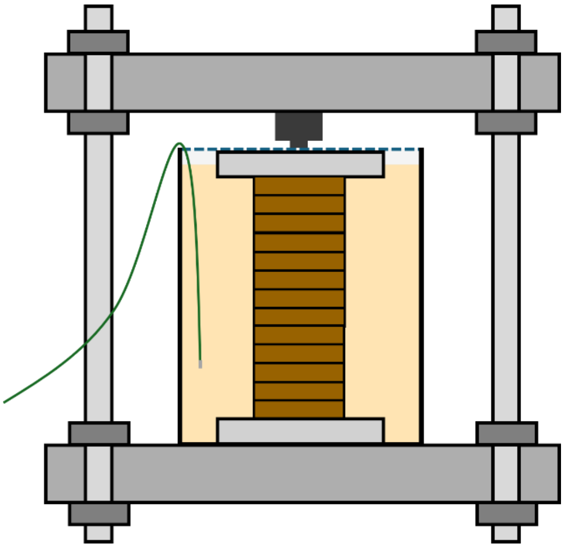



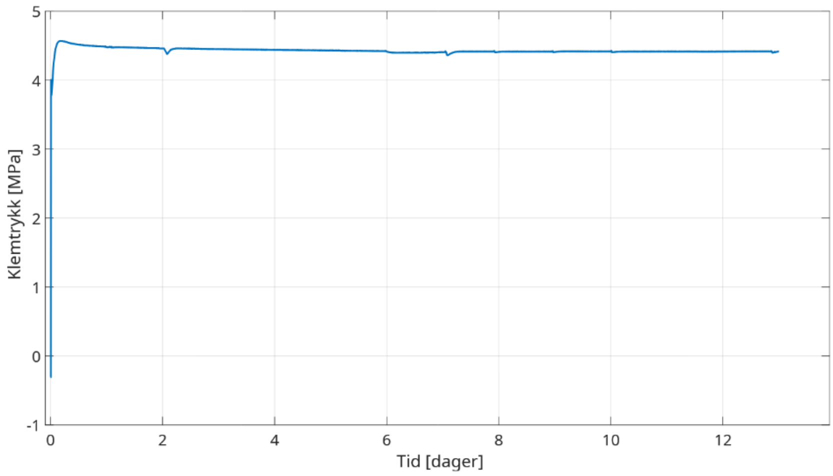
2. Svelling




3. Klemtrykk






**Konklusjon**

Forsøkene viser at fukt transporteres mellom olje og presspan, særlig ved høy temperatur. Økt fuktinnhold fører til svelling og redusert mekanisk stivhet i presspan, og over tid kan dette gi lavere klemtrykk. Impregnering av presspan reduserer fuktopptaket noe, men ikke tilstrekkelig til å forhindre disse effektene.

Det ble ikke funnet noen direkte sammenheng mellom svelling og økt klemtrykk. I stedet kan reduksjonen i klemtrykk se ut til å skyldes at fukt svekker materialets motstand mot komprimering slik at det blir mer ettergivende.

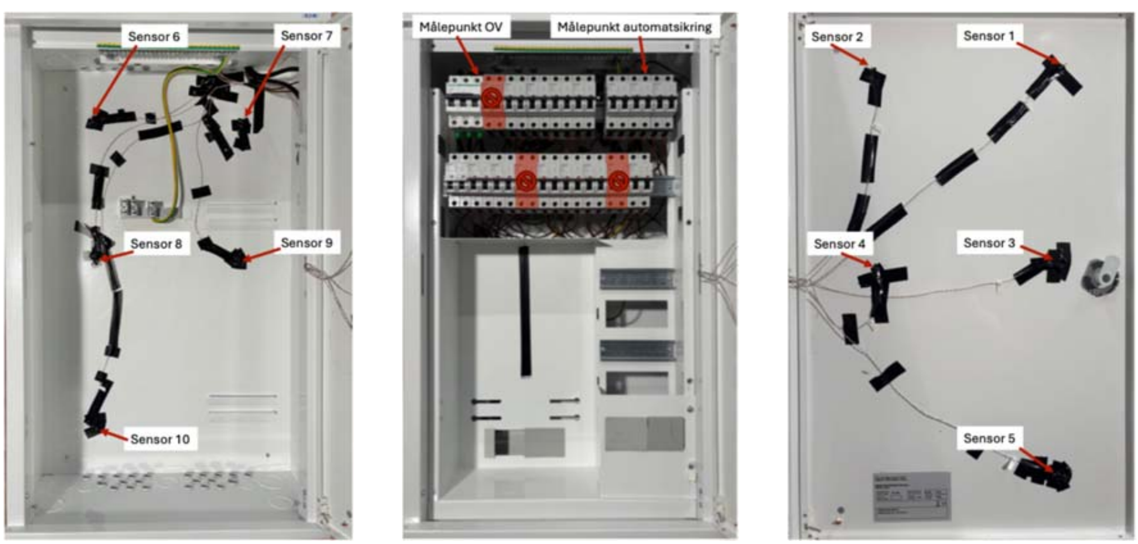
# Temperaturforhold i lavspente elektriske fordelinger

Student: **Jørgen Angelsen**
Veileder: **Eilif Hugo Hansen**

**Problemstilling**
Brann i bygninger utgjør en alvorlig risiko for liv og helse. Statistikk viser at elektriske feil er blant de vanligste årsakene til boligbranner i Norge, og mange av disse feilene oppstår i lavspente elektriske fordelinger. Forsikringsbransjen har over tid uttrykt behov for bedre løsninger for tidlig varsling av branntilløp i elektriske fordelinger, der temperaturmåling har vært et aktuelt tema.

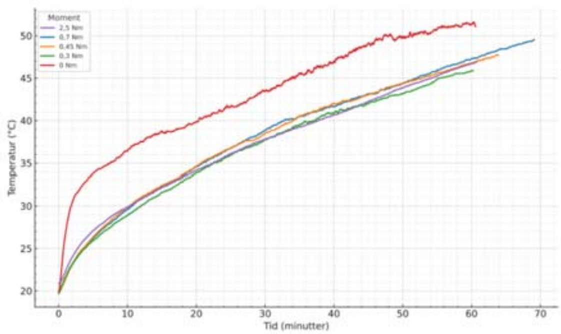
**Oppgaven**
Denne masteroppgaven undersøker om temperaturovervåkning kan benyttes som et forebyggende tiltak for å oppdage unormale driftstilstander i lavspente elektriske fordelinger. Videre vurderes det om datasimuleringer kan brukes som et verktøy for å estimere temperaturforhold under normal drift og ved ulike feiltilstander. Arbeidet omfatter en teoretisk gjennomgang av elektriske feil og feilkilder, utvikling av en simuleringsmodell i COMSOL Multiphysics, samt laboratorieforsøk for å undersøke temperaturforholdene under ulike feilsituasjoner. Resultatene fra simuleringene sammenlignes med laboratoriemålinger for å vurdere modellens nøyaktighet og praktiske anvendbarhet.

**Modell/målinger**
Det ble utviklet en simuleringsmodell i COMSOL Multiphysics for å undersøke om forventet temperatur i en elektrisk fordeling kan estimeres med datasimuleringer. I tillegg ble det utført laboratorieforsøk der både luft- og ledertemperatur ble målt under normal drift og ved ulike feiltilstander. Forsøkene inkluderte blant annet feil tiltrekkingsmoment i tilkoblinger, ledere med redusert tverrsnitt og brudd. Temperaturen ble målt med temperatursensorer og verifisert med termografikamera.

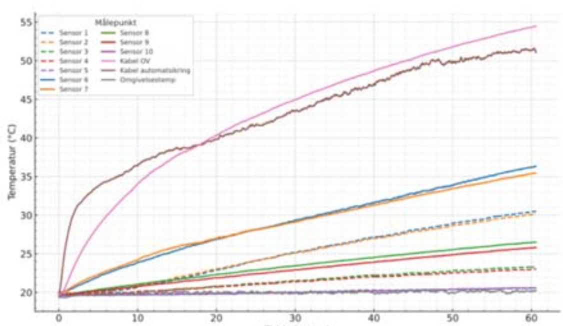


**Beregninger**
Forsøkene viste at lavt tiltrekkingsmoment i tilkoblinger forårsaket ustabil ledertemperatur som kunne detekteres ved overvåkning av lederne. Lufttemperaturen viste derimot ingen tydelige utslag ved de undersøkte feilene og anses derfor som en lite pålitelig indikator. Det ble registrert høye lufttemperaturer i fordelingen, noe som førte til varmgang i enkelte komponenter selv uten feil. Dette antyder at utsatte komponenter med høy belastning bør plasseres i nedre del av fordelingen for å redusere risikoen for varmgang. Datasimuleringene beregnet lufttemperaturer som var betydelig høyere enn det som ble målt i laboratorieforsøkene, noe som tyder på at modellen ikke samsvarer med reelle forhold.

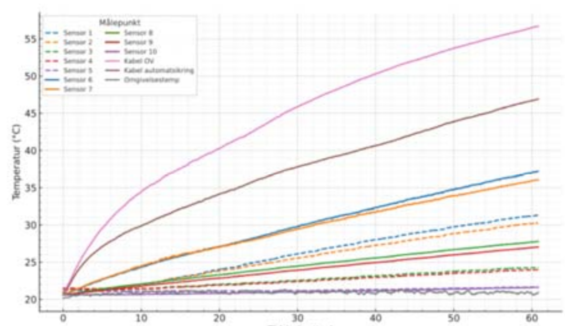
Ustabil ledertemperatur ved ulikt tiltrekkingsmoment automatsikring




Alle målepunkter ved feil tiltrekkingsmoment automatsikring:




Alle målepunkter ved normal drift:




**Konklusjon**
Overvåkning av ledertemperatur fremstår som mer pålitelig enn måling av lufttemperatur for enkelte feil. Datasimuleringene hadde begrenset nytteverdi, men kan med videre utvikling gi nyttig innsikt i temperaturforhold i elektriske fordelinger. For videre arbeid anbefales det å undersøke flere feiltyper i reelle installasjoner for å vurdere praktisk bruk av temperaturovervåkning som et brannforebyggende tiltak.

# Characterization of HVDC XLPE stressed with mechanical loading

Student: **Ådne Anmarkrud**
Supervisor: **Øystein Hestad**
Co-Supervisors: **Frank Mauseth, Markus Jarvid, Espen Doedens**
Collaboration with: **Nexans Norway AS**

**Problem description**

As HVDC extruded cable systems are being developed for even higher voltage levels, it is crucial to understand the effect of different stresses on the long-term ageing behavior of the insulation. On technique is to cut the HV cable into cable peelings, allowing a high amount of electrical test results from a short piece of cable. Such samples allow for testing different energization patterns to evaluate their impact on “real” cable insulation (cable insulation that is produced with full-size cable equipment).

**The task**

The project is mainly experimental and is based on applying dynamic loading on thin XLPE peelings with a thickness of 100-450 micrometer. The dynamic loading is in form of tensile stress where the peelings are elongated 5% and 50%. Electrical tests, such as space charge measurements, breakdown tests and dielectric response will be performed on the mechanically loaded samples and compared with the original samples.

**Model/ measurements**

Thin peelings are mounted in a stretching machine shown in Figure 1. This enables accurate elongation of the cable insulation prior to the electrical tests. Breakdown tests were performed where the peeling was placed between two electrodes, and the voltage was quickly and steadily ramped up using MATLAB until a breakdown occurred. Space charges were conducted for up to seven days at an electric field of 28 kV/mm. Additionally, crystallinity was measured using differential scanning calorimetry (DSC), and the viscoelastic properties of XLPE were analyzed in dynamic mechanical analysis (DMA).

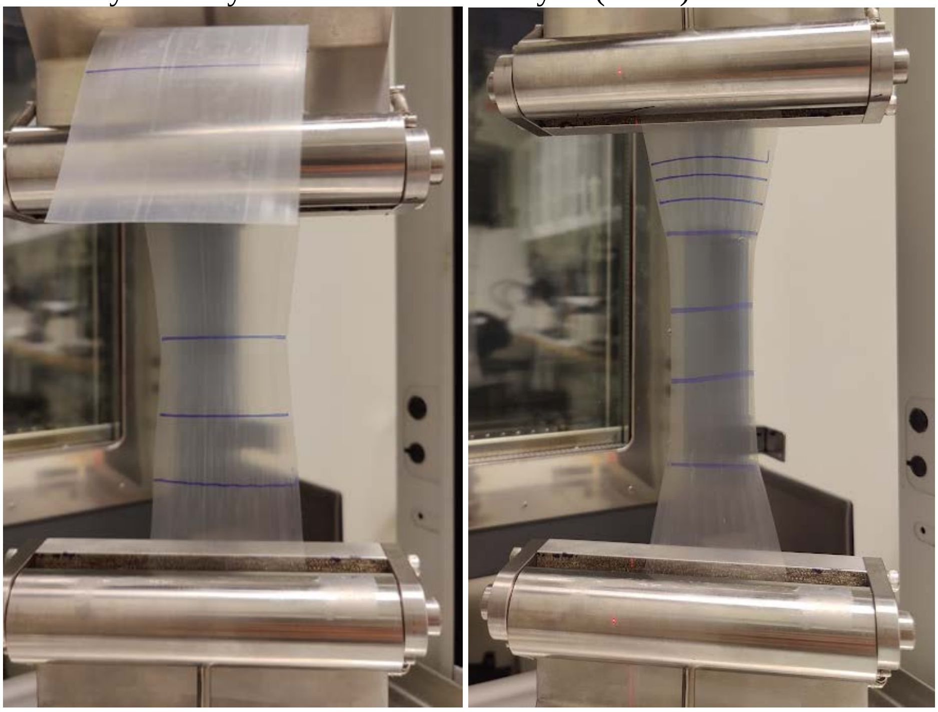


**Figure 1: Elongation of XLPE peeling in the stretching machine.**

## Results

The results showed a slight improvement in crystallinity and electric breakdown field strength of XLPE after subjected to mechanical loading. The difference is considered insignificant. Some differences are seen in the dielectric response and the measurement of tan(delta). Additionally, there are observed more accumulated space charges in the elongated samples in the space charge measurements. Figure 2 shows the results from the breakdown tests presented in the two-parameter Weibull distribution.

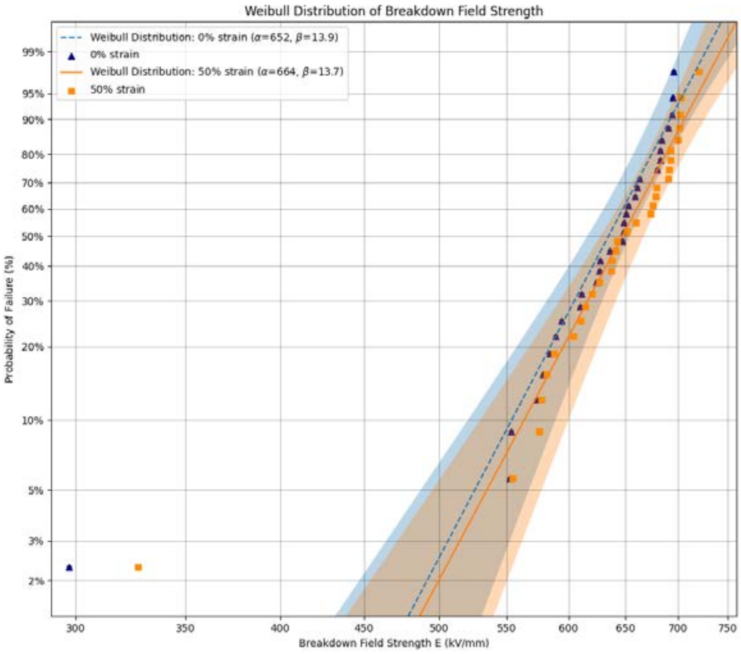



**Figure 2: Breakdown test results. The mechanical loaded samples perform slightly better.**

## Conclusion

The short-term mechanical loading of XLPE that has been performed in this study does not significantly change the electric breakdown field strength and the crystallinity of the insulation. However, some interesting changes are seen in the dielectric response and space charge measurements. Due to a low sample size and the equipment being sensitive to noise, this should be analyzed critically and researched further.

# Radial Forces and Vibration in PMSM Drive for Marine Propulsion

Student: **Eirik Blekastad Anvik**
Supervisor: **Pål Stabel Keim**
Contact: **eirik.blekastad.anvik@gmail.com**

**Abstract**
The permanent magnet synchronous machine (PMSM) is well suited for electric propulsion due to its high power density and efficiency. However, electromagnetic (EM) vibration remains an important aspect of the machine performance, influencing both passengers and surroundings. To gain valuable insight into the PMSM vibration characteristics, this thesis develops an electromechanical vibration model, aiming to predict its vibration response and further verify it in the laboratory. While the model struggled to capture the complete dynamic system behaviour, certain EM force frequencies were identified experimentally. In addition, the experiments revealed high frequency content in the vibration spectrum, indicating influence from the power electronic (PE) converters. Furthermore, experimental limitations restricted the scope of model verification, yet, valuable practical experience in vibration measurement was gained. These findings contribute to better understanding of vibration in the PMSM drive, and highlights areas where the model requires improvement.

**The task**
The thesis main objective is to model the vibration response of the PMSM and verify it experimentally, according to Figure 1.1.

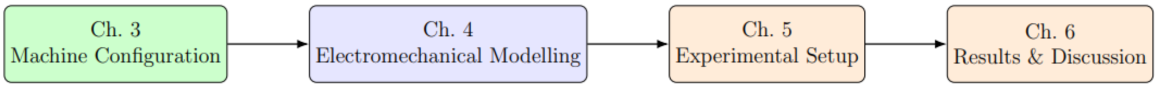



Figure 1.1: Overview of the thesis structure and progression towards the objectives.

**Model and Measurements**
Electromechanical model setup:

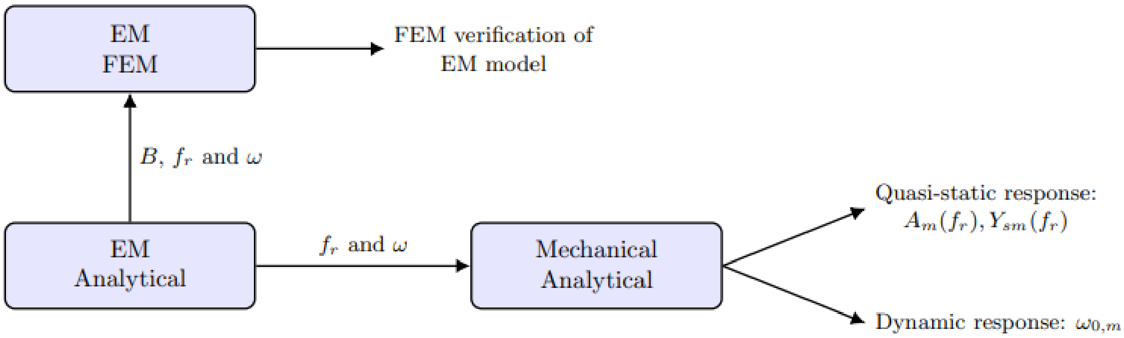
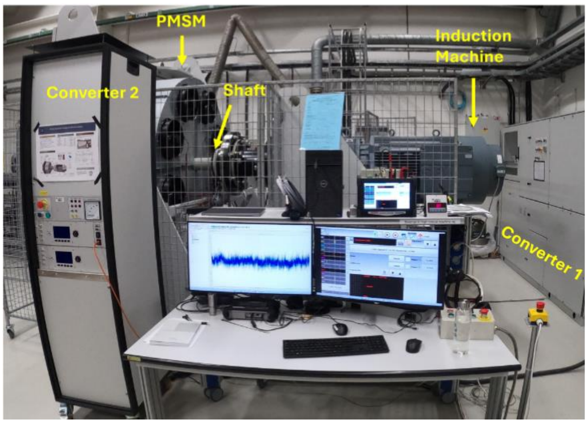
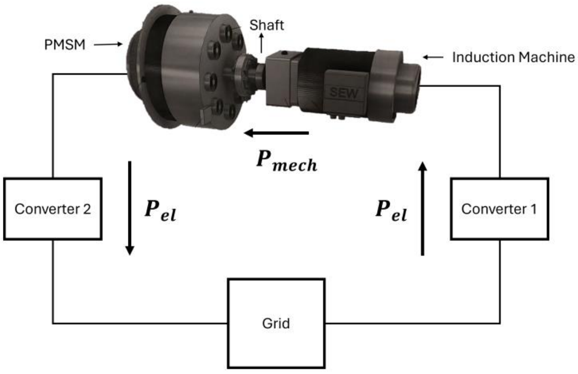



Figure 4.1: Structure and flow of the electromechanical model. $f_r$ is the radial force harmonic of spatial order $r$.

Experimental setup:




**Calculation**

Modelled deflection (Am) and eigenfrequencies:

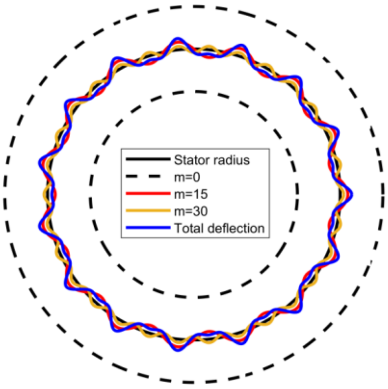
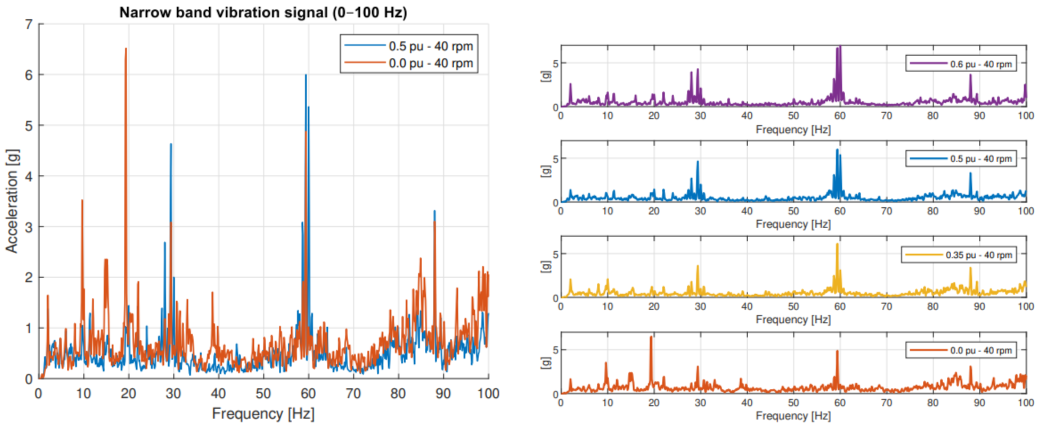



Table 4.2: Eigenfrequencies $f_{0,m}$ for selected circumferential modes $m$ of the stator system.

| Mode $m$ | Stator Core [Hz] | Frame [Hz] | Assembly [Hz] |
|---|---|---|---|
| 0 | 750.7 | 1153.6 | 887.5 |
| 1 | 5.8 | 1134.8 | 732.9 |
| 2 | 29.6 | 1088.4 | 703.2 |
| 3 | 70.5 | 1038.0 | 672.0 |
| 6 | 293.3 | 1081.4 | 723.4 |
| 9 | 664.9 | 1543.0 | 1084.3 |
| 12 | 1185.2 | 2344.5 | 1694.9 |
| 15 | 1854.2 | 3465.2 | 2535.4 |
| 30 | 7429.0 | 36484 | 24042 |

Measured vibration:




(a) Load vs no-load comparison.

(b) All load cases.

Figure 6.2: Narrow band acceleration spectrum given in g $10^{-3}$.

**Conclusion**

The electromechanical model struggled to capture the dynamic mechanical response, while the EM model showed some conformity with the measured vibration frequencies. Valuable experience was obtained from the experimental process.

# Impedance-Based Eigenvalue Participation Analysis in Offshore Wind Farms

Student: **Arnesen, Ingrid Wiig & Skram, Andrea Marie**
Supervisor: **Føyen, Sjur**

## Abstract

Worldwide initiatives to combat climate change have set ambitious targets to reduce greenhouse gas emissions from the energy sector. As a result, there is an increasing integration of wind power and other converter-based resources (CBRs) in the modern power grid. Despite its central and important role in supporting clean energy transitions, it is also fundamentally altering the power system as we traditionally know it. As CBRs gradually replace conventional synchronous generators, overall system inertia is reduced, resulting in a power system with different dynamic characteristics. In addition, the occurrence of sub-synchronous oscillations (SSO) in wind farms threatens the reliable operation of the grid.

Addressing these oscillatory phenomena is complicated. Traditional approaches based on state-space modelling require detailed models of the system's parameters and internal states to compute participation factors for oscillatory modes. In practice, such detailed information is often unavailable due to vendor confidentiality and the absence of standardised models in CBR-dominated systems.

This thesis explores the emerging field of impedance-based modelling as an alternative approach to stability assessment under limited system transparency. Emphasis is placed on the eigenvalue participation method, which is grounded in linear algebra and derives participation factors from networked-impedance models. These factors enable the quantification of dominant admittances and the identification of parameters contributing to poorly damped modes. Furthermore, the method provides practical guidance for tuning system parameters to enhance the overall stability.

The impedance-based eigenvalue participation method is not widely adopted in power system analysis. This thesis seeks to contribute to a broader understanding of the method. This is achieved by clarifying the interpretation of the participation factors, implementing the method in Python, and demonstrating its practical value through application to simplified power system representations.

The method and its Python implementation are critically evaluated through case studies. Findings reveal that dominant admittances and parameter contributions under simplified conditions are correctly identified. While some errors were present, the overall results confirm the method's potential to deliver meaningful insights. This supports its suitability for broader application, particularly in systems without detailed dynamic models.

## Utilization of Flexibility in the Distribution Grid, Considering Transmission System Operation Needs

Student: **Askeland, Julie Krag**
Supervisor: **Oleinikova, Irina**

### Abstract

The ongoing energy transition toward a low-carbon society, driven by climate policies such as the Paris Agreement, is fundamentally reshaping power system operations through large-scale integration of Variable Renewable Energy (VRE) sources and widespread electrification of end-use sectors. These developments introduce new challenges for grid stability, particularly in the form of increased volatility in voltage and frequency, as well as heightened pressure on transfer capacity. The Distribution System Operators (DSOs) are increasingly required to accommodate growing consumption and decentralized generation and asset utilization within the distribution network. Traditional approaches such as grid reinforcement are often costly, time-consuming and insufficient to meet urgent capacity needs. In this context, flexibility has emerged as a critical enabler to enhance the utilization of existing grid infrastructure, reduce congestion, maintain reliability and support secure system operation.

This thesis investigates the role and utilization of flexibility in modern power systems, with particular emphasis on its deployment at distribution level and the implications for the Transmission System Operator (TSO). Through a comprehensive literature review, the research delineates key definitions of flexibility, classifies relevant resources, maps the value chain and examines prevailing market structures. The research includes a detailed case study using the CINELDI MV reference grid, a representative medium-voltage radial distribution system developed for Norwegian conditions. By analyzing voltage profiles, load patterns and grid limitations, the study identifies capacity challenges and quantifies the need for flexibility. A Battery Energy Storage System (BESS) is introduced at a critical bus in the system and its impact is simulated, demonstrating that flexibility integration reduces peak load, mitigates congestion and enables the grid to accommodate new consumption without violating operational constraints.

Furthermore, the thesis explores how Distributed Energy Resources (DERs) not only alleviate distribution-level bottlenecks and optimize asset utilization, but can also provide value at the transmission level by participating in ancillary service markets. Various models for TSO-DSO coordination are evaluated, highlighting the importance of clear roles, robust data exchange and harmonized market mechanisms to unlock the full value of flexibility. The findings underscore that, while technical and organizational barriers remain, the strategic use of flexibility is essential for a resilient, sustainable and cost-effective power system.

## Assessing Techno-Economic Viability of Floating Offshore Wind Energy Integration

Student: **Bartels, Zoe Katharina**
Supervisor: **Anaya-Lara, Olimpo**

**Abstract**

Floating offshore wind enables the use of wind resources in water depths between 60m and 2000m, which represent over 75% of global offshore potential. Due to limited shallow-water sites, this technology is essential to meet the 1.5% climate target, requiring offshore capacity to increase from 68GW in 2023 to 494GW by 2030 and 2465GW by 2050. As of 2025, floating wind remains in a pre-commercial stage, with Hywind Tampen (88MW) being the largest project. A key technology gap is the grid integration of floating wind farms using substations. Current projects avoid offshore substations by using direct-to-shore connections, limiting scalability beyond 100MW. This thesis evaluates bottom-fixed, floating, and subsea substations for varying site conditions to identify the most cost-efficient and technically viable solution for floating wind farms. A case study is performed for two wind farms (300MW and 1.2GW) at water depths of 100m and 1000m and distances of 10km and 100km from shore. A techno-economic framework using CAPEX and OPEX adapted from an established offshore cost-benefit model is applied, extended with recent industry reports. A MATLAB simulation determines reactive power needs and maximum HVAC cable length for 66kV direct-to-shore transmission. The results show that for 1000m water depth, subsea substations are the most cost-effective solution with and without maintenance. In scenarios with high energy prices and low discount rates, floating designs can outperform subsea alternatives due to lower maintenance and curtailment costs. At 100m depth, bottom-fixed substations remain the preferred choice. Floating substations using the turbine foundation do not offer an actual cost benefit over foundations designed for substations with the assumed cost framework. Uncompensated 66kV HVAC direct to shore connections are limited to 40km, but subsea compensation extends this to 100km. The main advantage of switchgearless subsea substation over floating substations is the simplified architecture, absence of floaters and mooring systems, ease of installation and cable layout optimization, which comes with a trade-off regarding fault isolation, grid code compliance, and complex subsea environment in case of a failure.

# Optimization of Batteries through Participation in Ancillary Markets: Fast Frequency Reserves and Spot Market

Student: **Simen Aaseth Besseberg**
Supervisor: **Magnus Korpås**
Contact: **Jonatan Ralf Axel Klemets**
Collaboration with: **SINTEF**

**Problem description**

The increased integration of inverter-based renewable energy sources, such as PV and wind, has led to reduced system inertia in the Nordic power grid. This compromises frequency stability, particularly during low-demand summer periods. In response, the Norwegian TSO Statnett has introduced the Fast Frequency Reserve (FFR) market to address rapid frequency deviations. Battery energy storage systems (BESS) are well suited for FFR participation, but the economic implications of multi-market strategies that combine sport market arbitrage and FFR services remain uncertain.

**The task**

The thesis investigates the techno-economic potential of a commercial-scale, PV-connected BESS participating simultaneously in the spot market and the FFR market. The primary goals are to (i) quantify opportunity costs and derive bid price thresholds for FFR participation, (ii) assess the impact of grid tariff structures and forecast uncertainty, and (iii) provide sizing recommendations for BESS deployments based on economic performance metrics such as net electricity cost and Levelized Cost of Storage (LCOS).

**Model/ measurements**

A linear programming optimization model was developed and implemented in Pyomo (Python), incorporating battery degradation via a 4-segment piecewise linear cycle-depth-based cost function. Three model variants were used:

1. A deterministic model with perfect foresight
2. A deterministic model including fixed grid tariffs
3. A rolling 72-hour horizon model using naïve forecasts

Input data includes historical spot prices (2023-2024), load and PV profiles from Powerhouse Brattørkaia, and BESS investment costs based on NREL's 2040 cost projections. Technical feasibility and regulatory conditions were aligned with the Nordic FFR market.

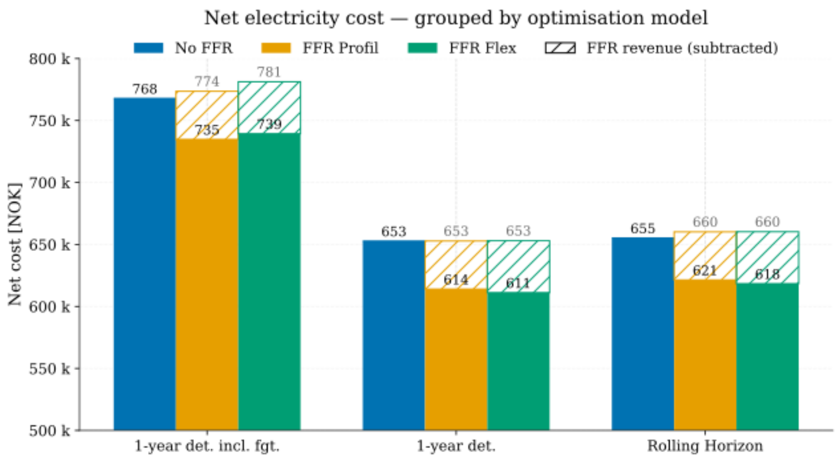



*Figure 1: Net electricity cost at Powerhouse Brattørkaia using different models. Simulated using 2024 NO3 spot prices and 2024 FFR prices.*

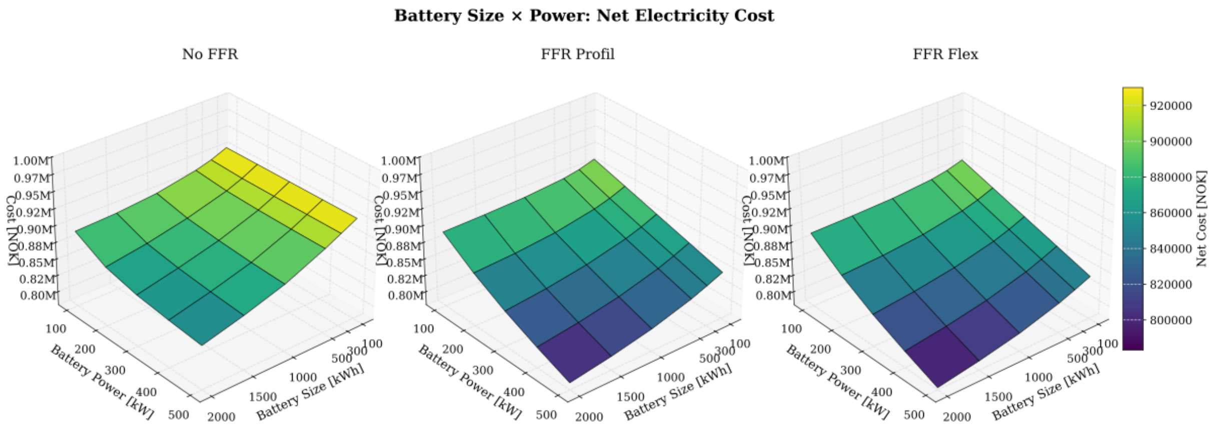



*Figure 2: Net electricity cost for different battery sizes in different market strategies. Simulated using PV- and load profiles from Powerhouse Brattørkaia, 2024 NO2 spot prices, and 2024 FFR prices.*

**Calculation**
Simulation results show that for a 1 MWh / 1 MW BESS with perfect foresight and fixed grid tariff logic, the minimum profitable bid prices range from 2.65-3.39 NOK/MW/h (FFR Profil) and 20.71-25.02 NOK/MW/h (FFR Flex). Under rolling horizon operation, annual electricity cost savings from FFR participation reach up to 165,000 NOK, with a 32% reduction in degradation. Optimal battery sizing shifts toward shorter durations (1-2 hours) when FFR is included, while the lowest LCOS is consistently achieved with 3-hour durations.

**Conclusion**
The results indicate that FFR can be a profitable complement to spot market optimization, especially if bid prices reflect degradation and tariff-related opportunity costs. Multi-market participation significantly enhances the economic viability of BESS installations. The developed model framework also supports investment planning and bid strategy design for grid-connected batteries in Norway and similar Nordic context.

# Distributed Hybrid Model for Inflow Forecasting

Student: **Sverre Beyer**
Supervisor: **Jayaprakash Rajasekharan**
Contact: **jayaprakash.rajasekharan@ntnu.no**
Collaboration with:

**Problem description**
Climate change and the global transition to renewable energy sources have created a growing need for accurate and adaptable forecasting tools within the hydropower sector. Traditional hydrological models such as HBV are grounded in physical processes and offer interpretability but often fall short in adapting to non-stationary conditions, such as extreme weather and altered precipitation patterns. Conversely, machine learning (ML) models can capture complex dynamics but often lack interpretability and climate sensitivity. There is thus a need for hybrid models that combine the strengths of both physically based and data-driven approaches.

**The task**
This master's thesis presents the development and evaluation of a distributed hybrid model for short-term streamflow forecasting. The study focuses on two Norwegian catchments, Stryn and Gaula, and compares the performance of LSTM and BiLSTM neural networks against both the standard HBV model and a customized HBV implementation in the Enki hydrological modelling framework. Emphasis is placed on model accuracy, interpretability, climate sensitivity, and uncertainty quantification.

**Model/ measurements**

The modelling setup includes:

- Physically based models – using HBV and a customized HBV structure in Enki
- Machine learning models – LSTM and BiLSTM trained on time series of meteorological and hydrological data.

A hybrid architecture is used, see Figure 1, where a LSTM is used as a base model to interpret distributed input values and make a prediction of streamflow values supplied with interpretability using the Integrated Gradients (IG) method to analyze input influence, and the Hidden Markov Model (HMM) is applied for state-wise uncertainty quantification by distinguishing between wet and dry hydrological periods.

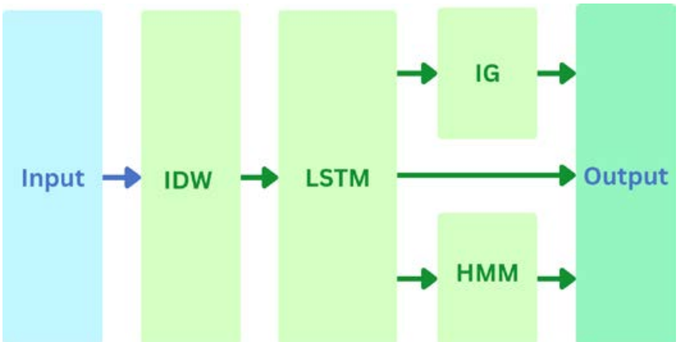


**Figure 1: Model Flow: Hybrid model implementation**

**Calculation**

- Stryn: The LSTM model outperforms HBV during high-flow periods (NSE > 0.8), while BiLSTM performs well in low-flow regimes.
- Gaula: ML models show more variable performance, with the physical model performing better during extreme events. Limited data reduces ML performance.
- IG analysis reveals that evaporation and temperature are often more influential than precipitation in model predictions.
- HMM effectively separates hydrological states, showing increased prediction uncertainty during wet periods.

**Conclusion**

- LSTM-based models can match or outperform traditional hydrological models under data-rich conditions.
- Hybrid models offer robustness by combining physical realism with data-driven flexibility.
- Interpretability is improved through IG, and HMM adds operationally relevant uncertainty estimates.
- These methods support the development of reliable, explainable, and operationally viable inflow forecasting tools, especially important in the face of climate variability and renewable energy integration.

# Numerical modelling of the effect of temporary overvoltages in extruded HVDC cable insulation

Student: **Simon Boonants**
Supervisor: **Øystein Hestad**
Co-supervisor: **Håvard Bærug**
Collaboration with: **Nexans, Statnett & SINTEF**

**Problem description**

With the rise of many HVDC projects at the 525 kV level, it becomes crucial to consider temporary overvoltages (=TOVs) due to pole-to-ground faults in subsea HVDC cables. At that stage, there was inadequate expertise to determine whether TOV testing was needed and whether the existing test procedures covered all possible stresses and failure modes. Taking into account the importance of these projects, a conservative strategy was adopted to carry out these TOV tests.

**The task**

The practical part of this thesis, which is part of the DeMoKab project aims to contribute to the knowledge about the effect of TOVs with different rise- and fall times on the insulation of extruded HVDC cables by using numerical modelling in COMSOL.

The numerical model in COMSOL must predict the effect of temporary overvoltages on the temperature distribution and electric field distribution around defects in the XLPE insulation, and take into account the space charge accumulation in the XLPE insulation.

**Model/ measurements**

The test object in COMSOL is a 2D axisymmetric geometry and is shown in Figure 1. The symmetry line is shown as a vertical dotted line in the middle of the test object. The different parts of the test object are highlighted with numbers. Number 1 is the upper-semicon, number 2 is the XLPE insulation, number 3 is the oxidized contaminant to replicate defects in the insulation and number 4 is the lower-semicon. An electro-thermal model is used.

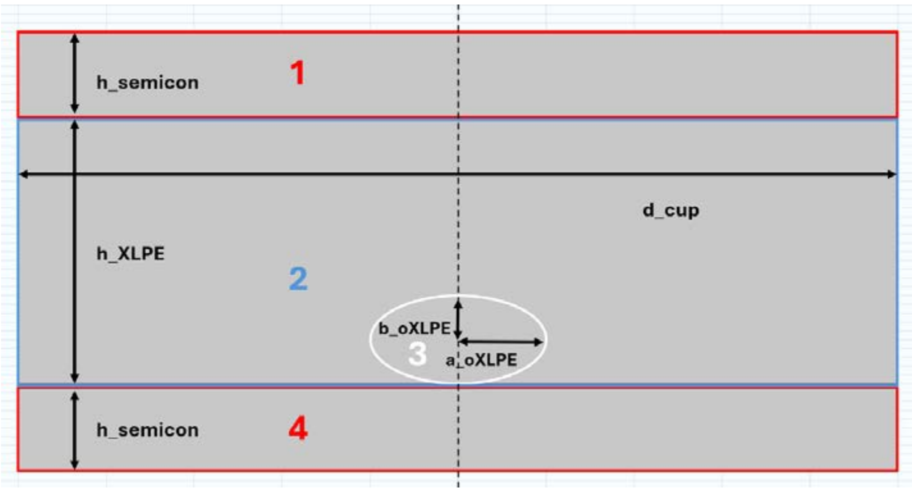



**Figure 1: numerical model of the test object in COMSOL**

First, the initial DC voltage $V_{0,i} = 40\ kV$ is applied with a rise time of 5 ms. After one minute the first TOV of the 5 initial TOVs are applied with peak voltage $V_{TOV,peak,i} = 80\ kV$ . In between the TOV waveforms, there is a time span of 1 minute. After applying the 5 initial

TOVs, the DC voltage $V_{0,i}$ is increased by 2.5 kV after 1 minute to the second DC voltage $V_{0,2} = 42.5\ kV\ (dotted\ line)$. This is then followed by the 2nd sequence of 5 TOVs peaking at 2.5 kV higher than the 5 initial TOV peak voltage $V_{TOV,peak,i}$ resulting in a peak voltage $V_{TOV,peak,2} =$ 85 kV. After the second sequence of TOVs and a timespan of 1 minute the DC voltage $V_{0,2} = 42.5\ kV$ is increased with again 2.5 kV to the third DC voltage $V_{0,3} = 45\ kV$. This methodology is further implemented up to 15 unipolar DC electric potential levels with a final DC voltage of $V_{0,15} = 75\ kV$, to which a sequence of 5 TOVs with a peak voltage of $V_{TOV,peak,15} = 75\ kV$ is applied. Figure 2 displays this full voltage waveform that was applied across the test object. This test procedure was not only executed during simulations, but also during real physical experiments in the DeMoKab project with the same type of test object.

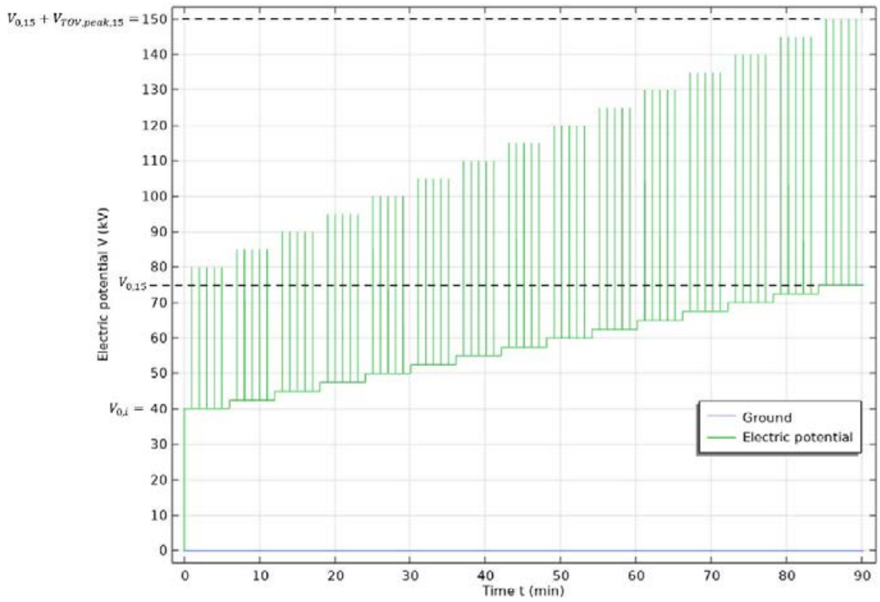



**Figure 2: applied voltage waveshape to the test object**

**Results/conclusion**

The analysis of the results of the simulations provide insights to better clarify the results of the DeMoKab experiments. During the experiments, if breakdown occurred of the test object it was almost always at the first TOV pulse of the sequence at a certain DC level.

The simulations verify this since when the first TOV of the DC sequence is applied, the peak of the electric field in the test object is always larger than for the other TOVs at the particular DC sequence. A possible explanation for the test objects where breakdown occurs at the other TOV pulses of the particular DC sequence may be that degradation occurs during the application of the first peak, which causes a reduced breakdown strength that is then reached during one of the other TOV peaks.

The difference in peak electrical field values achieved with the different types of TOVs is too minimal to conclude that one type of TOV is much more severe to the test object than the other type of TOV. Also, because of the spread in thickness and spread in the size of the contaminants between the test objects with a theoretical thickness of 0.5mm in the experiments, the difference in peak electric field reached during the different types of TOVs at a particular DC level is negligible to trace its influence in the results.

# Non-Invasive Fault Detection of Stator Inter-Turn Short Circuit Fault in Salient Pole Synchronous Generators

Student: **Andreas Bruvik**
Supervisor: **Arne Nysveen**
Co-supervisor: **Hossein Ehya**

## Problem description

Stator inter-turn short circuit faults are the most common faults in synchronous generators, accounting for 60% of faults in large electrical machines. These faults, caused by insulation degradation, lead to high circulating currents, localized heating, and potential escalation to severe phase-to-ground or phase-to-phase faults. Traditional protection relays cannot detect these faults as they involve internal circulating currents without external ground or phase connections. The challenge is to develop non-invasive detection methods that monitor these faults during operation without requiring machine disassembly, ensuring early detection to prevent costly downtime and damage

## The task

The objective of this thesis is to investigate non-invasive methods for detecting stator inter-turn short circuit faults in salient pole synchronous generators. Two techniques are explored: frequency analysis of rotor field current and analysis of induced voltage in externally mounted search coils. These methods aim to identify faults without internal measurement equipment, using finite element method simulations and laboratory experiments on a modified 100 kVA, 14-pole synchronous generator at NTNU. The study evaluates the sensitivity and reliability of these methods under healthy and faulty conditions, including the impact of rotor geometry and eccentricity.

## Model/ measurements

The study combines FEM simulations using Ansys Maxwell and laboratory experiments.

- Simulation Model: A 100 kVA, 14-pole salient pole synchronous generator was modeled in Ansys Maxwell, incorporating fault conditions. The model simulated healthy and faulty operations under no-load and full-load conditions, analyzing field current and search coil voltage.
- Laboratory Setup: A modified 100 kVA synchronous generator was tested under no-load conditions at 50 Hz and 400 V. The setup included an asynchronous driving the generator via a gearbox.

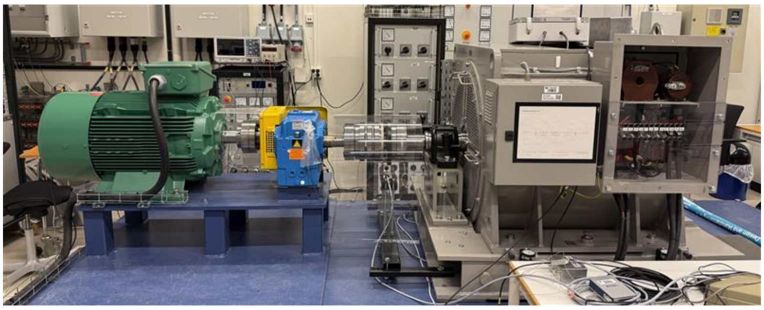


**Figure 1: Laboratory setup**

## Conclusion

The thesis has been withheld from publication for three years after submission. The findings and conclusion from the thesis are therefore not available.

# Claw Pole motor – torque optimization

Student: **Mari Bendikte Brødsjømoen**
Supervisor: **Arne Nysveen**
Contact: **arne.nysveen@ntnu.no**
Collaboration with: **Eltorque AS**

**Problem description**

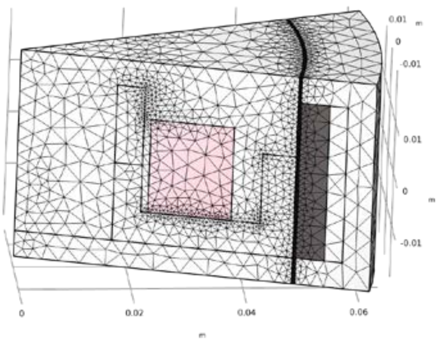
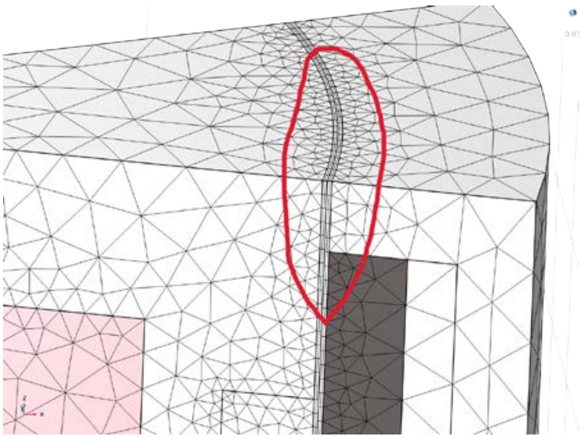
As the maritime industry develops with more electrical solutions, there is need for improved electrical machines. Eltorque has a claw pole machine (CPM) used in one of their actuators. This CPM was made around 20 years ago, and the maritime industry has developed since then. CPMs have typically high torque density [1][2], so Eltorque wanted to investigate whether the torque of their old CPM could be improved.

**The task**

The master thesis presents analysis of a simulation model developed in Comsol in the specialisation project. It compares the model with Eltorque's test results to estimate the accuracy. Then, average torque from several operating points is gathered in torque curves to optimize the CPM. The different design variations are changed dimensions of the existing design, new stator core material and new magnets. The previous patented claw detail is compared to the claw

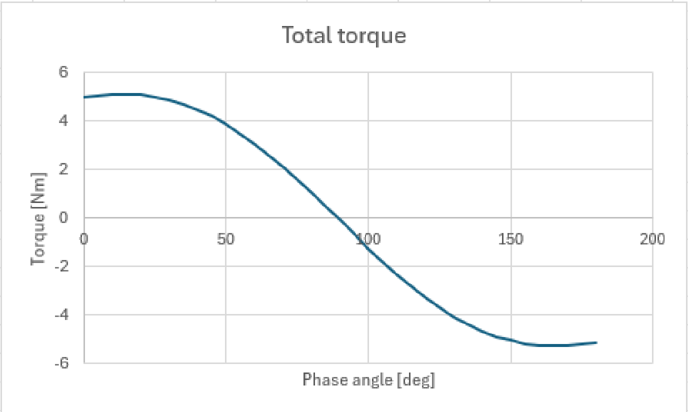
**Model/ measurements**

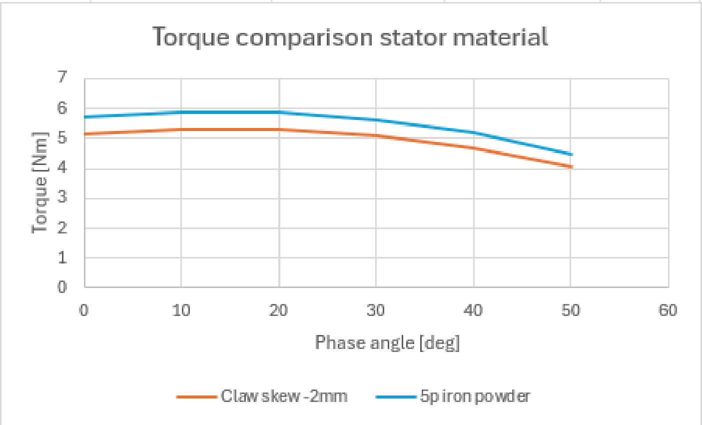
The model is simulated in Comsol, a Multiphysics simulation tool, where a section of the geometry is drawn. In this software, the relevant materials are added and applied to the geometry. Further, the mesh is investigated to study the accuracy of the model. The deviation percentage of the solutions and calculation time are compared, and the fine mesh is chosen.

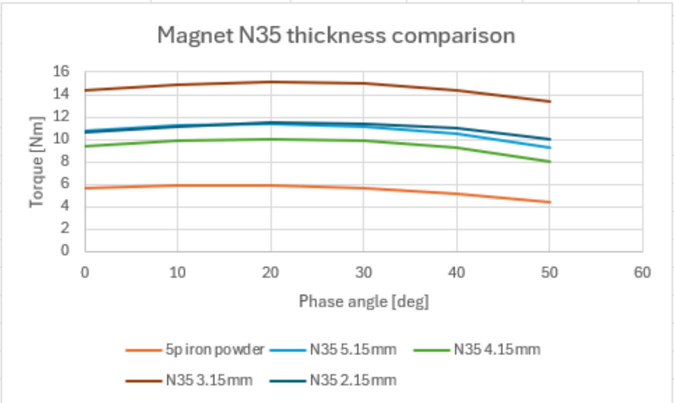



**Calculation**

The first figure is of the torque curve from the original geometry. The phase angle at the x-axis is the angle between the current and the induced voltage. Further, the improvement in torque with 5p Somaloy 1000 iron powder is presented in the second figure. Dimensions and details of the claw have already been simulated before the new iron powder, so the second figure shows the best torque with ferrite magnets. The improvements already simulated are sloped claws which are 2 mm longer, and claw skew to reduce torque ripple. The torque with neodymium N35 magnets is presented in the last figure, where 3.15 mm thick magnets give the highest torque. This torque curve is up to 3 times higher than the best design with ferrite magnets. The efficiency is improved over 20% with N35 magnets compared to ferrite magnets.




## Conclusion

The best design to obtain the highest torque with ferrite magnets is 2mm longer sloped claws with claw skew and Somaloy 1000 5p iron powder. Further, the best design with neodymium magnets is 3.15 mm thick N35 magnets, where the torque is up to 3 times higher compared to ferrite magnets. The improvement in efficiency with these magnets are over 20%.

## References

[1] W high efficiency aluminum motors 2100E Issue 3e, 2004.

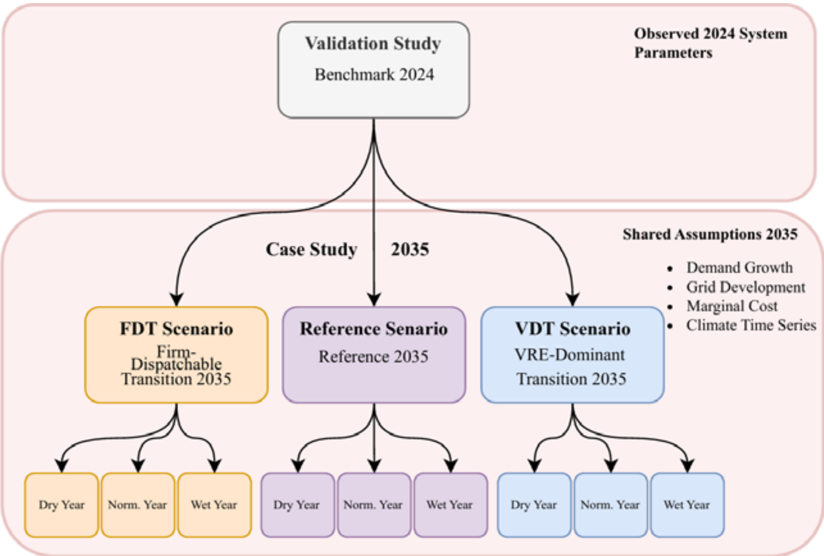
[2] FAS T series brushless servomotors, Vickers Catalogue EPC-GB-B-4030, 1991.

## Investigating Different Energy Pathways: A Techno-Economic Analysis of the Nordic Power System

Student: **Einar By & Aleksander Veum Skavlem**
Supervisor: **Magnus Korpås**
Contact: **Jonas Kristiansen Nøland & Martin Hjelmeland**
Collaboration with: **NERES**

**Problem description**
This master's thesis investigates how different energy transition pathways, particularly nuclear expansion versus high variable renewable energy (VRE) integration, will affect the Nordic power system by 2035. Using the open-source simulation tool PowerGAMA, the authors develop and validate 2024 benchmark model of the Nordic grid and assess three 2035 scenarios: a Reference scenario aligned with current transmission system operator (TSO) development plans, a Firm-Dispatchable Transition (FDT) scenario with new nuclear capacity, and a VRE-Dominant Transition (VDT) scenario characterized by large-scale offshore wind deployment.

**Modeling Scenario Framework**




**Results**
Key findings from the future case studies indicate that the 2035 Reference scenario, based on current TSO projections, delivers inadequate system performance under both normal and dry conditions. Frequent load shedding and sustained high prices point to insufficient generation and grid capacity to meet the anticipated industrial demand growth in the price zone SE1.

Nuclear power enhances system reliability by reducing pressure on reservoirs during dry periods, without displacing hydropower in normal and wet years. Consistent hydro capacity factors across scenarios indicate that nuclear complements, rather than competes with, reservoir-based hydro generation.

Large-scale wind deployment reduces overall system costs but heightens dependence on hydropower and interregional transmission to manage variability. In areas with limited firm-dispatchable capacity, periods of low wind availability result in deeper reservoir drawdowns, increased incidence of load shedding during peak stress events, and elevated price volatility.

**Conclusion**

The thesis concludes that a balanced mix, combining dispatchable and variable renewables, firm-dispatchable capacity, and strong grid infrastructure, is necessary to ensure a reliable, cost-effective, and decarbonized Nordic power system.

## Power Electronic Energy Cybernetics For Scalable Stability Certificates

Student: **Fredrik Dalbakk**
Supervisor: **Gilbert Bergna-Diaz**

### Problem description

The main objective of the so-called primary-controls of renewable energy interfacing power converters is to stabilize the system and limit potential deviations. Unfortunately, present-day industrial solutions are not designed to automatically **scale** with the much-needed growth of such systems, as they rely heavily on *case-specific computationally intensive* analyses, i.e., every minor change in the system threatens to invalidate previous designs. Therefore, if we are serious in meeting the ambitious targets set by the UN sustainable development goals, we **need to rethink completely the way in which we operate these ever-growing renewable energy-dominated power grids.**

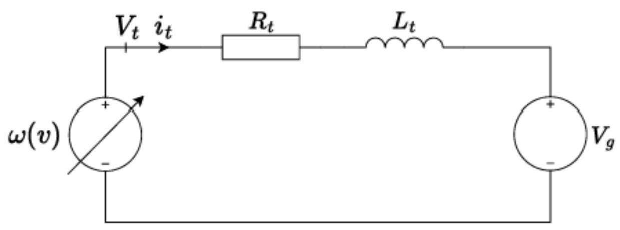
In this context, this research aims to challenge established power system primary-control conventions by moving away from data-driven and computationally intensive standard solutions to adopt a radically new analytical (energy-based) perspective. This will allow for timely needed, safe and scalable ever-growing renewable energy grids.

### The task

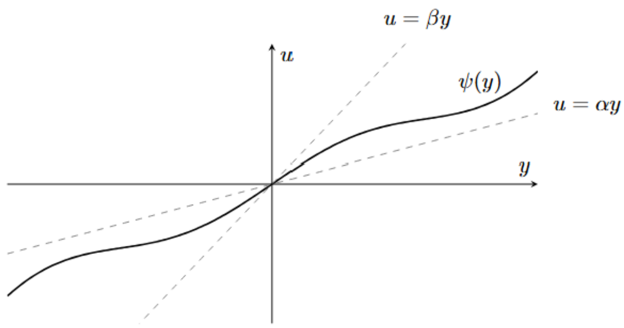
This master thesis aims to widen the set of tools available for the electrical engineering community. By combining the research areas of electrical engineering, and advanced cybernetics, this aims to find scalable solutions for power systems analysis. By a thorough literature review of the theory and methods of absolute stability theory, and direct analytical calculations this aims to shed light on possibly applicable methodology for further research developments in this field.

### Model/ measurements

The model is based on a simple linear converter structure connected to a strong grid. It is then implemented non-linear terms into the model, such as saturation, which then will be analysed using analytical tools provided by absolute stability theory.



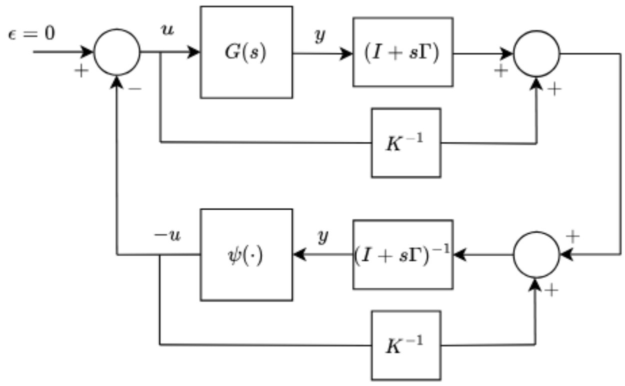

The non-linear terms is on a special form, and is calles sector-bounded nonlinearitites. These hold special characteristics which is utilized to provide the special energy-functions from the theory.




The primary goal is to show the applicability of advanced cybernetic methodology to obtain stability certificates. This in turn aims to provide clarity, in whether the methods will help obtain energy-functions which allows for stability proofs in a wider conceptual framework.

**Calculation**

The calculation utilizes the special structure of the model, and can be loop transformed according to the Popov criterion. The Popov criterion guarantees the existence of the energy function, and provides stability proofs with a flexible multiplier shaping the energy-function.




**Conclusion**

Most important findings of this thesis are that the theoretical framework conserves the linear behaviour of structure. The non-linear saturation has the same stability proof, as if it was a linear system.

Differing structurally changing non-linearities in the model poses different analytical challenges in terms of complexity. Nevertheless, general solutions is obtainable in all cases. This in turn proves the existence of energy-like functions to be used in a wider context.

# Optimizing Household Flexibility Under the New Capacity-Based Grid Tariff

Student: **Simen Myhra Danielsen**
Supervisor: **Kasper Emil Thorvaldsen**
Contact: **simenmd@stud.ntnu.no**
Collaboration with:

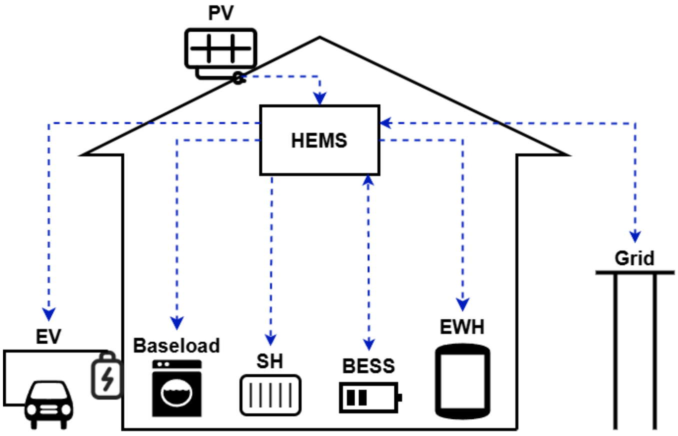
**Problem description**
This thesis investigates the new capacity-based grid tariff introduced in Norway and its impact on motivating end-users to shift their electricity consumption. The grid tariff consists of a capacity charge and an energy charge. The capacity charge is based on the average of the three highest hourly power peaks from different days, which is used to determine the capacity charge through a stepwise pricing structure. The energy charge is based on energy import, with a price applied per kilowatt-hour. The thesis also examines how the presence of flexible resources affects this ability. The grid tariff is formulated as a deterministic linear optimization problem, analyzing a single household equipped with flexible resources such as a battery energy storage system (BESS), electric vehicle (EV), space heating (SH), electric water heater (EWH), and a photovoltaic (PV) system. The operational and economic performance under various flexible resources and different designs of the capacity-based grid tariff is analyzed.

**The task**
As the need for flexibility and demand response becomes increasingly important for the power grid, this thesis aims to address several key research questions. These are developed to investigate how the new capacity-based grid tariff can motivate end-users to utilize flexibility and reduce peak power import in an efficient and cost-effective manner. The main research questions are as follows:

• How can the new capacity-based grid tariff design be formulated and represented within optimization problems?
• How does the presence of flexible resources affect the end-user’s ability to reduce electricity costs under the new capacity-based grid tariff?
• What impact do different designs of the new capacity-based grid tariff have on end-users’ cost-saving potential and behavior?

**Model/ measurements**
A deterministic linear optimization model has been developed, where the primary objective is to minimize the total electricity cost for a household by optimizing energy import, energy export, and the operation of various flexible resources. All flexible resources are modeled as grey-box models, as they are constructed based on a combination of physical knowledge and collected or assumed data to complete the models. However, some flexibility resources are more physics-based than others.

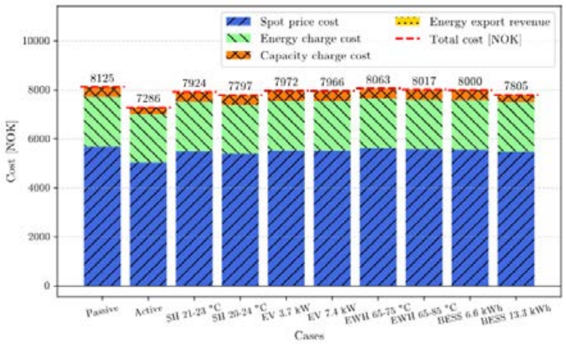
As demonstrated in the Figure, the household is connected to the electricity grid and can both import and export energy. It is also equipped with a PV system, flexible resources, and an inflexible baseload. The flexible resources include EV, SH, BESS, and EWH. A HEMS is used to monitor and optimize the use of flexible resources based on electricity spot prices and grid tariff costs. The analyses are simulated for January and July, and input data correspond to the year 2024, while the baseload represents measured household demand from 2021. The grid tariff design and associated costs are based on the current design used by Elvia.

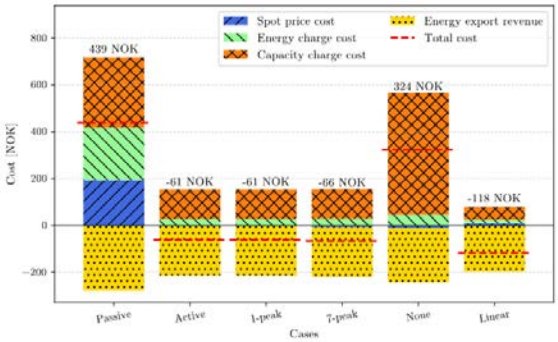



### Calculation

By only considering one flexible resource active at a time, there was limited reduction in the capacity charge. In the January scenario, only the BESS with a storage capacity of 13.3 kWh was able to reduce the capacity charge by one step, however SH provided the highest cost savings, with 4%.

Considering all flexible resources active, the end-user was able to reduce the capacity charge, where a linear capacity charge provided even greater monthly peak reductions, with 97.4% in the July scenario.




### Conclusion

The results underscore the importance of the grid tariff in motivating end-user participation in demand response programs. Neglecting the capacity charge results in minimal savings through spot price and energy charge reductions, outweighed by higher capacity charge costs. Additionally, the number of daily peaks considered and the pricing structure significantly affects the motivation for adjusting consumption. An increased number of daily peaks weakens the motivation for peak load reduction by allowing more periods with higher consumption. Conversely, a linear capacity charge provides stronger motivation, while a stepwise structure does not always incentivize peak load reduction if achieving the next step is neither feasible nor economically beneficial.

## A techno-economic model of the European power system and markets

Student: **Dauchat, Liam**
Supervisor: **Korpås, Magnus**

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

## Skånsam kraftutbygging i verna vassdrag

Student: **Elias Eide**
Faglærer:
Veileder: **Tor Haakon Bakken**

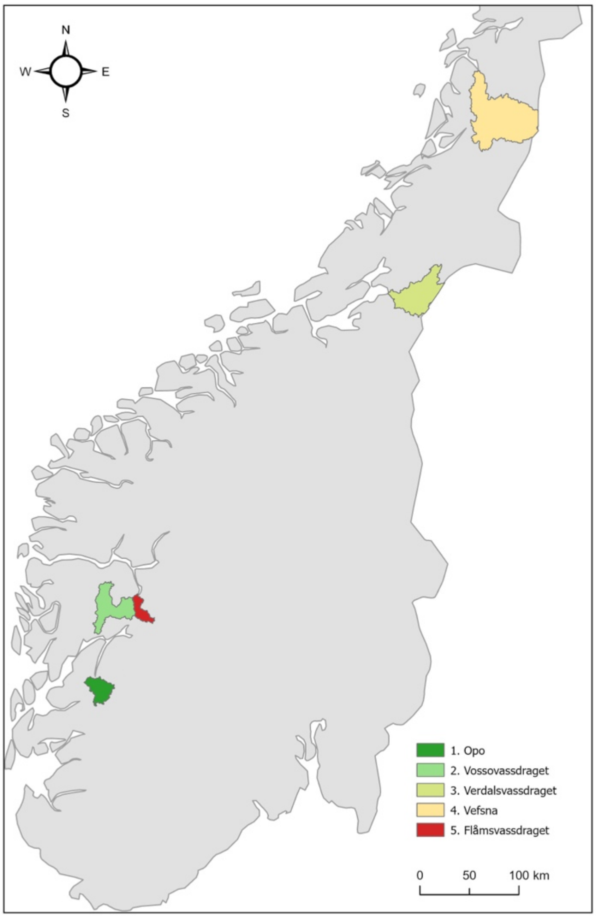
**Problemstilling**
Med bakgrunn i klima- og naturutfordringane, behovet for meir fornybar energi og flaumdemping skal det i masteroppgåva greiast ut følgjande:

1. Gjere kort greie for kraftsituasjonen og dei nyaste politiske føringane kring verna vassdrag.
2. Gjere greie for omgrepet «skånsam utbygging», og kome med døme på kva dette er – eller kan vere.
3. Utvikle ein modell som kan samanlikne potensielle vasskraftprosjekt.
4. Identifisere tidlegare føreslåtte eller potensielle vasskraftprosjekt i verna vassdrag, og nytte modellen for å samanlikne nye potensielle vasskraftprosjekt i verna vassdrag.
5. Vurdere dei føreslåtte prosjekta og føreslå ei rangering basert på eigendefinerte kriterium.
6. Diskutere funna i lys av planane for verna vassdrag, EUs taksonomi og kriterium for berekraftig vasskraft samt politiske rammevilkår.

**Oppgåva**
Det er utvikla ein modell for å kunne samanlikne moglege vasskraftprosjekt med kvarandre. Fem nyleg gjennomførte utbyggingar er brukt som referanse, med tanke på den høge miljøfaglege standarden prosjekta har. Med ulike kriterium blir desse prosjekta samanlikna med fem moglege utbyggingsprosjekt i verna vassdrag. Fem prosjekt er vurdert; Opo, Vossovassdraget, Verdalsvassdraget og Flåmsvassdraget

**Modell**
Det er laga ein multikriteriemodell for å kunne samanlikne referanseprosjekt opp mot moglege utbyggingar i verna vassdrag.

## Resultat




Basert på modellen som er utvikla er det mogleg å bygge ut alle dei fem prosjekta i verna vassdrag på ein skånsam måte. Prosjekta er rangert i figuren etter kor gode dei er etter modellen. Opo kjem best ut og Flåmsvassdraget dårlegast ut. Men det er alle gode prosjekt.

**Konklusjon**

Det samla utbyggingspotensiale for dei fem ulike prosjekta er på 2,6 TWh. I lys av dei siste års utbygging, og kraftselskap sine framtidige planar er dette ei betydeleg mengde kraft. Det er grunn til å tru at det kan finnast andre prosjekt blant dei 385 andre verna vassdraga som også kan eigne seg for skånsam utbygging, enten med eller utan flaumdempande effekt. Dette bør det likevel gjerast grundigare utgreiingar av.

For å kunne ta dei beste avgjerslene for framtida, treng vi eit best mogleg kunnskapsgrunnlag. Dei verna vassdraga bør ikkje vernast frå oppdatert kunnskap. Vernevedtaka må tole å kunne få nytt lys kasta på seg.

Noreg har gjort mange kloke val i vassdragsforvaltning. Skal vi ta like gode val framover kan ikkje dei verna vassdraga vernast frå ny kunnskap. Rammevilkår må henge saman med politiske ambisjonar. Heldigvis er energipolitikken fornybar.

# AI based PMU anomaly detection algorithms

Student: **Einar Ekeland**
Supervisor: **Umit Cali**

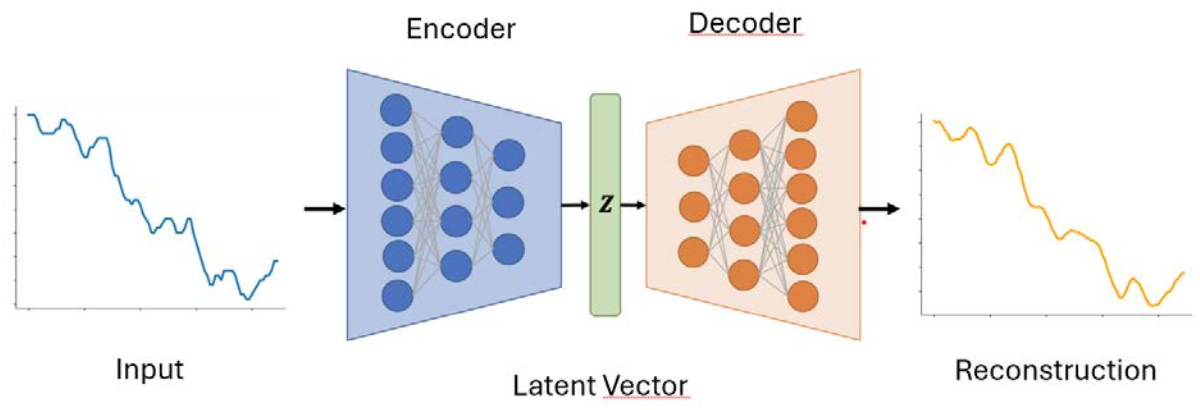
**Problem description**
As society becomes more digitalized, the power grid faces increasing complexity due to electrification and renewable energy integration. Traditional SCADA systems lack the resolution to capture fast events, prompting the need for more advanced monitoring. Phasor Measurement Units (PMUs) offer high-frequency, time-synchronized data that enhances grid visibility and state estimation. However, the reliance on real-time data introduces vulnerability to errors and cyber threats. To address this, Machine Learning (ML), particularly autoencoder models, can detect anomalies by learning normal system behavior. This thesis investigates using Multilayer Perceptron, LSTM, and CNN autoencoders to detect bad data in PMU streams caused by sensor faults or attacks.

**Model/ measurements**

The core model explored in this thesis is the Autoencoder (AE), an unsupervised neural network that compresses input data into a lower-dimensional latent representation and then reconstructs it. The model learns to retain only the most essential structures of the data. Anomalies are identified by comparing the original input with its reconstruction—large deviations suggest abnormal behavior. An illustration of an autoencoder structure is shown below.

The process begins with data collection, visualization, and preprocessing to ensure the dataset is intuitive, clean, and suitable for modeling. The dataset used originates from NREL and the University of Texas at Austin, consisting of one hour of PMU data from five locations in Texas. Data preparation includes angle unwrapping, noise filtering, and normalization, adapted for each signal type.

Models are implemented and trained using TensorFlow, with validation data used to prevent overfitting and improve generalization. Three types of autoencoders are implemented, specifically Dense, LSTM, and CNN architectures. To evaluate anomaly detection performance, synthetic anomalies—spikes, offsets, noise, and drift—are injected into the test set, simulating bad data or cyber attacks. Results are compared to previously developed predictive models (CNN, LSTM, BiLSTM, and C-LSTM) to highlight the strengths and limitations of both approaches.



**Calculation**
After refining the hyperparameter tuning process to increase model complexity, all models showed good generalization, with the CNN AE achieving the most accurate signal reconstructions, especially for fine-grained variations.

In detecting anomalies, the LSTM AE stood out with perfect spike detection (100% precision and recall), while the Dense AE also performed strongly. The CNN AE, though effective at identifying all spikes, produced more false positives due to its tendency to reconstruct anomalies too closely. For offset anomalies, all models responded well, though the CNN AE recovered faster post-event, while the Dense and LSTM AEs flagged extended anomalies. In noise detection, the CNN AE had the highest recall, but the LSTM and Dense AEs maintained higher precision. The LSTM AE also responded earliest and most distinctly to drift anomalies, where the Dense AE struggled.

While results are not fully comparable to the previously developed predictive models due to differences in data types and anomaly setups, Dense and LSTM Autoencoders outperformed them in spike detection precision and F1-score, with all models achieving perfect recall. Previous models were more effective for noise anomalies, though AEs had higher precision. Both approaches handled offset anomalies similarly, but only the AEs detected drift.

**Conclusion**
This thesis shows that Dense, LSTM, and CNN autoencoders effectively detect anomalies in PMU data, with LSTM performing best overall. All models identified spikes and offsets reliably; CNN was more sensitive but produced more false positives, while Dense and LSTM offered better generalization in noisy conditions. Compared to previous algorithms, the new models improved spike and drift detection but were slightly less effective for noise. They also aligned well with traditional non-ML methods and matched their performance with adjusted thresholds. All models achieved real-time inference, confirming their suitability for practical grid monitoring.

# Utforming av AgriPV-anlegg med fokus på vindpåvirkning og energiproduksjon i Norge

Student: **Isabell Ellefsen**
Veileder: **Steve Völler**

## Problemstilling

Behovet for økt fornybar energiproduksjon og matproduksjon vokser, noe som legger et stadig større press på arealbruken. Begge sektorene krever store landområder, og det blir derfor viktigere enn noensinne å finne løsninger som utnytter arealet på en mer effektiv og bærekraftig måte. En lovende tilnærming er AgriPV, der solenergi og mat kan produseres side om side på samme areal. Denne typen flerbruk av areal presenterer et viktig steg mot et mer bærekraftig samfunn, der energi- og matbehov kan dekkes uten å gå på bekostning av hverandre. Eksempelvis kan AgriPV konstrueres slik:

## Oppgaven

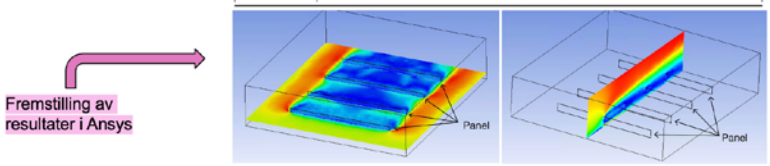
Denne oppgaven simulerer hvordan solcellepaneler med vertikal, skråstilt med 45 graders helningsvinkel og horisontal orientering påvirkes av varierende vindhastigheter. Den undersøker også hvordan energiproduksjonen varierer mellom disse paneloppsettene i fem norske byer: Tromsø, Bodø, Trondheim, Bergen og Kristiansand.

## Modell/målinger

Simuleringsprogrammene Ansys og PVsyst er henholdsvis benyttet for å simulere vind og energiproduksjon. Figurene nedenfor er hentet fra simuleringene i Ansys.

Paneloppsett i Ansys

| Scenario | Paneloppsett |
|---|---|
| S1 | Vertikalt orienterte solcellepanel plassert 0,8 meter over bakken |
| S2 | Vertikalt orienterte solcellepanel plassert 3 meter over bakken |
| S3 | Paneler med 45° helning passert 0,8 meter over bakken |
| S4 | Paneler med 45° helning plassert 3 meter over bakken |
| S5 | Horisontalt orienterte solcellepanel plassert 3 meter over bakken |




## Konklusjon

Basert på funnene anbefales det at AgriPV-panelene installeres slik:

- Panelene bør monteres med en helningsvinkel på rundt 45 grader for å gi en god balanse mellom energiproduksjon og vindbelastning.
- Lav montering nær bakken anbefales for å redusere trykkbelastningen og samtidig gi vindskjerming for avlinger.
- Det bør benyttes lange, sammenhengende panelrader for å skape et stabilt midtparti bak panelene.
- Den fremste panelraden bør monteres ekstra robust, da den er mest utsatt for vindtrykk når vinden kommer rett forfra.

# New Methodology for On-Site Determination of Stresses in HV Cable Loops

Student: **Elliott, Simeon**
Supervisor: **Hestad, Øystein**

## Abstract

As global electricity demand rises, High Voltage Direct Current (HVDC) technology is increasingly adopted for efficient long-distance power transmission. To ensure reliability, HVDC cable systems undergo rigorous testing, where non-uniform environmental conditions and installation geometries can lead to localised overheating, or 'hot spots'. Traditional thermal assessment methods often fail to capture these complex spatial effects. This thesis investigates the feasibility of using 3D scanning technology to analyse thermal distributions in cable test loops by extracting detailed geometric data and incorporating it into an empirical thermal model.

The study focuses on quantifying how the cable's proximity to the floor and support trestles affects temperature distribution. Laboratory experiments and COMSOL simulations were used to characterise these influences, showing, for instance, that cables resting on concrete exhibit lower temperatures due to better thermal conduction, and that the thermal impact of a trestle is spatially limited to about one metre. Two 3D scanning methods—a high-precision laser scanner and a consumer-grade LiDAR scanner—were compared. The laser scanner provided accurate results but required extensive set-up, while the mobile LiDAR lacked sufficient resolution for most applications.

An empirical model, expanding upon IEC 60287 standards, was developed and implemented in a MATLAB program with an intuitive interface. This program processes 3D scan data to extract geometric features of cable test loops and estimate their steady-state temperature profiles. The model successfully reproduced localised temperature effects from trestles, offering more realistic predictions than the conventional IEC approach.

While the concept was demonstrated successfully, challenges remain in scanning accuracy, data processing, and model calibration. Nevertheless, the work highlights the potential of integrating 3D scanning and thermal modelling to enhance the reliability of HV cable qualification, laying the foundation for more accurate and spatially resolved temperature assessments in future testing protocols.

## Converter Control Functionalities and their Stability through a Unified Integral Control Framework

Student: **Eskil Oftebro Enge and Varg Førland**
Supervisor: **Sjur Føyen**

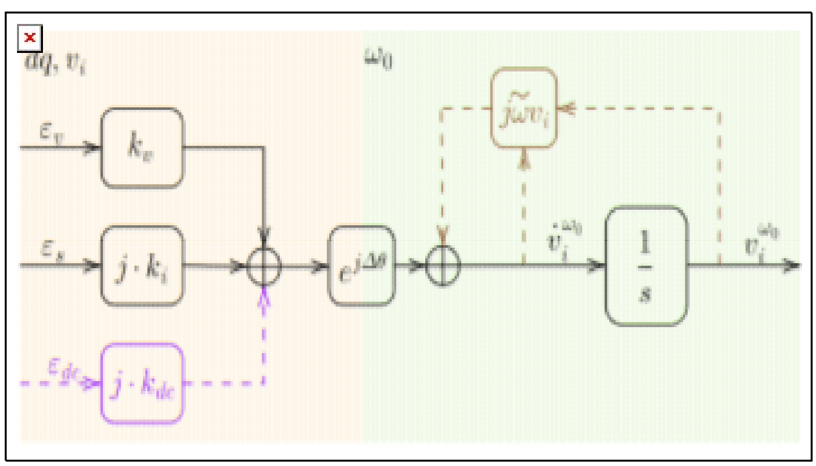
**Abstract**
Converter-based resources (CBRs) are increasingly integrated into power grids which fundamentally alters system operation and dynamics. As CBRs replace or coexist with synchronous machines, the responsibility for grid stability becomes shared, requiring converters to provide grid-supporting functionalities.

To further the understanding of CBR functionality, this thesis introduces the Unified Integral Control (UIC) framework. The framework is a representation of functionality and is used to systematically attribute synchronization and dispatch to specific control mechanisms, as well as the grid-forming functionality of droop or grid-following functionality of perfect tracking of set-points. We investigate similarities and differences in grid-forming control schemes such as Virtual Oscillator Control and Droop Control, as well as grid-following control. It is shown that when the controllers are expressed as complex differential equations in a constant frequency frame, they equate to the UIC. Equivalences are confirmed through simulations in PSCAD. The framework yields complementary insights on the choice of filtering, point of dispatch, and time-domain operation. This is used to showcase GFL operation without a Phase-Locked-Loop (PLL-less), and Droop Control without the need for power filtering. The functionality of synchronization and dispatch is shown to be similar across converter implementations. Stability analysis is conducted to assess the impact of these functionalities.

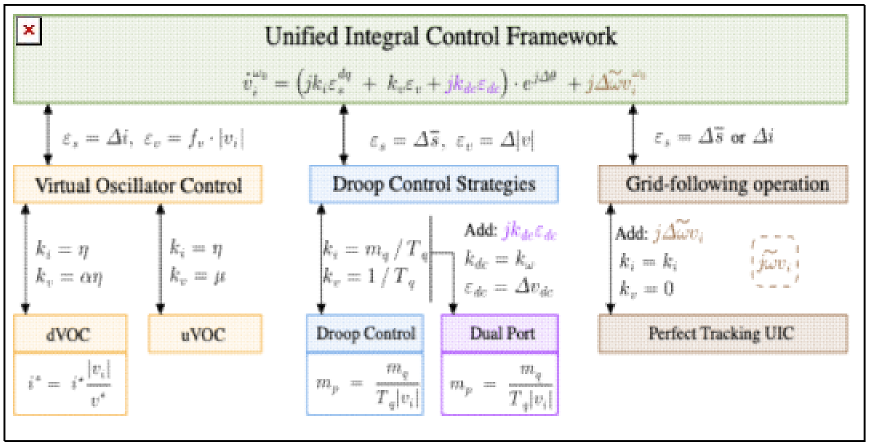
The UIC provides a framework to unify apparent differences in control implementations, and facilitates a functionality-based perspective on operation and stability. This can further the understanding of functionality in CBRs, giving a clearer perspective for the design, implementation, and analysis of converters in the grid

**Unified Integral Control**
This thesis presents a Unified Integral Control framework, in which Droop Control, dVOC/uVOC, Dual Port, and GFL control will be expressed. Many of the apparent differences between these controllers do not exist with this representation. A unified view of converter control implementations helps clarify the underlying principles shared across different approaches, making designing, comparing, and understanding their functionality easier. The UIC framework acts as a representation of functionality.

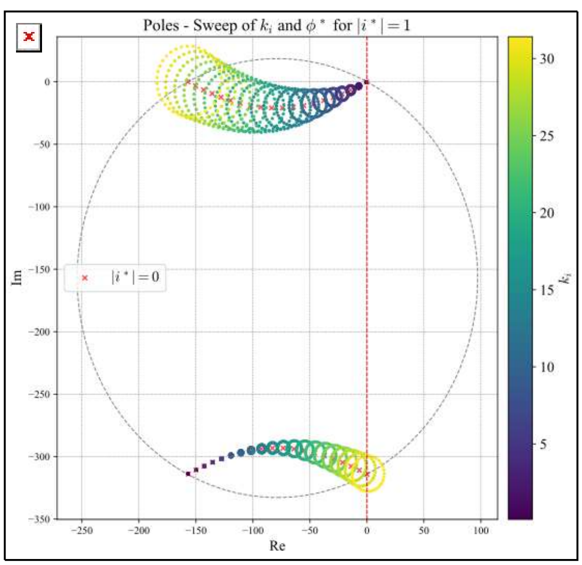
The Unified Integral Controller utilizes different coordinate frames to achieve the functionality of droop, most notably what is referred to as the omega-zero-frame, a coordinate system rotating with a constant nominal frequency. The variables are complex and transformations between coordinate frames are

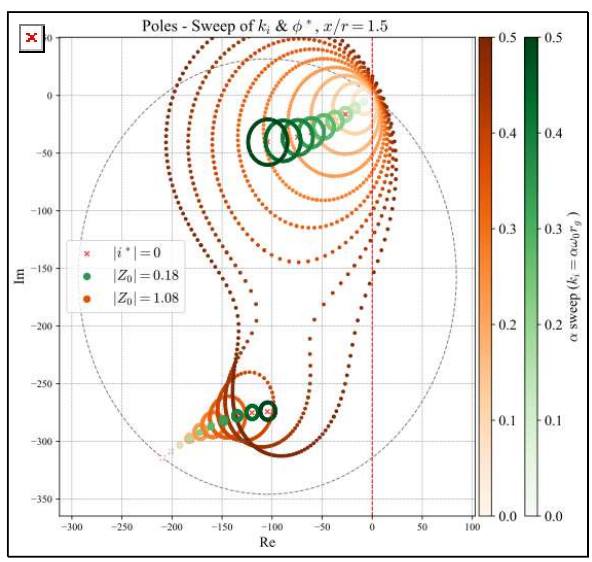


done by rotating the complex variables. The *synchronous error* is either a current or power error. This is scaled by a gain and rotated ninety degrees, aligning droop to the correct axes i.e. active power-frequency droop. Reactive power-voltage droop is achieved through voltage control. The error terms are expressed in the internal voltage's *dq*-frame, and rotated to the omega-zero-frame. This rotation enables droop, as the error terms are integrated. More functionality such as DC side dynamics can be implemented through additional error terms. In addition, the controller can be set to operate in grid-following mode by enabling perfect tracking of the reference.




**Stability Analysis**
Using the UIC we present connections between stability functionality, such as synchronization and dispatch. We look at the impact of variables and functionality on the eigenvalues and responses of the system. In the figures below, the poles are shown. Here the gain is increased, moving the poles. Dispatch is added, i.e. power set-points, a circle is drawn around the pole trajectory, and weak grid stability is investigated.



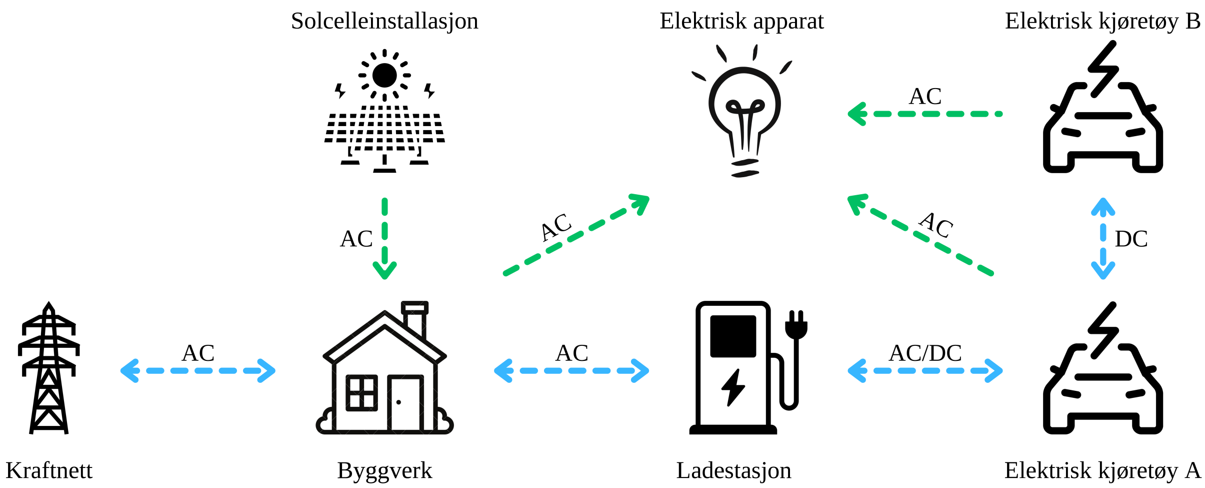
**Utforming av installasjoner for toveis energiutveksling mellom elektriske kjøretøy og elektrisk infrastruktur**

*En teknisk-regulatorisk vurdering av elsikkerhet med bakgrunn i norsk elektroteknisk standard*

Student: **Marius Englund**
Veileder: **Eilif Hugo Hansen**

**Problemstilling**

Per i dag foreligger det ingen standarder som tilstrekkelig reflekterer den praktiske anvendelsen av teknologier som V2H (vehicle-to-home), V2B (vehicle-to-building) og V2G (vehicle-to-grid), samtidig som de sikrer etterlevelse av Forskrift om elektriske lavspenningsanlegg (FEL) med hensyn til et forsvarlig nivå av elsikkerhet. For at det norske distribusjonssystemet skal kunne utnytte fordelene som tilbys av disse teknologiene, er det derfor avgjørende at det utvikles metoder for utforming.




I denne studien undersøkes hvordan en lavspenningsinstallasjon kan utformes for V2H, V2B og V2G, samtidig som den ivaretar beskyttelsen av mennesker, husdyr og eiendom mot fare og skader forårsaket av isolasjonsfeil.

**Tilnærming**

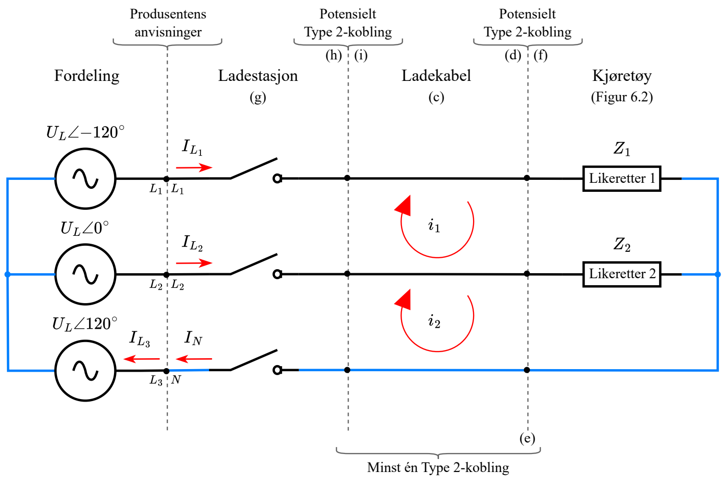
For å nærme seg en løsning på problemstillingen, omfatter studien blant annet følgende delmål og forskningsspørsmål, med formål å identifisere normtekniske svakheter og foreslå aspekter som bør vurderes av en normkomité i videre elektroteknisk standardiseringsarbeid:

- Kan tekniske og/eller regulatoriske forhold i norsk elektroteknisk standard og/eller gjeldende installasjonspraksis for *forsyning* av elektriske kjøretøy, medføre begrensinger og/eller ineffektiv bruk av teknologi for *energiutveksling* med elektriske kjøretøy?
- Kan og/eller bør elektrisk utstyr utformet for *enveis* energioverføring benyttes uten modifikasjoner i installasjoner for *toveis* energiutveksling?
- Hvordan påvirkes et fordelingssystem dersom et elektrisk kjøretøy med strømforsyningsformål tilkobles en lavspenningsinstallasjon i distribusjonsnettet?
- Hva påvirker størrelsen på feilstrømmer i en normal driftssituasjon, og i hvilken grad kan dette utgjøre en risiko for liv, helse og/eller materielle verdier?
- Kan særlige påvirkninger som utilsiktede lederbrudd og/eller forhold som valg av koblingsutstyr medføre økt risiko for berøringsfarlige spenninger i installasjonen?

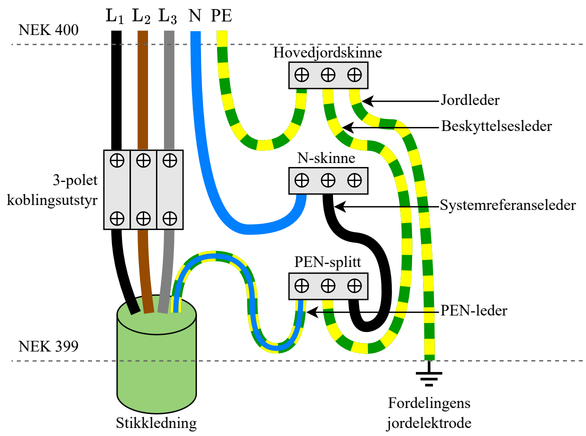
## Konklusjon

Basert på en vurdering av beskyttelsestiltak mot elektrisk sjokk, samt enkelte knyttet til overstrømsbeskyttelse, identifiserer studien et klart behov for justering og videreutvikling av norsk elektroteknisk standard for installasjoner som omfatter elektriske kjøretøy:

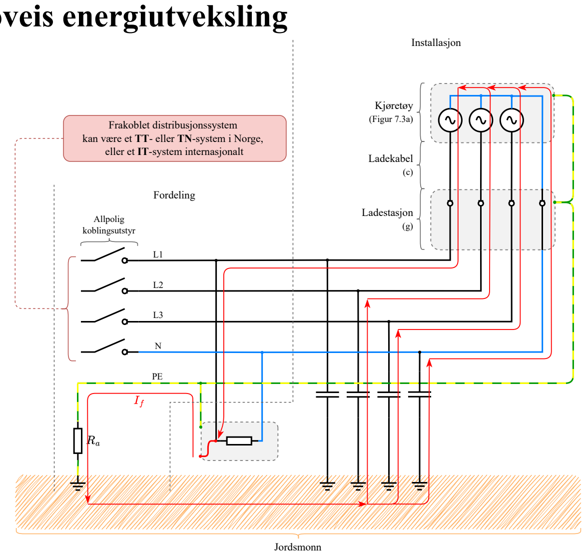
- **Tilpasning av norsk standard for toveis energiutveksling med Type 2-kontakter**
  - Til tross for at et lavspenningsanlegg *uten* nøytralleder er utformet i samsvar med produsentens anvisning for nettilkobling av en ladestasjon, vil trefaset AC-lading befinne seg i en normativ gråsone i henhold til NEK 400:2022.
  - Likevel kan produsentenes anvisninger tilby opptil dobbelt så høy ladeeffekt, og dermed forbedre utnyttelsen av V2X- og V2G-teknologi i store deler av Norge.
  - Forutsatt at disse særnorske installasjonene tilfredsstiller studiens forslag til krav, foreligger det *ingen* indikasjoner på at særnorsk ladepraksis svekker elsikkerheten.




- **Koblingsutstyr i lavspente fordelinger med elektriske kjøretøy**
  - Elektriske kjøretøy som forsyner enhver type fordeling etablerer et lokalt IT-system dersom *samtlige* spenningsførende ledere frakobles en annen fordeling.
  - Forekomster av slike jordingssystemer kan oppstå dersom vern og/eller brytere med allpolig brudd er benyttet i ulike deler av distribusjonssystemet.
  - For et lavspenningsanlegg utformet *med* nøytralleder, kan dette innebære risiko for driftssituasjoner med et flytende nullpunkt – som er forbudt i Norge.
  - I praksis kan dette unngås ved konsekvent bruk av 3-polet koblingsutstyr i *alle* deler av installasjonen *oppstrøms* for kursavgangen til et elektrisk kjøretøy.




- **Beskyttelse mot elektrisk sjokk i installasjoner med toveis energiutveksling**
  - Valgfriheten i NEK 400 ved beskyttelse mot elektrisk sjokk i *laderetningen*, kan medføre ombygging dersom kurser skal gjenbrukes til *toveis energiutveksling*.
  - Ved toveis energiutveksling er det mest hensiktsmessig å ivareta beskyttelsen mot elektrisk sjokk ved et strømstyrt jordfeilvern av Type B, hvor strømtilførselen *må* være utformet med dobbel eller forsterket.
  - Ved bruk av andre typer strømstyrte jordfeilvern enn Type B, kan dette medføre kjernemetning i installasjonens øvrige vern ved energiflyt *fra* kjøretøyet, særlig dersom anlegget inneholder vern av Type F.
  - For å sikre beskyttelse av *ladekabelen* i V2X- og/eller V2G-drift, bør ladekabelen være utformet med dobbel eller forsterket isolasjon.



# Optimization and Control of a Hybrid Energy System consisting of a Combined Cycle Gas Turbine and Offshore

Student: **Edward Remi Eriksen**
Supervisor: **Ümit Cali**

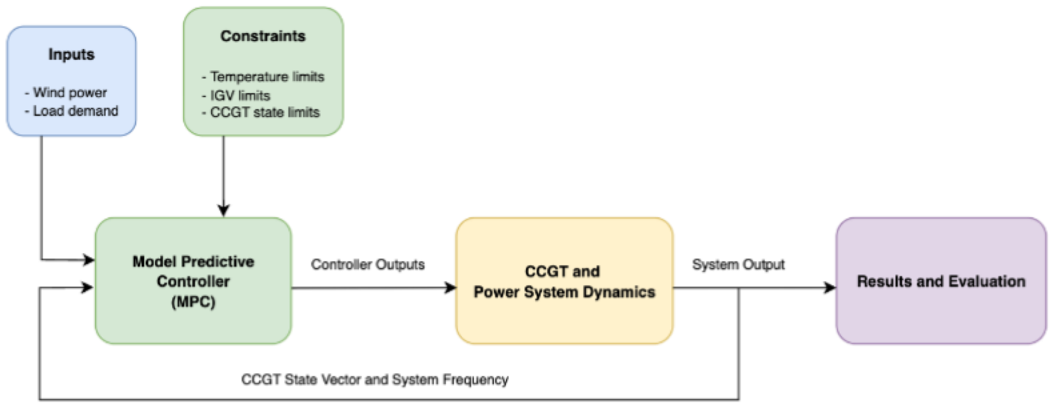
## Problem description

The global energy transition demands innovative solutions to integrate renewable energy sources with traditional power generation systems, especially for sectors that are difficult to decarbonise, such as offshore oil and gas operations. Offshore platforms have traditionally relied on open-cycle gas turbines, which have lower efficiency and emit significant amounts of greenhouse gasses compared to the Combined Cycle Gas Turbine (CCGT). The integration of wind power with CCGT systems presents a promising hybrid energy solution for reducing emissions and improving energy efficiency. However, the hybridisation of such systems poses complex challenges, including the dynamic management of power and heat demands, variability in renewable energy production, and need for optimisation to balance costs, emissions and operational reliability. A co-simulation framework is required to model, simulate the interaction between wind farms and CCGTs under varying load conditions by designing optimal controllers.

## The task

A dynamic simulation framework is extended to include wind power and used to analyze its interaction with an existing CCGT model. A Model Predictive Controller (MPC) is designed to optimize CCGT operation using three control inputs, governor control, temperature control, and inlet guide vane angle. The MPC is tested with two different objective functions. The first minimizes frequency deviation from nominal value, while the second extends this formulation to also include exhaust gas temperature tracking.

## Model




Flowchart of the hybrid energy system including the MPC

## Conclusion

Simulation results show that the extended MPC formulation achieves improved performance by maintaining frequency stability while simultaneously regulating thermal behavior. The MPC demonstrates improved flexibility and dynamic response under variable operating conditions.

## Determinants of the Highest Capacity Prices in the Frequency Containment Reserve for Normal Operation in Sweden: An Econometric Analysis

Student: **Julie Helen Evenstuen**
Supervisor: **Gro Klæboe**
Contact: **Ellen Krohn Åsgård**
Collaboration with: **Aneo AS**

### Problem description

Given the increasing importance of ancillary service markets and the evolving dynamics of the Nordic power system, there is a pressing need better to understand the formation of the highest FCR prices. This thesis examines the driving forces behind the highest prices of the FCR market in the Nordic region, with a primary focus on Sweden.

*What are the key determinants of the highest observed prices in the Frequency Containment Reserve - Normal (FCR-N) markets in the Nordic region, particularly in Sweden, and how do interactions among constraints, spot market prices, hydrological conditions, seasonal variability and the production mix contribute to these prices*

### The task

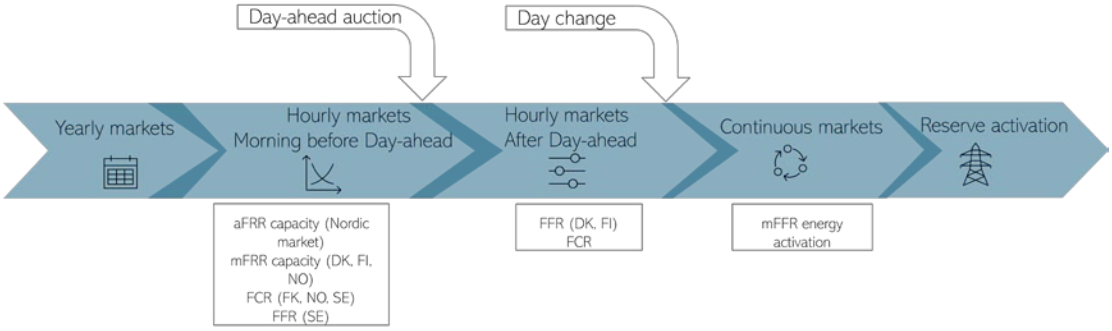
The aim of this research is to identify the factors most strongly associated with high prices for FCR-N during different seasons and across years. The study seeks to provide valuable insights for market participants and policymakers on mitigating reserve cost volatility and anticipating the impact of periods of increased system stress on prices.

The thesis defines four main research areas:

1. The Influence of Spot Market Prices on High FCR-N Prices
2. The impact of Hydrological Constraints on High FCR-N Prices
3. The role of Hydro Production in High FCR-N Prices
4. The role of Production Mix in High FCR-N Prices

### Measurements and Results

The Nordic balancing market is organised into distinct segments to meet both system needs and grid stability requirements in real time. Figure 1 provides an overview of this market structure, illustrating the different layers of procurement and their interaction with system operations. This framework contextualizes the subsequent analysis of high-price dynamics in the FCR-N market.



To empirically investigate the research areas, the analysis has mapped the distribution of high-price events before linking them to explanatory factors. High-price events are defined as the top 10% of hourly FCR-N prices within each calendar year. Figure 2 displays a heatmap of weekly FCR-N price peaks across the Swedish bidding zones (SE1–SE4). The visualisation highlights clear spatial and temporal clustering, suggesting that high price outcomes are systematically linked to seasonal patterns and hydrological variability rather than occurring randomly.

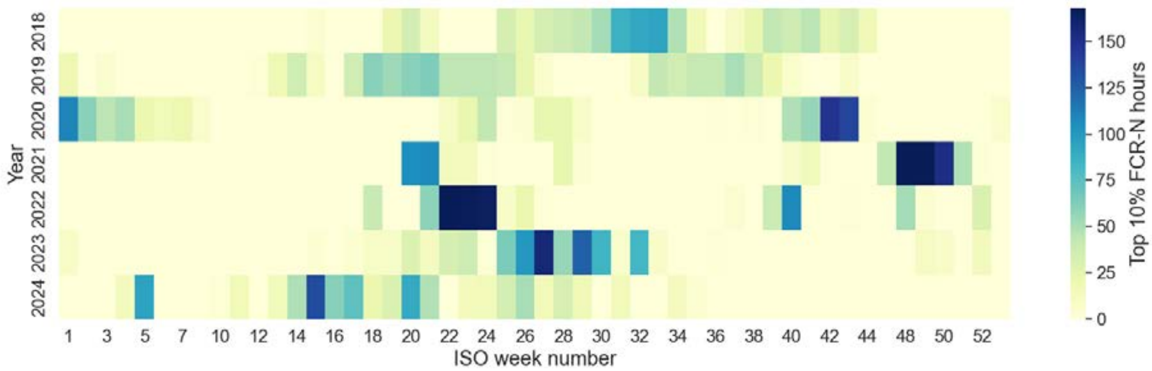
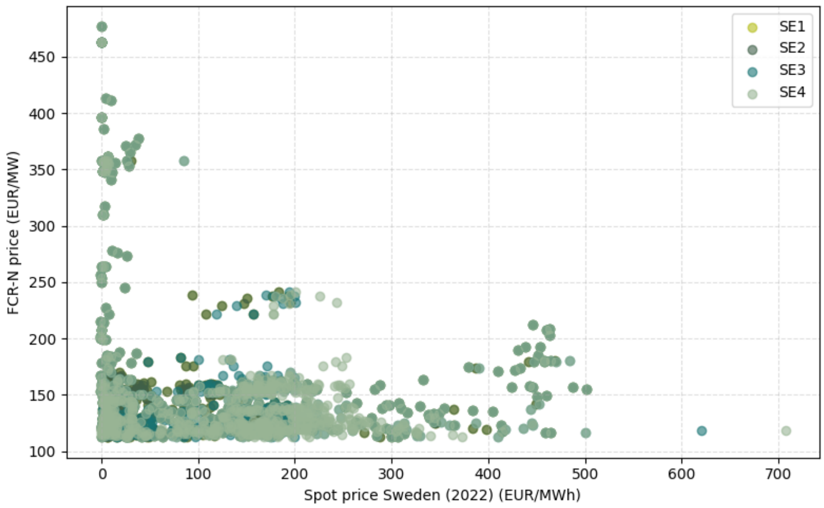



Figure 3 illustrates one of the empirical results, showing the relationship between the top 10% of FCR-N prices and hourly day-ahead spot prices across the four Swedish bidding zones (SE1–SE4) in 2022.




## Conclusion

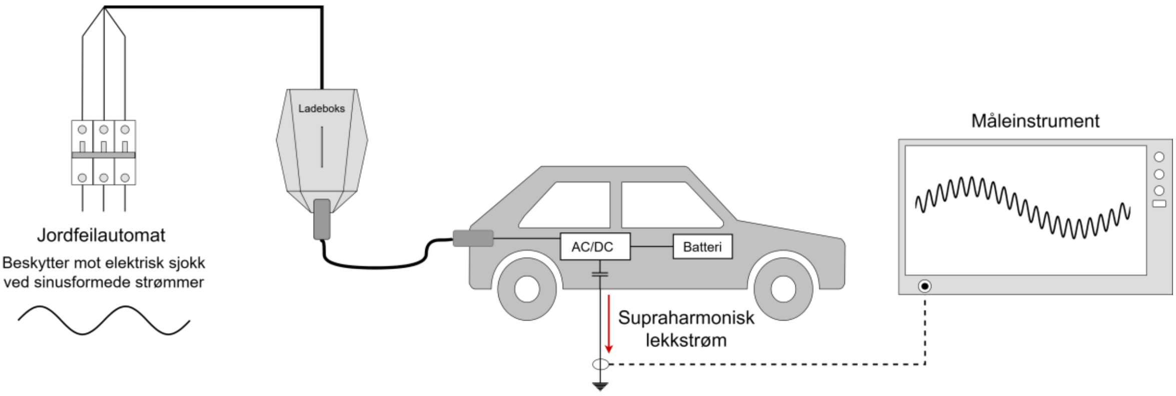
The findings in the thesis demonstrate that the highest FCR-N prices are not driven by a single factor but by the interaction of spot prices, seasonal variability, and hydrological conditions. The results contribute to a more nuanced understanding of high price formation in ancillary service markets and provide insights relevant for market design, risk management, and energy policy.

# Supraharmonisk lekkstrøm fra elbil

Student: **Simon Kjøpstad Finnøy**
Student: **Simen Rudsengen Hansen**
Veileder: **Eilif Hugo Hansen**

## Problemstilling

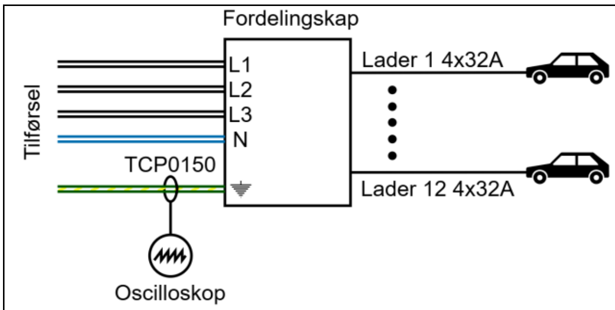
Under lading av elbiler kan det oppstå høyfrekvente strømmer til jord i frekvensområdet 2 kHz til 150 kHz. Disse strømmene omtales som supraharmoniske lekkstrømmer. Ladeinstallasjoner er utstyrt med jordfeilvern for å beskytte mot elektrisk sjokk ved å detektere om det går en strøm til jord som overstiger en gitt terskelverdi. Dersom jordfeilvernet utsettes for strømmer det ikke er konstruert for – som supraharmoniske lekkstrømmer – kan dets funksjon svekkes. Dette betyr at beskyttelse mot elektrisk sjokk ikke lenger kan garanteres.




***Hvilke supraharmoniske lekkstrømmer kan oppstå under lading av elbil, og hvordan kan disse påvirke jordfeilverns evne til å beskytte mot elektrisk sjokk?***

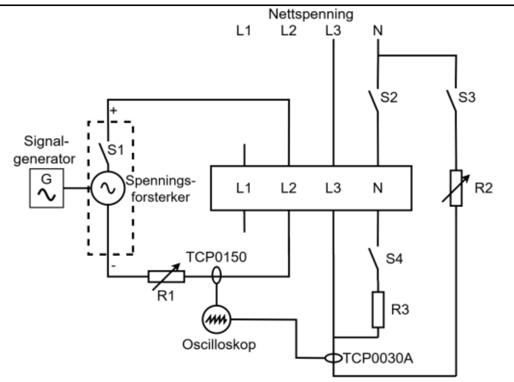
## Metode

Målt ett ladeanlegg ved NTNU



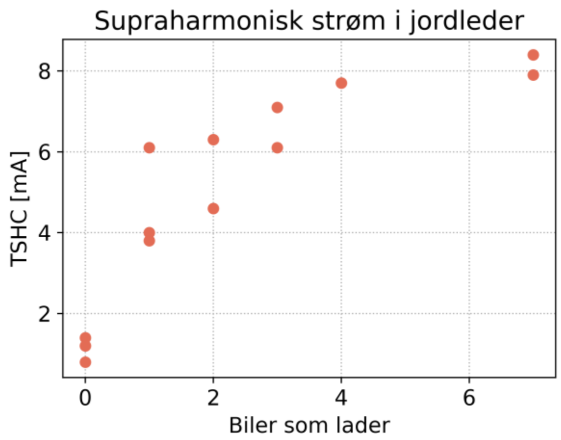

- Hvor stor kan den supraharmoniske lekkstrømmen bli?
- Hvilke frekvenser kan strømmen bestå av?
- Måledata ble innhentet over en uke.

Testet 5 ulike jordfeilvern

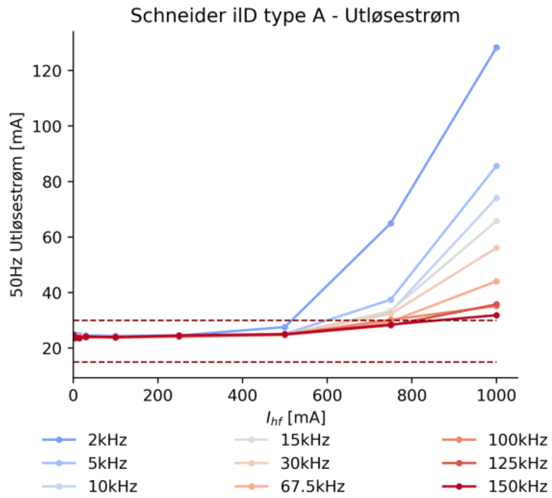


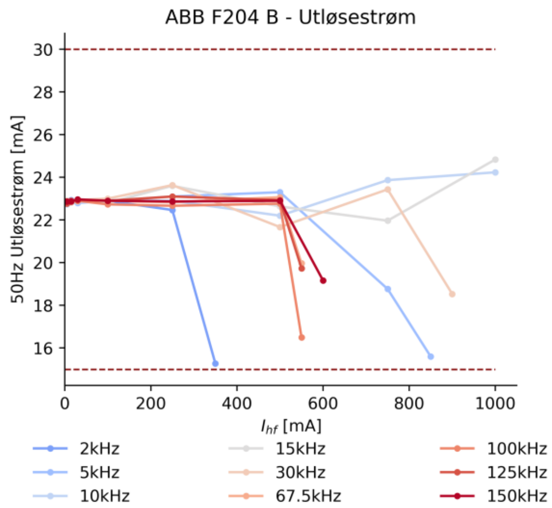

- Hvordan påvirker supraharmoniske strømmer utløserstrømmen og utkoblingstiden?
- Det er utført over 3000 enkeltmålinger.

## Måleresultat




- Påvist 10mA supraharmonisk lekkstrøm ved NTNU.
- Det er estimert denne kan bli 250mA i store ladeanlegg.
- Påvist strømtopper ved 16kHz og 67,5kHz, men det forventes at lekkstrømmer kan oppstå mellom 10kHz og 120kHz.




- Et jordfeilvern type A fikk økt 50Hz utløsestrøm når den supraharmoniske lekkstrømmen ble over 500mA. Påvirkningen ble derimot redusert med økende frekvens
- Utkoblingstiden til type A vernet ble ikke påvirket, før vernet sluttet å koble ut den simulerte jordstrømmen.
- Type B vernet og det innebygde vernet i en Easee-lader fikk redusert utløserstrøm og utkoblingstid.

## Konklusjon

Det ble påvist at jordfeilvern type A kan få økt 50Hz utløsestrøm som overstiger 30mA og medføre fare for elektrisk sjokk. Oppgaven har vurdert ulike installasjonsmetoder for lading av elektriske kjøretøy hvor jordfeilvern type A kan benyttes. Det er konkludert med at det kun er ved store ladeanlegg lekkstrømmen kan nå nivåer av betydning. Det er imidlertid hverken påvist eller forventet at lekkstrømmen vil bli stor nok til å påvirke jordfeilvern. Utløsestrømmen til jordfeilvern er derimot udefinert for supraharmoniske reststrømmer. Andre jordfeilvern kan derfor være mer følsomme for supraharmoniske lekkstrømmer, noe som gjør det vanskelig å konkludere sikkert. Det er behov for videre forskning for å vurdere om det er nødvendig med strengere krav knyttet til jordfeilvern ved lading av elektriske kjøretøy.

# Modelling the Three-Peak Average Capacity-Based Grid Tariff for Residential End-Users

Students: **Guro Kvilten and Jeanette Fjeldstad**
Supervisor: **Kasper Emil Thorvaldsen**
Contact: gurokvilten@gmail.com, fjeanette@live.com

**Problem description**

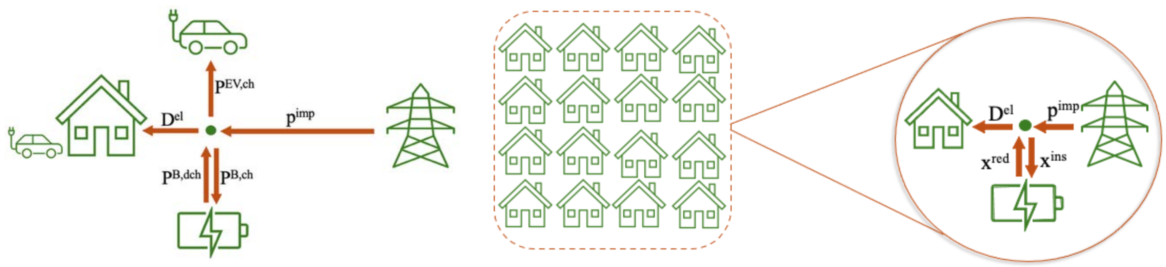
To accommodate rising electricity demand and integrate renewable energy sources, grid operators must manage peak loads effectively. Traditional flat-rate grid tariffs do not incentivize users to alter consumption patterns, contributing to inefficient grid usage and higher infrastructure costs. In response, capacity-based tariffs, such as the newly introduced three-peak average model in Norway, aim to shift consumption by charging based on peak usage. However, this new tariff structure is unexplored in literature, and have not been analysed in terms of its effectiveness or impact on residential consumers.

**The task**

This thesis develops a deterministic optimization model to simulate residential electricity consumption under the three-peak average demand charge tariff. The objectives include assessing the tariff's potential to encourage peak shaving, improve grid efficiency, and influence household behaviour. The model is applied to both single and aggregated household scenarios, evaluating how flexible technologies (e.g., batteries and EVs) interact with the tariff structure.

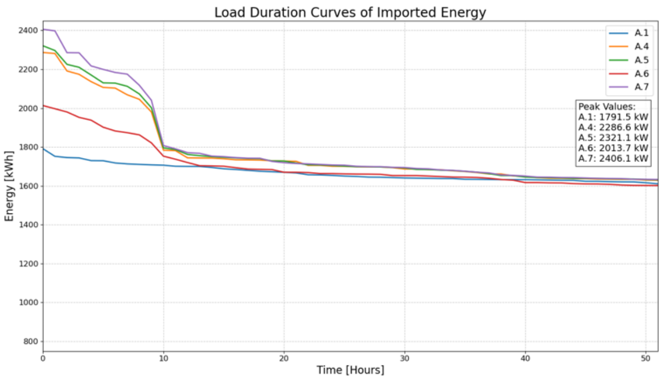
**Model/ measurements**

The optimization model is formulated using Mixed Integer Linear Programming (MILP) and implemented in Python with the Gurobi solver. Real-world data, including hourly electricity prices, consumption profiles, and technical specifications for batteries and EVs, is used. Two case perspectives are studied: (1) a single residential household and (2) an aggregation of households. Simulations are run for different configurations of flexibility and consumption patterns to evaluate operational and economic outcomes.



### Calculation

The model identifies the three highest daily peak import hours for each month and calculates the grid cost based on their average. Simulations analyse how different user flexibility resources (battery storage, EV charging schedules) impact peak demand, total cost, and consumption profiles. Additional configurations test variations in flexibility availability, pricing, and system constraints.




The results show that DCTs can be effectively utilised to reduce the peak demand and lower electricity costs in combination with flexibility. For the single household, peak imports under the three different DCTs were reduced by 13-42%, and total monthly costs by 3–6% compared to the non-flexible base case. For aggregated users, the model achieved peak reductions of 5-16% compared to flexible end-users not considering costs of DCT. Load shifting to off-peak hours was observed, increasing nighttime peaks if not properly managed. Aggregated consumers adjust their consumption differently due to diversity in demand patterns and flexibility resources.

### Conclusion

The three-peak average grid tariff has potential to reduce peak loads and improve grid utilization when combined with consumer-side flexibility. The analysis also showed limitations in the current Norwegian demand charge tariff. The most apparent being that the three-peak stepwise demand charge does not provide any incentive for peak reduction within the respective step. Thus, consumers who are not able to reduce their peaks sufficiently, are rather inclined to increase their hourly consumption to take advantage of lower spot-prices

## Breakdown and partial discharges in an triple junction with applied bipolar and unipolar sinusoidal voltages

Student: **Chris-Andre Framvik**
Supervisor: **Frank Mauseth**
Contact: **Frank Mauseth**
Collaboration with: **NTNU**

**Problem description**
Investigate partial discharges and breakdown voltages for a triple junction in technical air.

**The task**
In this report, is a test object consisting of two electrodes with an insulation shaft passing through them placed inside a pressure vessel filled with technical air, with a gap distance of 25 mm investigated for partial discharges(PD) and breakdown(BD) voltage. Three different 50 Hz sinus voltages was applied: bipolar sinus voltage, positive unipolar sinus voltage and negative unipolar sinus voltage. The unipolar voltages was archived by using a diode to cut of one of the half-periods in the sinus wave. The three different absolute pressures investigated was: 0.7 bar, 1.0 bar, 1.3 bar. Streamer criteria simulation was performed in COMSOl Multiphysics to estimate the BD voltages, because its assumed that streamers and BD would occur around the same voltage duo to the small gap distance.

**Model/ measurements**
For detecting the PD and BD, both optical detection and current pulse detection was applied. For optical detection, an photomultiplier tube(PMT) connected to a 2 300 V external DC source was applied. Then for current pulse detection, an Omicron MPD600 in combination with a coupling capacitor and Quadripole was applied

**Conclusion**
For the statistically found 2 % chance for breakdown voltages(V02) from the BD results, showed that the average critical electron number(K(x)) for bipolar was 5.80, then for unipolar voltages was the average 9.14. The low critical electron number for bipolar was explained by surface charges generated by Townsend discharges in one half-period, then at the second half-period when the polarity switch, the surface charge enhance and altering the electric field, resulting in low BD voltages for the applied bipolar voltage.
It was only observed PD activity for the bipolar voltage, this was also explained by surface charges altering the electric field distribution resulting in a more inhomogeneous field that allows PD to occur before breakdown. A trend of more and longer duration of PD at lower pressure was observed. Where the longest duration was almost 4 minutes(11 780 periods) at 0.7 bar, then for 1.3 bar was the longest duration almost 5 seconds(235 periods). This was explained by the increase in the electronegative effect of the gas, when increasing the pressure

# Life Cycle Assessment of Refrigerators: Evaluating the Environmental Trade-offs of Smart Feature Integration

Student: **Elise Gjester**
Supervisor: **Alexey Matveev**
Co-supervisor: **Kim Rainer Mattson**
Contact: gjesterelise@gmail.com

**Problem description**

There is an urgent need to address sustainability challenges associated with the life cycle of electric and electronic equipment (EEE). The corresponding waste streams (WEEE) are considered one of the fastest growing, parallely as waste management methods remain inefficient. In particular, valuable and scarce metals are lost. This thesis aims to investigate environmental impacts in terms of climate change and metal depletion, through a comparative life cycle assessment (LCA) of one specific EEE-device; the refrigerator. Moreover, it analyses the trend of smart feature integration, which requires greater amounts of metal-intense electric and electronic components. Through comparison of a Smart firdge and a Conventional fridge, the projects seeks to contribute to the academic discussions of EEE sustainability.

**The task**

The analysis was conducted using the LCA methodology, in alignment with ISO Standards. LCA requires inventory modelling of the product system(s) in question, which in this case included data collection on refrigerator products with and without smart features. Further, the impact assessment was conducted using the software Activity Browser from Brightway. The LCA provided results from a contribution analysis and a Monte Carlo uncertainty analysis. Moreover, sensitivity was tested for two parameters. In addition, the literature review followed an iterative approach.

**Model/ measurements**

The model of the refrigerator product system can be vizualised as a flowchart (Figure 1):

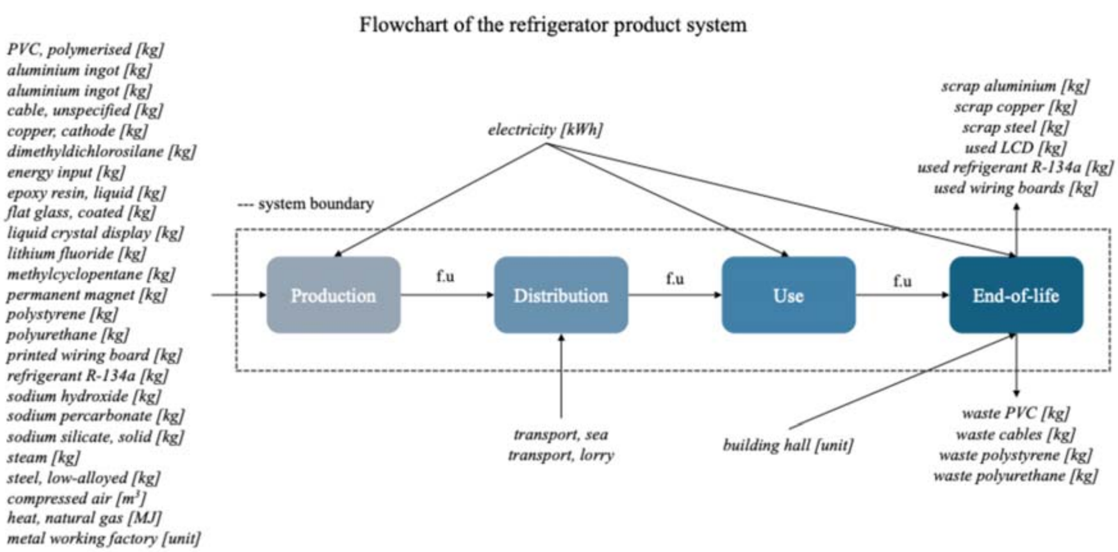



**Figure 1: Flowchart of the refrigerator product system.**

The flowchart represents the task of inventory mapping, investigating life cycle phases and their respective inputs and outputs. By quantifying this model, through the collection of secondary sources, it could be modelled in Activity Browser and used for the impact assessment of climate change and metal depletion impacts.

**Calculation**
The results found the Smart fridge model to induce greater GWP (climate change) and MDP (metal depletion) impacts, by 5.6% and 4.9%. For climate change, electricity use during use-phase dominates GWP results. If clean energy is utilized, significance shifts towards production and end-of-life phase. For MDP, production is the most significant phase. Further, EEC components are identified as both energy-intensive and metal depleting.

**Conclusion**
Three main conclusions are found:

1. There must be stringent requirements to innovation of smart products, they have to; demonstrate environmental sustainability benefits, comply with eco-design criteria, and demote obsolescence.
2. Long-term perspectives must be the basis of product development, especially due to the criticality of metal resource scarcity.
3. Value-based decisions must underpin the developments, as sufficiency and transparency will be detrimental to ensure sustainability of EEE streams.

## Solar production, flexibility and storage at Brunvoll AS

Student: **Eirik Gløersen**
Supervisor: **Steve Völler**
Contact: Halvard Brekken, Erlend Fjørstad, Eivind Stormyr, Ole Andre Huse (Brunvoll)
Collaboration with: **Brunvoll AS**

**Problem description**
Global electricity demand is rising faster than overall energy efficiency improvements. Brunvoll AS installed a 1.653 MWp rooftop PV plant in 2024 (forecast 1.37 GWh/year) to cut emissions and demonstrate sustainability leadership, but its real-world performance and economic impact remained unverified

**The task**

The task was threefold: to verify the plant's first-year generation, cost and $CO_2$ effects, to assess how adding an AC-coupled 1 MWh / 250 kW battery at each main switchboard affects energy costs, self-consumption (SC) and self-sufficiency (SS), and to compare perfect-information scheduling with a more realistic stochastic receding-horizon controller (RHC).

**Model/ measurements**
Hourly PV production and facility load were recorded from April 2024 to March 2025. A Pyomo optimisation model was first validated for PV-only operation and then extended with a 1 MWh / 250 kW battery energy-storage system (BESS) at each board. Four simulation cases were analysed: Case 0—the measured PV-only baseline, Case 1—the validated PV-only model, Case 2—the PV-BESS system operated with perfect information and Case 3—the same system controlled by a stochastic receding-horizon controller using 48-hour forecasts with perfect information and with the remaining of the year stochastic.

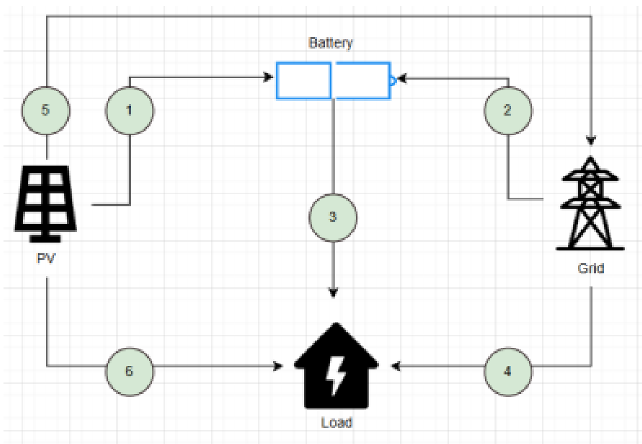



**Figure 1: Suggested battery system at brunvoll with the different power flows**

## Calculation

| Metric | Forecast | Measured (Case 0) | +BESS, PI (Case 2) | +BESS, RHC (Case 3) |
|---|---|---|---|---|
| PV generation | 1.37 GWh | **1.12 GWh** (-18 %) | – | – |
| Self-consumption | 83.1 % | **74.56 %** | **83 %** | 80 % |
| Self-sufficiency | 23.6 % | **16.40 %** | **18.4 %** | 17.7 % |
| $CO_2$ avoided | 416 t (2021 factor) | **466 t (2023 factor)** | unchanged* | unchanged* |
| Grid-electricity cost | baseline | **-68 kNOK** vs forecast | **-10.9 %** / -360 kNOK | **-6.6 %** (~60 % of PI saving) |

## Conclusion

This master thesis has investigated the performance of the PV plant at Brunvoll for its first production year, and how implementing a battery for each of the main switchboards with the PV plant affects the system cost, self-sufficiency and self-consumption. By combining measured operation with optimization studies, the thesis therefore provides a complete investigation of performance, cost, $CO_2$ reduction, self-consumption and self-sufficiency during the first year of operation.

The PV plant underperformed compared to the predictions, generating 18 % less than the forecast made by the installer Bluetec AS. The main reason for the deviation was the reduced solar irradiation for the year analyzed. Nevertheless, the total reduction of $CO_2$ was 466 tonnes and the export of PV energy reduced the electricity cost by 68 kNOK. The plant supplied on-site load with a self-consumption of 74.56 % and reached a self-sufficiency of 16.40 % in its first year of operation, confirming that even a below-forecast PV year delivers considerable environmental and economic value.

Implementing a 1 MWh / 250 kW AC-coupled BESS for each of the main switchboards reduced annual cost by 10.9 % with perfect-information forecast and 6.6 % with receding-horizon control, resulting in RHC obtaining 60.5 % of the cost reduction of perfect information. Self-consumption increased by 6.6 percentage points to 83 %, and self-sufficiency increased by 1.5 percentage points to 18.4 % compared to the results of the optimization code without battery. These numbers show that battery storage contributes to both cost reduction and sustainability metrics.

The self-consumption and self-sufficiency are similar for PI and RHC, mainly since RHC uses more PV energy directly to load and buys more energy directly from the grid, while perfect information has increased charging operation, reducing the peak-consumption hours through discharge obtained from grid charging. This means that the total power bought from the grid is similar with and without uncertainty. However, PI uses its advantage of perfect foresight to better utilize grid and PV energy, saving more energy for later to reduce consumption peaks. Brunvoll should evaluate the hours of usage of the machines, especially high-load machines, during peak spot-price and consumption hours. Further, Brunvoll should consider shifting non-critical machinery consumption to hours of high PV generation.

Future work should include implementing degradation-aware modelling of the battery, upgrading data granularity to 15-minute intervals, and full economic and life-cycle analyses for realistic assessments of BESS feasibility. Additionally, it should include improved scenario creation, multi-service stacking and evaluate second-life battery modules. Lastly, it should include realistic grid constraints and investigate shared peak-power considerations to close the gap between simulations and real-world operation. The points addressed in future work will be important to close the gap between simulations and real-world operation.

# Model Predictive Control

Student: **Gondra, Jon**

Supervisor: **Nilsen, Roy**

### Problem description

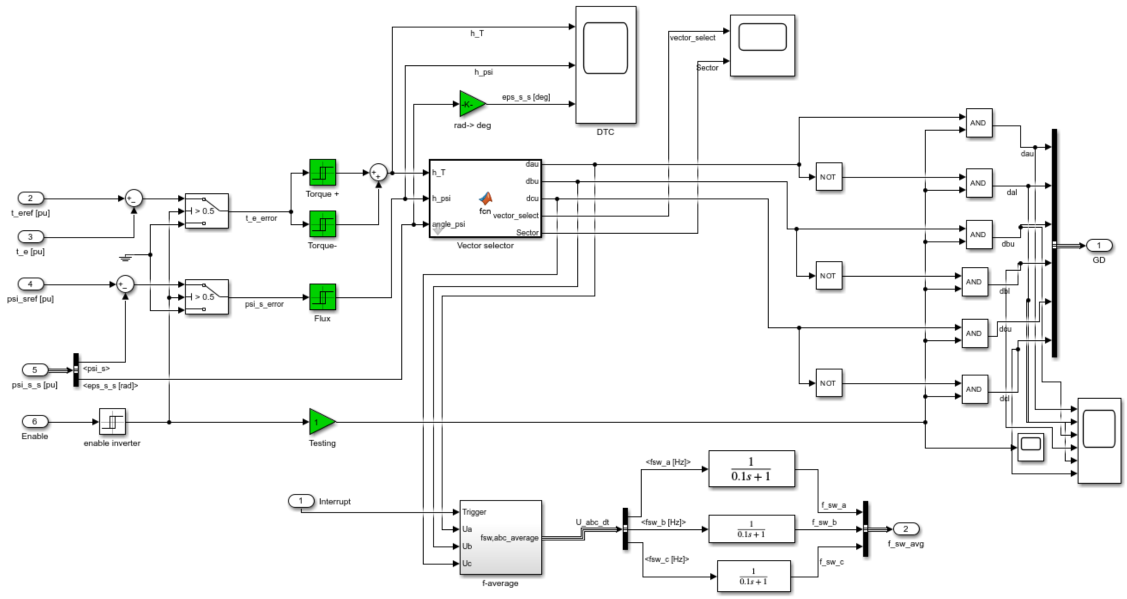
This thesis presents a comparative analysis of torque control techniques where classical PI(D)s and PWM control methods based inner current controllers are implemented for electric motors (FOC). In these cases, sampling frequency of the controller is usually equal or twice the frequency of the triangular wave of PWM modulator and the switching frequency is fixed. If an improved bandwidth of the control loop is required, at least two options exist; use other controllers than PI or implement controller where the sampling frequency of the controller and the average switching frequency can differ. Therefore, other additional control methods should be analysed: Direct Torque Control (DTC) with hysteresis controllers and Model Predictive Torque Control (MPTC) with Finite States (FS-MPTC).

### The task

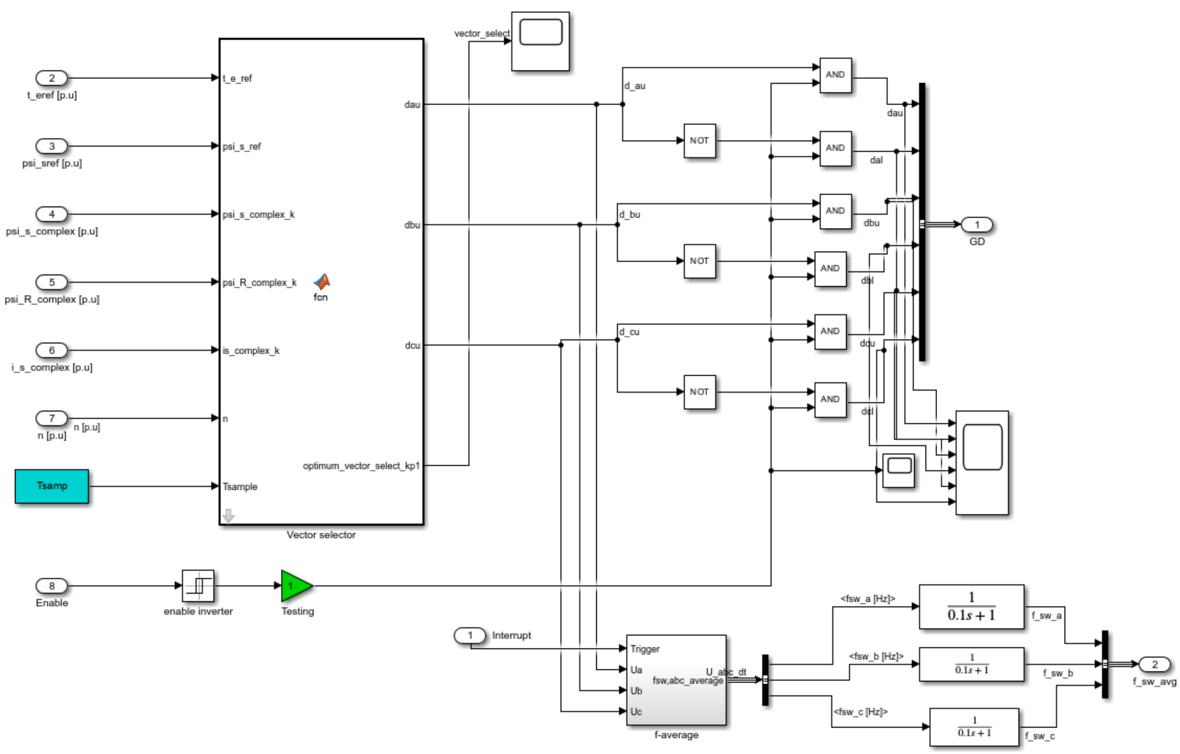
MATLAB-Simulink is utilised to validate theoretical findings, providing quantitative comparisons of the methods under various operating conditions for switching frequency analysis. Moreover, the variable switching frequency for the direct control strategies (DTC and MPTC) has been analysed in two different speed conditions to prove that the sampling frequency and the switching frequency can differ, maintaining at the same time the stability of the controlled system, compared with the classical Field Oriented Control (FOC). Finally, the performance during steady state conditions is evaluated in terms of torque, flux and current ripple, and voltage switching pattern, additionally, an analysis of torque dynamic response is executed for the three methods.

### Model/ measurements

DTC and MPTC are being modelled using MATLAB-Simulink. Additionally, a classical Field Oriented Control (FOC) MATLAB-Simulink model is used as a baseline to compare it with the previous models.



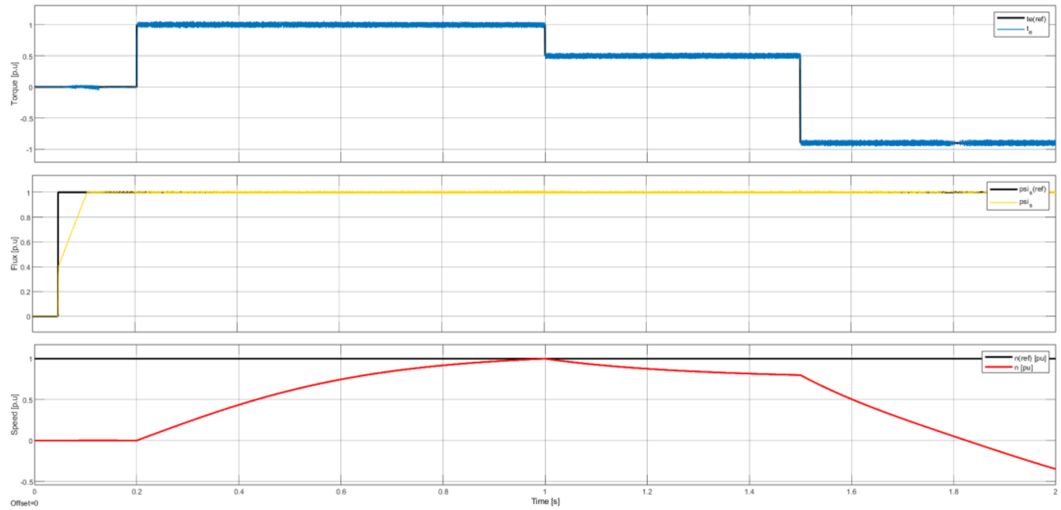

*DTC control scheme. MATLAB-Simulink*



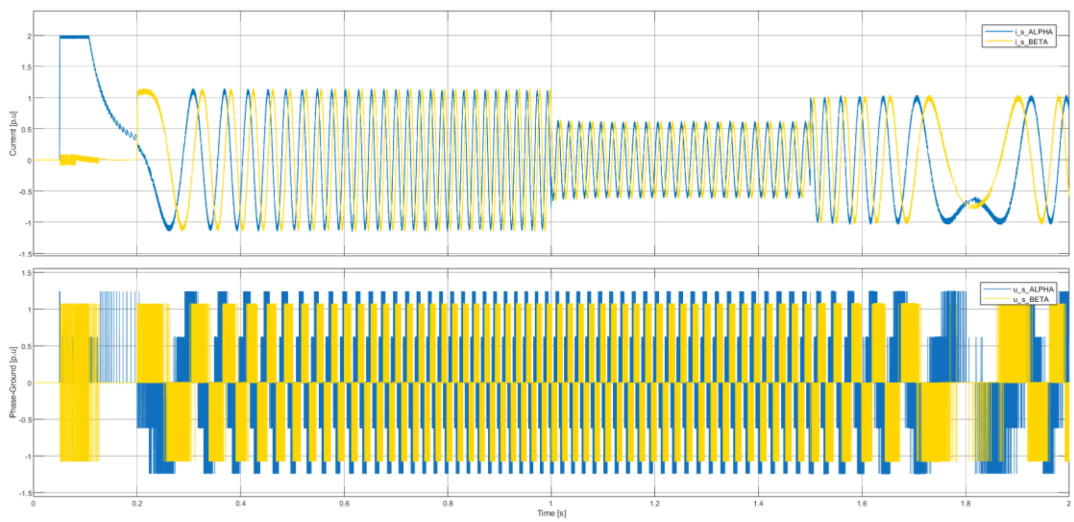

*MPTC control scheme. MATLAB-Simulink*

**Calculation**

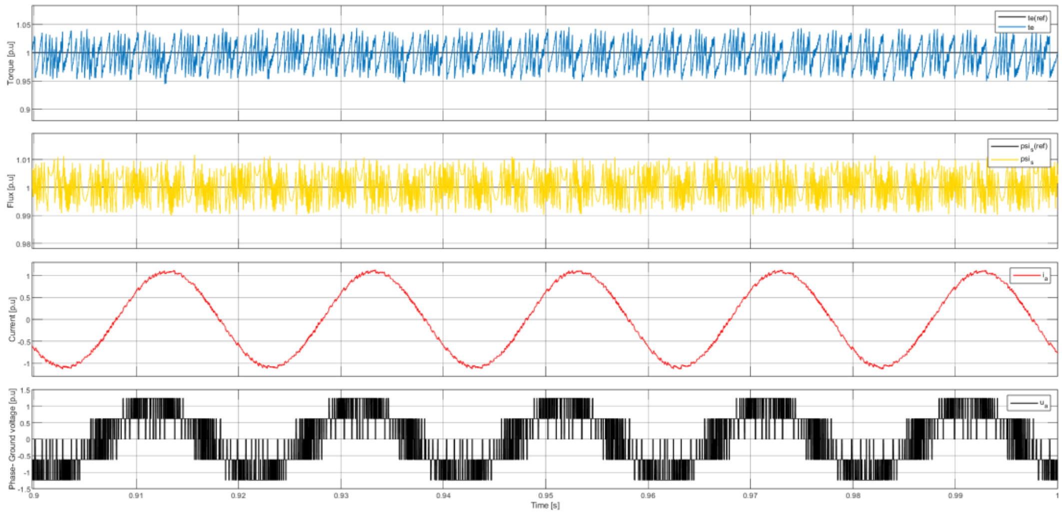
In this calculations results onty the MPTC is shown to prevent saturation with the high number of graphics.




*Dynamic Analysis of Model Predictive Torque Control*




*Dynamic Analysis of Model Predictive Torque Control*




*Steady state analysis of Model Predictive Torque Control*

**Conclusion**

In this thesis, the variable switching frequency pattern has been analysed for the direct control strategies (DTC and MPTC) in two different speed conditions to prove that the sampling frequency and the switching frequency can differ, maintaining at the same time the stability of the controlled system. Hence, it has also been proven that the control bandwidth has been improved compared with FOC, where the sampling frequency must be equal or twice the switching frequency, fixed by the PWM modulator, to be in the control bandwidth limits. In DTC and MPTC cases, instead, there is almost no limitation of the controller bandwidth.

The overall performance has been verified of the three methods are high and similar considering ripple, transient and steady state aspects. However, MPTC outlines over the rest for the straightforward implementation ought to low conceptual complexity and flexible constrains inclusion in the cost function definition. Furthermore, as it has been proven over the analysis conducted in this thesis, the predictive capability of the control strategy combines, as a result, a rapid dynamic response and high performance, making it suitable, for example, for electric drives applied for EVs.

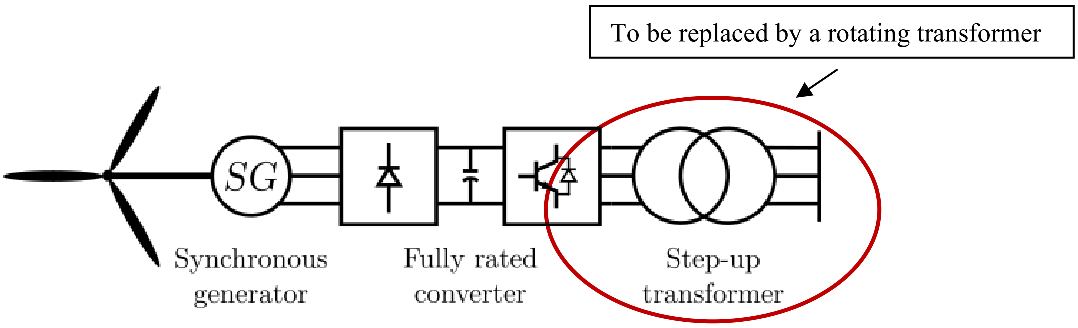
Some of the drawbacks, in real life applications, due to the computational effort required for this method, would be if the computation times exceed the sampling time. This would compromise the performance and the stability of the MPTC and thus, it is an essential parameter to consider when this method is implemented.

# Exploring a Rotating Transformer Concept for Wind Turbines

Student: Erlend Redi Haga
Supervisor: Olimpo Anaya-Lara

**Problem description**

Most renewable power generation lowers the frequency stability of the power grid by reducing the system inertia. This thesis investigates a rotating transformer, which is intended to provide frequency support when integrated with wind turbines. The rotating transformer could replace the conventional step-up transformer of the wind turbine.

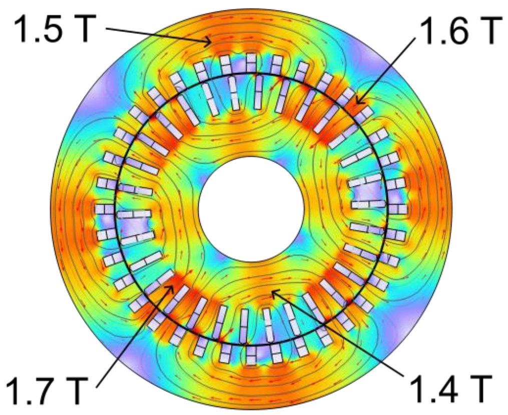


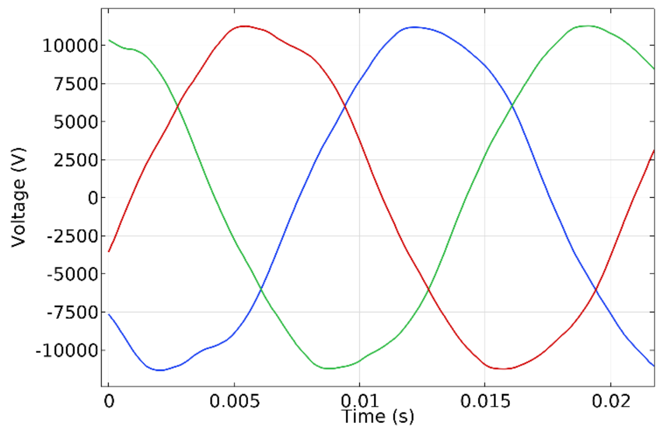

**The task**

To deepen the understanding of the rotating transformer on a component level, this thesis proposes a sizing procedure for a 2 MW rotating transformer, validates the design through FEM simulations and estimates the reactive power consumption of the machine over a speed range of ±5 Hz, for different rates of active power flow.

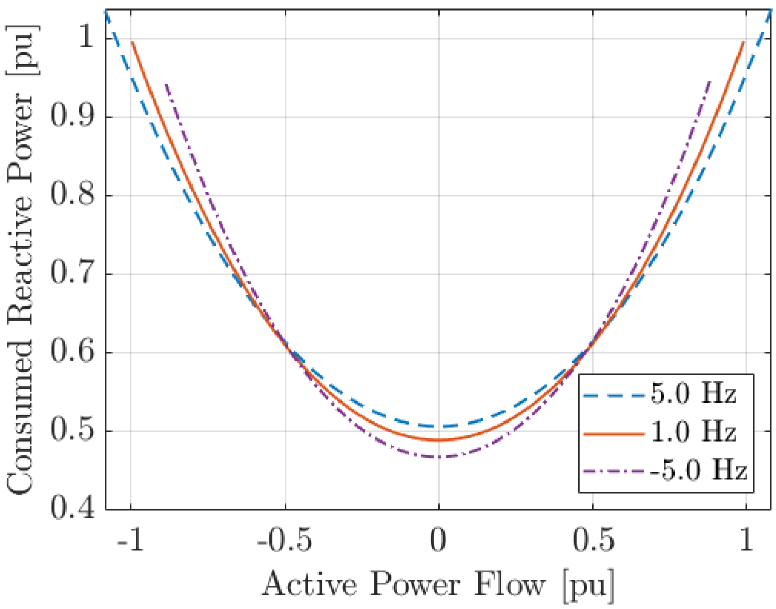
**Model/ measurements**

COMSOL Multiphysics has been used to perform time-domain FEM simulations of the designed machine, to verify that the performance is sufficiently close to the design specifications. To analyze the reactive power, winding inductances have been extracted from the FEM model and an electrical model in the synchronous reference frame has been used.



**Calculation**
The calculated reactive power requirements suggest a potential strategy for reducing the reactive power consumption of the rotating transformer during periods of low power production, by rotating the rotor opposite to the stator's magnetic field (negative direction in the plot)




**Conclusion**
The obtained machine dimensions are useful for understanding the physical requirements and stresses the machine imposes on the surrounding components. The estimated reactive power requirements contribute to a deeper understanding of the reactive power behaviour of the machine and enables approximate specification of required compensation equipment. They also showcase a potential strategy for reducing the reactive power consumption of the machine through appropriate control.

## Capacity Credit Assessment for Generation Systems including Wind Considerations

Student: **Aleksander Halstensen**
Supervisor: **Vijay Venu Vadlamudi**

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

## Co-simulation for Wind Turbine and Power System Dynamics

Student: **Hermansen, Lars Andreas Berg**
Supervisor: **Føyen, Sjur**

**Abstract**
This cover essay, together with the article \textit{"DynaWind: Co-Simulation for Wind Turbine and Power System Dynamics"}, constitutes the master's thesis in Energy and Environment at NTNU Trondheim. The work has resulted in the development of a simulation tool for analyzing interactions between wind turbines and dynamic power grids. The framework combines the high-fidelity wind turbine simulator OpenFAST with the RMS-based power system simulator TOPS. The electrical system of the wind turbine has been developed as part of this thesis and includes a permanent magnet synchronous machine (PMSM), a DC-link, and associated control systems. Together, this forms a flexible simulation platform that enables two-way coupling between mechanical and electrical domains, thereby capturing dynamic interactions between the wind turbine and the grid. The simulation tool is open-source and available on GitHub.

The cover essay differs from a traditional master's thesis by focusing primarily on documentation of the model structure, implementation, and further work. It is intended as a supplement to the article, and therefore includes both reflections on the working process and a detailed description of the software. In addition, it presents an extended section on suggested further developments, supporting the ambition to facilitate continued development of the tool.

The article is written in IEEE format with the aim of publication. It describes the structure, control schemes, and functionality of the simulation tool. Two simulation scenarios are presented to demonstrate the model's behavior and applicability: one curtailment event and one grid-side fault. These cases illustrate how the combined model captures interactions between the wind turbine and power grid under transient conditions.

## Automatic machine identification for PMSM drive with sine wave filter

**Student: Trym Kloster Hjellbakk**
**Supervisor: Roy Nilsen**
**Collaboration with: Siemens**
**Energy**

Permanent synchronous machines have gained widespread adoption in modern industrial applications due to their efficiency compactness and performance. Accurate parameter knowledge is vital for taking fully advantage of advanced control strategies such as vector oriented control. The advantage of having an automatic procedure for identification of such parameters during standstill through the variable frequency drive itself is therefore highly desirable from an industrial standpoint. This reduces commissioning time and reliance on manufacture data. However complexity arises when the drive has an embedded sine wave filter. These filters reduces noise and ensures smooth stator current at the cost of increasing the system complexity. This poses a challenge to such automatic procedures as the system order is increased. This is also reflected in the lack of literature.

This thesis addresses this gap by implementing a self contained automatic procedure for estimating the stator resistance ($R_s$) and synchronous inductance ($L_s$) at standstill for a surface mounted PMSM drive equipped with a sine wave filter. Due to time constraints the procedure for identifying the remaining electrical parameters $\Psi_m$and $L_q$ (IPMSM) have not been implemented. The implementation is based on review of available literature and the selection of a suitable method that can be adopted. The chosen method is then programmed into the drive software to be tested on the physical drive in a laboratory experiment.

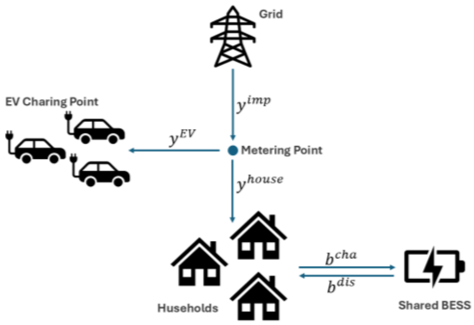
The conclusion drawn from the experiment shows that the automatic procedure can reliably estimate the given parameters with a deviation of $6\%$ and $8\%$ with respect to the rated resistance and inductance. The test procedure does not require user intervention or extra equipment other than the standard drive equipment. Further improvements include procedure for initial motor alignment as well as extending the routine to also account for $\Psi_m$ and $L_q$.

# Temporal Redistribution as a Strategy to Mitigate Rebound Effects Due to Demand Response Events

Student: **Othilie Rørlien Kvamme and Johannes Skotte Hope**
Supervisor: **Kasper Emil Thorvaldsen**
Contact: kasper.e.thorvaldsen@ntnu.no

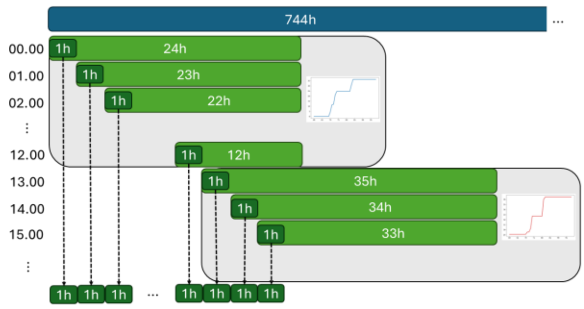
## Problem description

The growing share of Variable Renewable Energy Sources increases the need for demand-side management to balance the grid by, for example, load shifting. Emerging markets enable cooperation between Distribution System Operators (DSOs) and end users to reduce power consumption upon request from the DSO to relieve grid strain. However, the reactivation of the curtailed load can result in a surge in consumption. This can introduce additional grid challenges in the form of rebound effects.



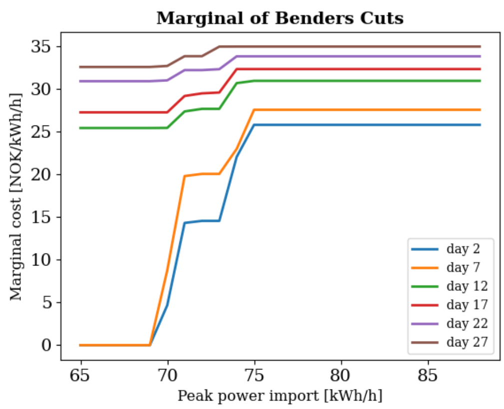

## The task

A situation where the DSO requests load reduction from an Energy Community (EC) for a given hour is investigated. The EC has 25 households, a Battery Energy Storage System (BESS) and smart Electric Vehicle (EV) charging that enable flexible load shifting to various predefined periods, depending on the case. This thesis explores a controlled load shifting strategy to reduce potential rebound effects and operational costs.



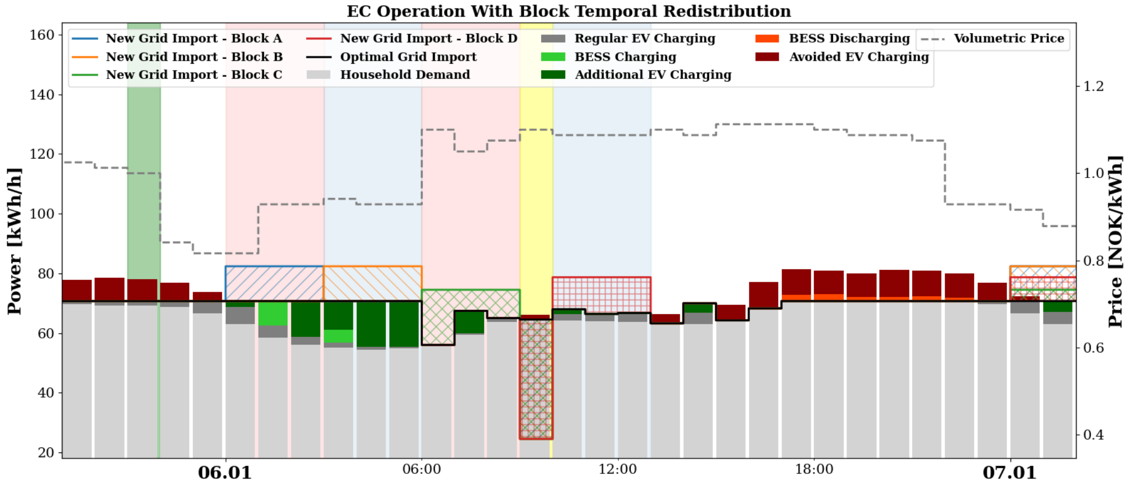

## Model

Using linear programming in Python – Pyomo, a combined Rolling-Receding Horizon (RRH) and Stochastic Dual Dynamic Programming (SDDP) method is developed. A RRH framework captures the daily revelation of spot prices, while a SDDP algorithm accounts for the long-term consequences of operational decisions. Input data is all sampled from NO3 and includes household demand, EV charging data, spot prices and grid tariffs. The model simulates January 2022.

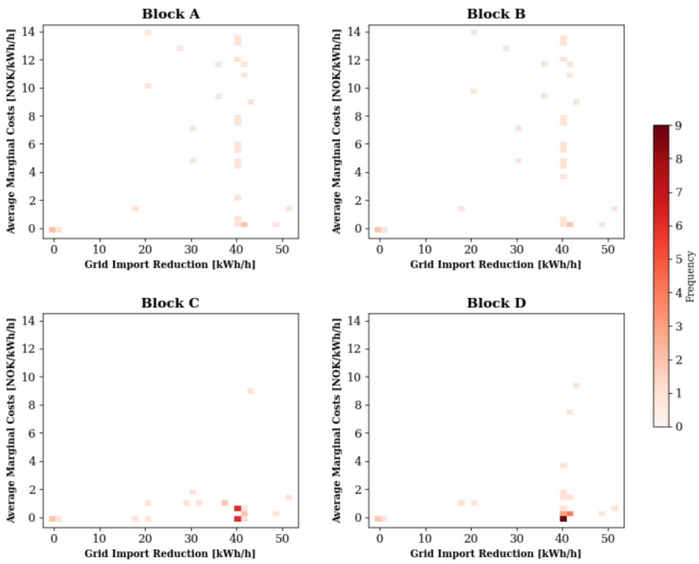



## Calculation

The three cases investigated impose increasingly stricter limits on load shifting, from no restriction to fixed three-hour periods. The request signal is received 12 hours before (green highlight) the restricted hour (yellow highlight). Grid import is reduced stepwise by 1 kWh/h until Energy Not Supplied (ENS) occurs. Marginal and total costs are calculated at each step. The cost of increasing peak power import by 1 kWh/h is 36.48 NOK, matching the variable demand charge. On January 7th (orange line), increasing peak import from 60 to 69 kWh/h has zero marginal cost, as the model anticipates a higher peak later in the month. Beyond 69 kWh/h, costs rise rapidly, reflecting the added demand charge. Raising the peak earlier enables better use of spot price variations, lowering marginal costs. As the month advances, this opportunity declines, causing marginal costs to rise. On January 31st (pink), the marginal cost stabilizes at 36.00 NOK/kWh/h, showing limited economic benefit from increasing peak import late in the month.




When restricting the grid import to predefined three-hour blocks, the grid import is equal for all three hours to keep the increase in demand charge as low as possible. The cost increase caused by having to raise the peak grid import, and therefore also the demand charge, can be mitigated by reducing the cost of the volumetric grid import for the remainder of the month. The significant rebound effects seen indicate that temporal redistribution of three-hour blocks may be a solution that is too limited with respect to grid import management. However, it offers control over when this rebound effect occurs and at what cost. Block A (9 hours before) and Block B (6 hours before) show varying average cost of the grid import reduction. Block C (3 hours before) and Block D (3 hours after) show fewer cases of raised peak grid import. Thus, the blocks placed around the restricted hour provide better alternatives than the other blocks. This is due to the time of day the signal is received. The flexible resources are typically fully charged in the morning, after utilizing the low prices at night, thus handling the restricted hour better. Optimizing for price signals restrict the ability of delivering additional flexibility.




## Conclusion

Including the demand charge in the optimization is superior to excluding it. Benefits include the ability to deliver more flexibility, while operational costs increase by a maximum of 0.79%. Stricter regulation of load shifting improves control over the duration and occurrence of rebound effects, though this comes at the cost of higher total expenses. From the most liberal to the most restrictive case, the marginal cost of providing flexibility ranges from 0.12 - 8.20 NOK/kWh/h. The low marginal cost suggests that the true value of this flexibility lies in its grid benefits. Consequently, the remuneration to the EC should reflect not only the operational costs but also the value provided to the grid.

# Praktisk tilnærming til optimal plassering av PMU i kraftsystemet for full observerbarheit med tilstandsestimering

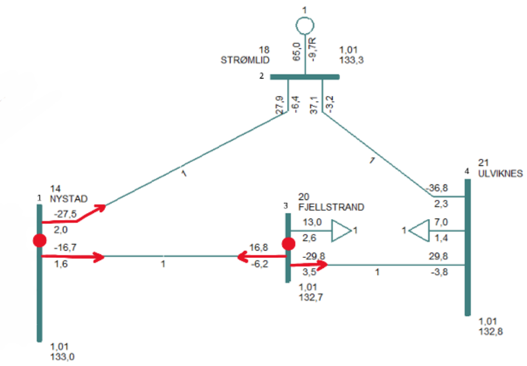
Student: **Ingrid Hovland**
Rettleiar: **Kjetil Uhlen**
Medrettleiar: **Ole Finseth**
I samarbeid med: **Statnett**

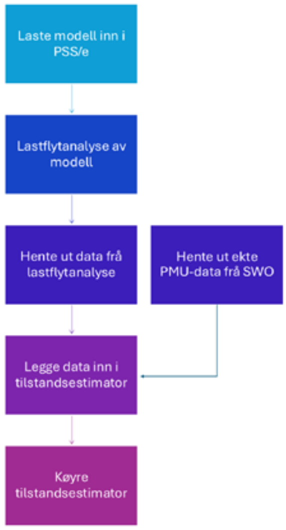
## Problemstilling

Denne masteroppgåva tek for seg optimal plassering av PMU (visarmålar) med fokus på tilstandsestimering av ein liten del av det norske kraftsystemet. Med aukande behov for elektrisk energi vert det bygd ut meir kraft. Dette fører til større fare for ustabilitet i kraftsystemet som igjen skapar eit behov for fleire og meir nøyaktige måleinstrument for å ivareta kontroll. Dette studiet fokuserer på ytterleg plassering av måleinstrument og vurdering av observerbarheit av nettet med dei måleinstrumenta ein har i dag.

## Oppgåva

Tilnærminga til problemstillinga er ein praktisk metode der datagrunnlaget kjem frå ein lastflytanalyse av ein forenkla modell av nettet i Noreg. Datasettet vert nytta i ei lineær tilstandsestimering for å vurdere kvalitet av dei estimerte verdiane og observerbarheita.




## Modell og resultat

Resultata frå tilstandsestimeringa tilseier at plasseringa i det valde utsnittet av nettet er tilstrekkeleg for å løyse systemet, men kvaliteten på estimeringa kan aukast med ei meir avansert matematisk tilnærming og fleire installerte måleinstrument. Det vart og funne at linjeparameter frå Statnett sin database ikkje tilsvarar linjeparametra i den forenkla modellen.

## Konklusjon

Stabil drift, observerbarheit og gode målingar er viktige fokusområder for tida framover. For å sikra desse fokusområda kan det vera nyttig å jobba vidare med plassering av fleire måleinstrument, samt få på plass gode algoritmar og verktøy for å visualisera og agera på dei stabilitetsutfordringane måleinstrumenta kan sjå.

# Investigation of Electromagnetic Emissions in a Motor and Drive System via High Frequency Modeling

Student: **Fredrik Håheim Hvaara**
Supervisor: **Roy Nilsen**
Co-supervisor: **Subhadra Tiwari**
Collaboration with: **Rolls Royce Electrical**

## Problem description

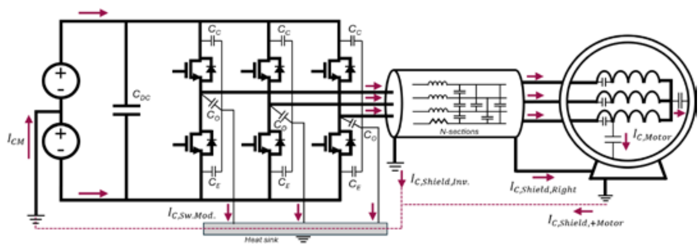
As switching technology is steadily enhancing, and switching characteristics are trending towards faster transients (high dv/dt and di/dt) and higher frequencies, the concern of Electromagnetic Interference (EMI) in power converters and motor drives becomes more relevant. Faster switching reduces switching losses, enabling higher switching frequencies. This enhances the potential for high power density converters and contributes to the downsizing of passive components. Moreover, fast switching characteristics drastically increases the significance of circuitry parasitic elements, and consequently the conducted EMI levels. Due to EMI noise regulations, these issues must be addressed. Among the EMI suppression techniques, passive filters remain one of the most commonly employed methods. Moreover, in switch mode power supplies (SMPS), these take up a considerable portion of the converter's weight and volume. The non-ideal behavior of circuit components at high frequencies will effectively compromise the filter's performance as parasitic elements start to surface.

## The task

The thesis aims to provide a rigorous understanding and fundamental knowledge of EMI sources, high frequency modeling, and EMI suppression techniques. It combines theoretical research with simulation-based analysis. Furthermore, an EMI filter design process is presented – with particular emphasis on the interrelation between input- and output-filters for Differential and Common Mode (DM and CM) mitigation based on the frequency dependent impedance. The filter Insertion Loss (IL) equations are derived for various input-filter topologies including their components' non-ideal nature.

## Model

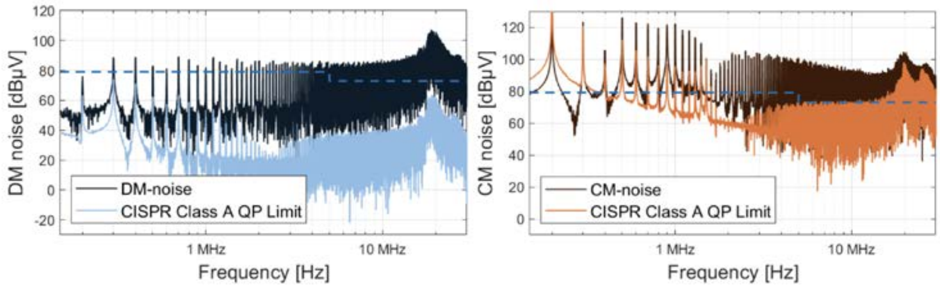
In the simulation software Qspice a detailed time-domain model of a battery driven Various Speed Drive (VSD) with relevant parasitic elements has been derived. The model consists of physical based switching devices (MOSFETs), lumped parameter equivalent cable models to approximate transmission line behavior, a high frequency motor equivalent, parasitic inductance, and essential ground coupling paths through stray capacitances distributed in the circuit. The model allows for thoroughly examining the propagation paths and characteristics of noise currents and thereby identifying the most critical capacitive coupling paths. A simplified illustration of the circuit schematic is presented in the figure below.



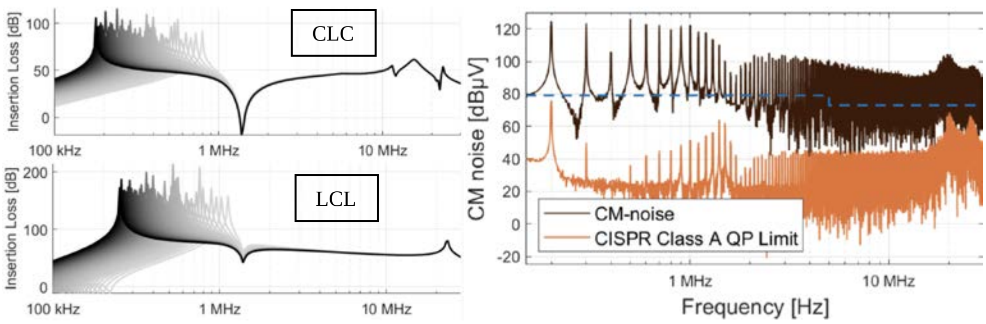
**Results**
From noise measurement sensitivity analysis, it is shown how exaggerating the details of the lumped cable model drastically increases simulation time, without a corresponding gain in accuracy. From the simulations it is found that the most critical coupling paths contributing to measured CM noise are the stray capacitances from the switching board to the heat sink.

While the most critical coupling paths are located at the power supply, implementing a dv/dt filter on the inverter output does also slightly reduce the measured EMI at certain frequencies on the input-side due to the consequential change in source- and load-impedance. The associated noise reduction is small and does not contribute to an input filter size reduction.

Based on the presented insertion loss method, and the measured source- and load-impedance, a suitable DM-filter is implemented on the supply side. From the leftmost figure below, it is evident that the DM-noise is sufficiently mitigated (compared with CISPR 11 Class A standards). The image to the right illustrates how the DM-filter components appear on the CM path, thus somewhat reduces the measured CM noise.




Based on the insertion loss equations for a wide range of CM-filter topologies, a CM-filter with sufficient insertion loss can be readily chosen from a parametric sweep of the filter inductance. The equations are functions of the filter layout, non ideal high frequency behaviour, and the measured frequency dependent load- and source-impedance of the VSD. The figure to the left shows the IL for two different topologies, and to the right is the impact of introducing an LCL-filter.




**Conclusion**
A comperhencive overview of EMI key principles and high frequency modeling techniques was provided highlighting esssential coupling paths and EMC mechanisms. From this a thorough analisys of the trade-off between accuracy and computational load as a function of the number of subdivided cable sections was conducted. A step-by-step filter design method aiming to reduce filter size and volume by considering the supply- and load-side interdependency was presented and examined in simulations.

# Applying Machine Learning Techniques to Analyse the Interplay Between Price Elasticity and User Behaviour

Student: **Høyland, Ida Waage**
Supervisor: **Oleinikova, Irina**

**Abstract**

This thesis investigates different machine learning and statistical methods to analyse the interplay between price elasticity estimations and end-user behaviour. The analysis is based on data collected by Statnett during the period 2020-2022. The spot prices for electricity in the areas investigate more than doubled on a monthly average and were more than six times higher in some hours compared to the prices before August 2021. The situation presented a good opportunity to conduct a case study on how consumers respond to unusually high electricity prices.

A regression model was used to make the price elasticity estimations for each household. The model is inspired by the model presented in [3], which is used to estimate changes in consumption. The results show that the model is statistically significant, with p-values below 0.05. After the price shock, the households with (statistically significant) negative price elasticity increased from 9.7 percent to 26.67 percent. This finding suggests that households change their consumption when prices are higher.

Machine learning models and statistical methods were used to analyse the relationship between end-user behaviour and price elasticity. The estimations from the regression model were used as the target value, and the survey data from the participating households were the features analysed. The best-performing model was Support Vector Machine (SVM), which used components constructed by Partial Least Squares (PLS), achieving an accuracy of 70%. PLS provides the highest accuracy in four out of five machine learning models. The most prominent features across the feature importance methods and machine learning models are age, city and how the residence is heated.

The suggested method for future analysis is to utilise feature selection methods, including Fisher Score, Chi-Squared Test, Mutual Information gain, Forward Selection, PLS, Logistic Regression, and, if needed, one tree-based model. Using two machine learning models should be sufficient for a feature analysis. The developed method can be used to identify groups within the consumer base that provide valuable insights into understanding consumer behaviour and can be used for targeted interventions or measures to apply demand-side flexibility.

## Optimizing demand flexibility for cost reduction and mFRR participation: A Case Study of a Supermarket with centralized cooling machine, roof-top PV and battery

Student: **Tiril Berge Vik, Elisabeth Ottesen Iversen**
Supervisor: **Karen Byskov Lindberg, Lasya Priya Kotu**
Contact: tirilberge@hotmail.no, elisabethIv_99@outlook.com

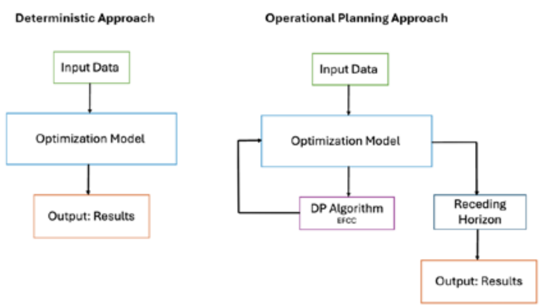
**Problem description**
The growing share of variable renewable energy sources, increased electrification, and decentralized energy production are making grid operation more challenging, particularly at the distribution level. Demand-side flexibility from distributed energy resources (DERs) is a promising solution by enabling end-users to adjust consumption in response to system needs or market price signals.

**The task**
The thesis performs a case study of the Norwegian supermarket COOP Extra Dr.Munk, located in Porsgrunn. The supermarket has real-time measurements and remote control of major power flows, enabling the use of real operational data to model the flexibility of its cooling system.

The objective is to evaluate how demand-side flexibility from the supermarket cooling machine (CM) can be utilized to minimize electricity costs and generate additional income from participation in the manual Frequency Restoration Reserve (mFRR) market. Two flexibility profiles, both with and without precooling, were derived from real-world flexibility experiments.

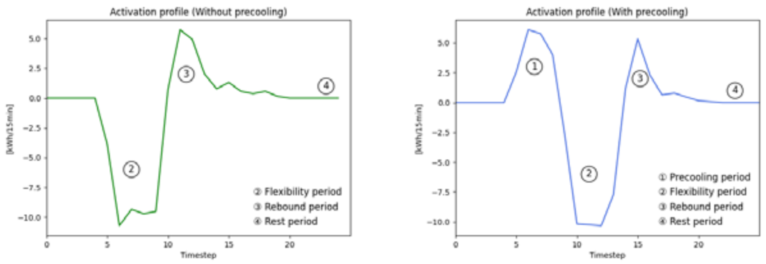
**Model/ measurements**
Four cases were developed by combining the CM, roof-top PV production, and a battery. Two modelling approaches were applied:

- A Deterministic Approach with perfect foresight.
- An Operational Planning Approach based on a receding horizon framework guided by expected future cost curves (EFCCs) from a dynamic programming algorithm.




The thesis applies a black-box approach by using experimental data to directly estimate the demand-side flexibility of the supermarket. In this approach, the thermal dynamics of the CM are not explicitly modeled. Two flexibility profiles represent the flexibility from the CM, one with and without precooling, and are used as input to the optimization model. The flexibility profiles are derived from aggregated multiple real-world experiments and a Categorical Boosting Regressor machine learning model. The flexibility profile describes how the CM consumption changes from predicted baselines during a flexibility activation. Each flexibility profile consist of four main periods, as detailed below.

- **1. Precooling period:** Optional choice of precooling (load increase) the cabinets. The precooling period has a duration of 1 hour.
- **2. Flexibility period:** Switching off the CM to create a flexibility period (load reduction). A flexibility period has a duration of 1.25 hours.
- **3. Rebound period:** Followed by a rebound period (load increase) as the system needs to return to its temperature setpoint, with a duration of 2-2.5 hours.
- **4. Rest period:** Rest time of two hours between each flexibility activation due to defrosting cycles (recovery).



(a) Flexibility profile without precooling.  (b) Flexibility profile with precooling.

**Calculation**

Monthly simulations were run over a full year to capture seasonal variability and evaluate annual performance. The results show that CM flexibility is more effectively utilized when combined with PV and a battery. In the best-performing deterministic case, combining all three DERs led to a 13.81% (26,973.87 NOK) annual electricity cost reduction. The monthly simulations showed that the cost saving potential were higher through load shifting and peak load reduction. For all cases, the income from mFRR participation led to the lowest profit contribution.

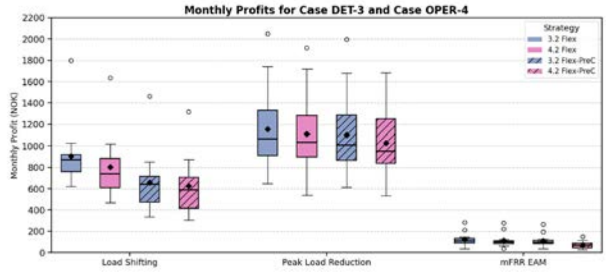


**Figure 1: Comparison of monthly profits between the Deterministic and Operational planning approaches, including all DERs.**

The Operational Planning Approach performed 7-8 % worse than the Deterministic Approach in terms of profit, due to the limited foresight from the RH framework. It significantly reduced the computational time and supported short-term decision making, leading to a more realistic operational modeling.

**Conclusion**

The evaluation of the two flexibility profiles, with and without precooling, revealed a trade-off between operational stability and economic benefit. While with precooling reduced profitability, it made the flexibility period more stable and predictable, which are critical qualities when bidding in the mFRR market. All cases showed that implicit flexibility through peak load reduction and load shifting contributes most to total profits. Income from mFRR participation remains limited but improves when combined with other DERs.

The findings confirm that CM flexibility has potential, especially when combined with other DER assets, to reduce electricity costs and provide grid services. However, unlocking the full potential of CM flexibility in real-world implementations requires overcoming practical barriers such as investment costs of technical equipment, profitability to end-users, and regulatory limitations in reserve markets.

# Battery Sizing for Sub-Synchronous Resonance Damping for Grid-Forming ES-STATCOMs

Student: **Dodou Jobe**
Supervisor: **Elisabetta Tedeschi**
Co-Supervisor: **Joseph Kiran Banda, Joao Henrique de Oliveira**
Collaboration with: **Sintef Energy Research**

## Problem description

The growing integration of renewable energy sources is reshaping the operation and stability of electric power systems. Converter interfaced generation is gradually replacing traditional synchronous machines, resulting in reduced system inertia. This makes modern power systems more vulnerable to oscillations and instabilities, particularly in weak grid conditions where the grid impedance is high. One of the most critical phenomena in such environments is sub synchronous resonance (SSR), which occurs when system components interact at frequencies below the nominal grid frequency. These oscillations can damage equipment, destabilize converter controls, and reduce power quality. Hence the main aim of this thesis is to damp these oscillations using ES-STATCOMs.

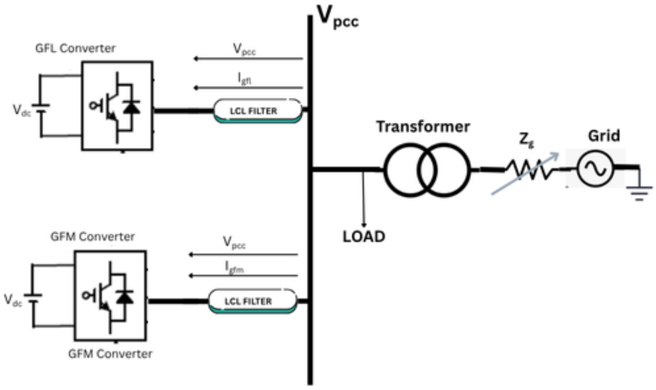
## The task

The main objective of this thesis is to identify how much energy is required from a battery to effectively damp sub synchronous resonance in a weak grid. This is achieved by studying the interaction between grid-following and grid-forming converters connected to the same network. The goal is to ensure that the energy storage static synchronous compensator (ES-STATCOM) has enough active power capability to dampen the oscillations during the most critical scenarios. The study also considers how different short circuit ratios influence the behavior of the converters and the system's stability.

## Model

The test system consists of a synchronous generator connected to a load with converters placed at the point of common coupling. One converter operates in grid following (GFL) mode, using a phase locked loop to track the grid voltage, while the other operates in grid forming (GFM) mode using droop control to set its own voltage and frequency. The short circuit ratio of the grid is varied between one and seven to simulate weak and strong grid conditions.

Fast Fourier transform is used to detect sub-synchronous frequency components in the power waveforms. These measurements help evaluate the effectiveness of the damping control strategy and the extent of the sub-synchronous resonance suppression needed.




**Results**

The results show that in weak grid conditions, the grid-following converter is highly unstable. It exhibits large oscillations in active power due to its dependency on the phase locked loop, which fails to synchronize accurately. These oscillations are characteristic of sub-synchronous resonance and can be sustained unless properly damped.

The grid-forming converter shows better stability even in weak grids. Its droop control allows it to set frequency and voltage independently, enabling it to inject active power to counteract oscillations. When both converters are connected in a hybrid configuration, the grid forming converter supports the whole overall grids strength in terms of oscillation damping by injecting active power at the point of common coupling. This leads to the damping of the oscillations and improved overall system response. The worst case energy demand is identified, and the battery size is calculated with a twenty percent safety margin to ensure reliability under practical conditions.

**Conclusion**

This thesis confirms that ES-STATCOMs operating in grid-forming mode can effectively suppress sub-synchronous resonance in power systems with low inertia. Their ability to regulate voltage and frequency and inject active power makes them suitable for stabilizing weak grids. The hybrid use of grid following and grid forming converters ensures coordinated power sharing and improved damping performance. This combination leads to a more reliable and stable power system, even as renewable integration continues to grow.

The developed method for battery sizing based on worst case damping scenarios provides a practical guideline for designing energy storage systems. By calculating the total energy required during the most severe oscillations and applying a safety margin, ensures that the inverters remain effective under real operating conditions.

# Frequency Performance under Stochastic Load Variations

Student: **Harald Dahn Johansen**
Supervisor: **Sjur Føyen**
Contact: **Sigurd Hofsmo Jakobsen**
Collaboration with: **Sintef**

## Problem description

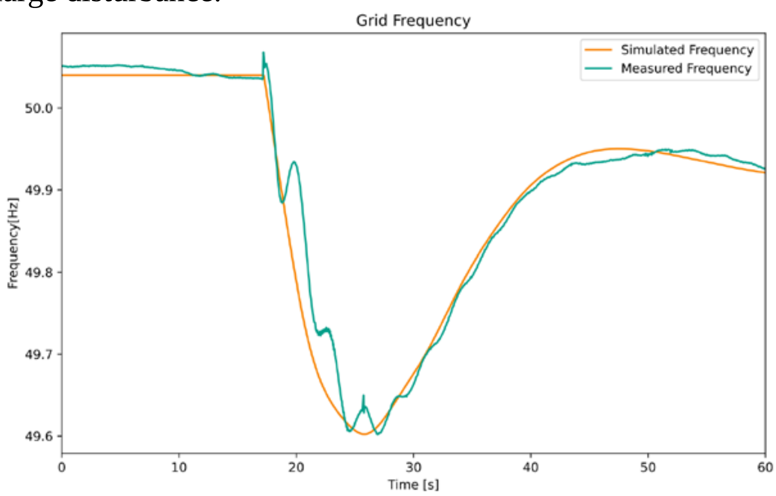
The rising share of inverter-based renewable energy, while essential for decarbonizing power systems, introduces new challenges for frequency stability due to reduced system inertia. This vulnerability was evident in the April 2025 blackout in Spain and Portugal, where high renewable penetration likely contributed to a widespread system failure. The Nordic Synchronous Area (NSA), traditionally stable due to hydro and nuclear generation, is now undergoing a similar transition. In response, Nordic TSOs have introduced new frequency-domain performance requirements to maintain grid stability. However, the effectiveness of these requirements under realistic, stochastic conditions remains uncertain.

## The task

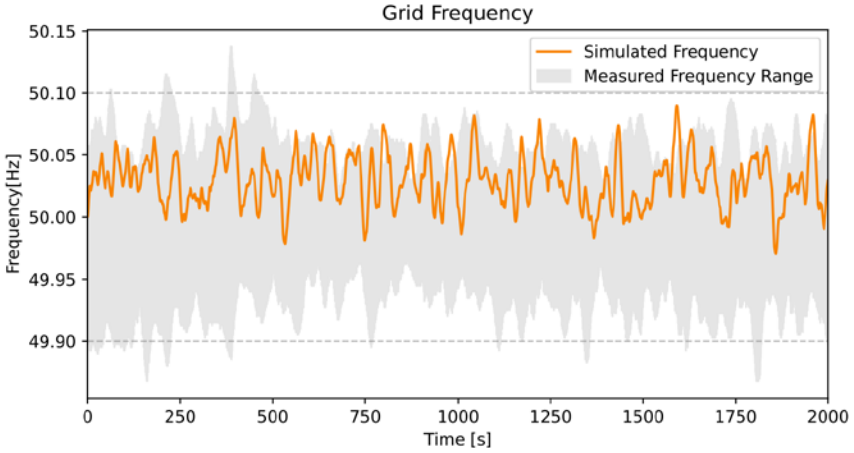
This thesis aims to evaluate the frequency domain performance requirement created by the Nordic TSO, for frequency containment reserves during normal operation. This will be done using simulation-based analysis that compares simplified linear models with more detailed nonlinear representations.

## Model/ measurements

In the Tiny Open Power System Simulator (TOPS), the generating units were first tuned to behave dynamically as the real Nordic grid through matching the frequency response for a large disturbance:

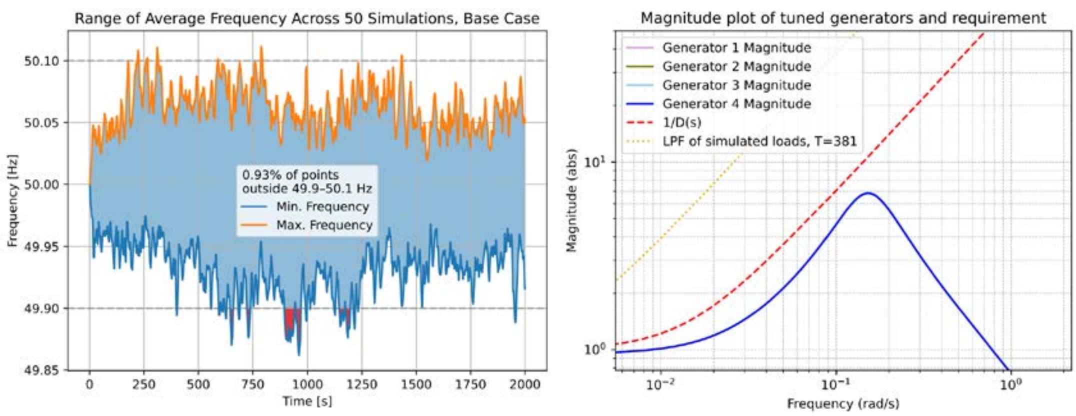


Several validation tools were used to find the typical stochastic disturbance of the grid, which was found to be represented by an Ornstein-Uhlenbeck process.




**Calculation**

Then, the typical stochastic disturbance of the grid was found and 50 simulations with random inputs were run for several different generating unit tunings. The results were used to see if the total frequency minutes outside tne normal band (MoNB) exceeded the goal of 1.9% while the generators made the requirement.



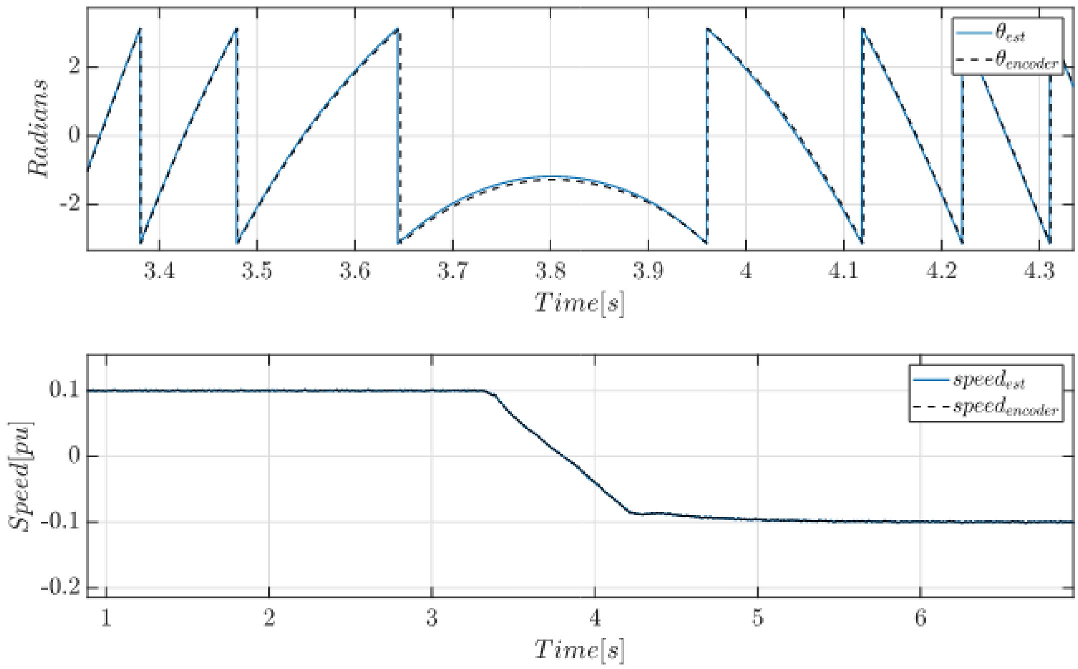

**Conclusion**

The results found that for almost all cases, the requirement is successful in keeping the MoNB below 1.9%. Exceptions were found when there was lacking FCR capacity in the grid, or when inertia was abnormally low (though the latter case was discarded by another requirement). Thus, as long as the Transmission System Operators (TSO) make sure there is enough capacity on the market, this study indicates that the requirement works well in cooperation with the other requirements. Nevertheless, simplifications and uncertainties through the creation of the framework must be considered, and further work is needed before any strong conclusions can be made. Future efforts can enhance the accuracy, reliability, and robustness of such grid performance assessments- an increasingly important task as the Nordic power system continues to integrate higher shares of inverter-based energy sources.

## Sensorless Control of Permanent Magnet Synchronous Machine with Sinusoidal Filter

Student: **John Wilhelm Ulversøy Johnsen**
Supervisor: **Roy Nilsen**
Contact: **Fredrik Göthner**
Collaboration with: **Siemens Energy**

**Abstract**
Permanent magnet synchronous machines (PMSM) are used in many industrial applications due to their high torque density and efficiency. When supplied by voltage source converters, the PMSMs performance can be optimized. However, the pulse width modulated (PWM) voltage generated by the converter introduces challenges, such as increased losses due to eddy currents, acoustic noise generation in the machine, shaft currents and voltage reflections.
To address these issues, a low-pass LC-filter can be installed at the converter output, producing nearly sinusoidal voltage at the machine terminals. However, the introduction of the output filter creates additional control challenges.
Modern industrial drives increasingly demand sensorless control capabilities to reduce system cost, improve reliability, and eliminate the need for position sensors in harsh environments. This thesis focuses on the theoretical development and practical implementation of sensorless control for a converter-fed permanent magnet synchronous machine equipped with a sinusoidal output filter. Key contributions include implementation and testing of a method for active damping of filter induced oscillations and a method for "flying-start" by synchronizing to a freely spinning machine without the use of a rotor position sensor.



# Brannrisiko i solcelleanlegg

Student: **Thea Hirth Klungreseth**
Veileder: **Eilif Hugo Hansen og Steve Völler**

## Problemstilling

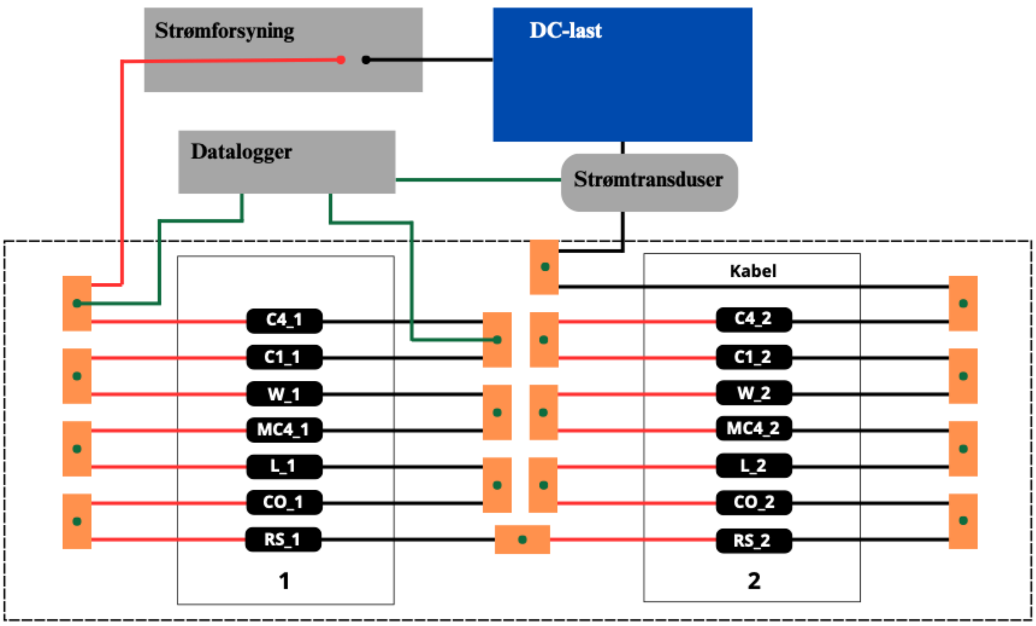
Den raske veksten i antall solcelleanlegg i Norge har ført til økt oppmerksomhet rundt sikkerhet, særlig med tanke på brannfare. Feil i elektriske kontaktpunkter, som kan føre til varmgang og lysbuer, er blant de vanligste årsakene til branntilløp i slike anlegg. Solcellekontakter er spesielt sårbare, ettersom feil ofte oppstår som følge av dårlig installasjon eller ytre påvirkninger. Samtidig utgjør serie-lysbuefeil en alvorlig risikofaktor i solcelleanlegg, og det er behov for teknologier som kan oppdage og avbryte slike hendelser automatisk før de utvikler seg til brann.

## Oppgaven

Oppgaven undersøker brannrisiko i solcelleanlegg med fokus på solcellekontakter og lysbuedeteksjon. Gjennom en kombinasjon av litteraturstudie og laboratorieforsøk vurderes potensialet for lysbuedeteksjon som et aktivt sikkerhetstiltak, og det ses nærmere på hvordan solcellekontakter påvirkes av ulike typer belastning. Litteraturstudien viser at korrekt montasje, vedlikehold og bruk av kompatible komponenter er avgjørende for å redusere risiko. Samtidig diskuteres nyere teknologier for lysbuedeteksjon, inkludert systemer basert på kunstig intelligens.

## Modell/målinger

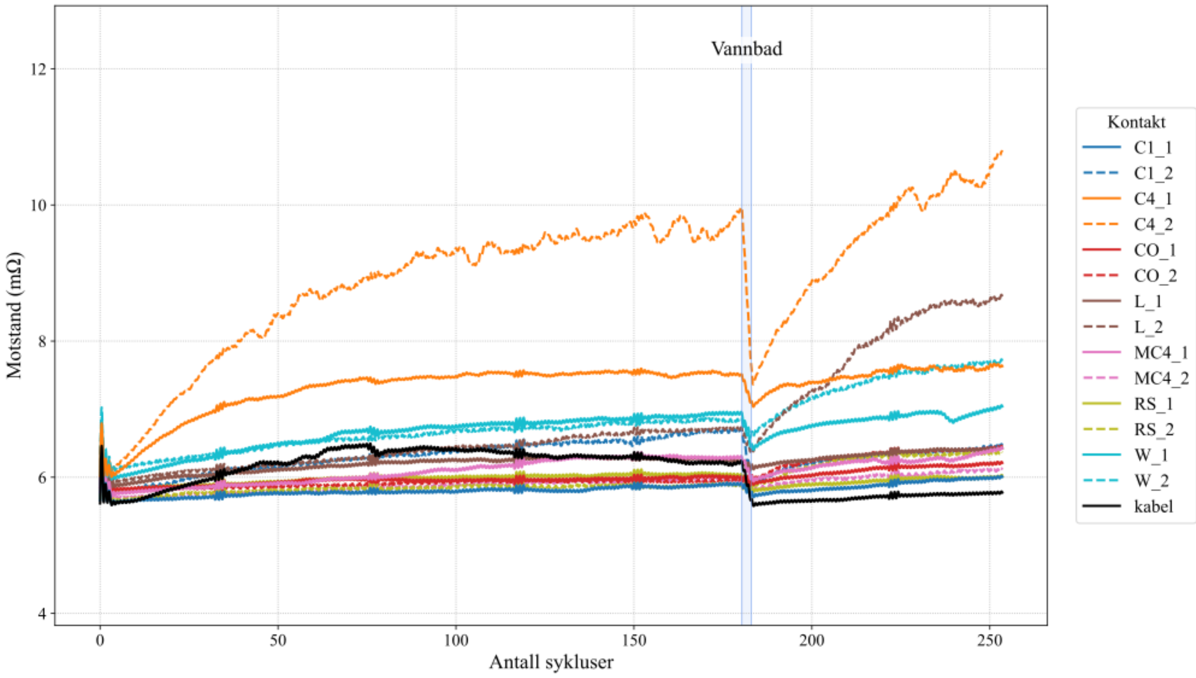
I laboratorieforsøket ble ulike typer solcellekontakter testet under høy elektrisk belastning og vekslende klima, inkludert termiske sykluser og nedsenking i vann. Målet var å vurdere hvordan overgangsmotstanden utvikler seg over tid. Kontaktene ble plassert inne i et klimaskap og belastet med likestrøm på rundt 30 A, mens spenningsfall over hver kontakt ble logget for å kunne beregne endringer i kontaktmotstand. Oppsettet er vist i figuren under.



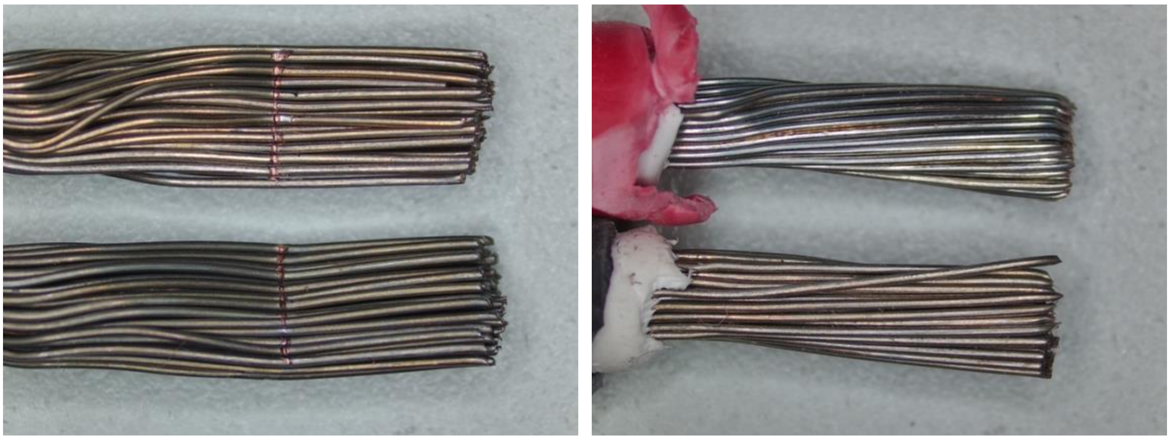

Komponentene inne i stiplet firkant skal plasseres inne i klimaskapet
- Ikke alle kablene til dataloggeren er vist i tegningen. Grønn prikk markerer hvert målepunkt.

*Figur 1 - Testoppsettet*

**Resultater**
Resultatene viste at fuktinntrengning i kabelen førte til korrosjon og økt overgangsmotstand, noe som igjen kan gi farlig varmeutvikling. Det ble observert variasjoner mellom kontaktmodellene, men forskjellene kunne i stor grad spores tilbake til kabelens tilstand og montasjekvalitet, ikke nødvendigvis selve kontakttypene. Forsøket tydeliggjør hvor viktig god beskyttelse mot fukt og korrekt montering er for å opprettholde lav kontaktmotstand over tid.




*Figur 2 - Måleresultatene fra hele forsøket. Viser overgangsmotstanden over kontaktparrene*



*Figur 3 – mikroskopbilde av korrodert svart kabel til C4_1 og C4_2 (venstre) og rød og svart kabel til L_2 kontakten (høyre)*

**Konklusjon**
Brannsikkerheten i solcelleanlegg er avhengig av både teknisk kvalitet og driftsrutiner. Pålitelig montasje, godt vedlikehold og bruk av kompatible komponenter er avgjørende for å forebygge brann. Lysbuedeteksjon fremstår som et lovende tiltak for å redusere risiko ytterligere, spesielt i bygningsintegrerte anlegg hvor visuell inspeksjon er vanskelig. En kombinasjon av forebyggende tiltak og aktiv overvåking anbefales for trygg og langsiktig drift.

# Solar at Campus Gløshaugen

Examining the technical, economic, and architectural dimensions for the future energy roadmap

Students: **Lars-Erik Wikheim Lang and Eskil Walde**
Supervisor: **Steve Völler**

**Problem description**

NTNU aims to reduce its climate footprint by increasing local renewable energy production. Installing solar PV systems on campus buildings is a key strategy to reduce reliance on grid electricity. This thesis evaluates the solar potential of existing and planned structures at Campus Gløshaugen to support NTNU's Environmental Development Plan.

**The task**

The main objective of this thesis is to evaluate the solar energy production potential of selected rooftops and facades at NTNU's Gløshaugen campus. The study aims to identify which surfaces are most suitable for PV installations and to simulate system performance under local climatic conditions. Both existing buildings and planned new constructions are considered to provide a comprehensive overview of the campus's future solar capacity. The task includes assessing technical feasibility, architectural integration, cost-efficiency, and seasonal production characteristics to determine which PV systems can make meaningful contributions to NTNU's energy and sustainability targets.

**Model/ measurements**

To evaluate the solar potential of Gløshaugen campus, the study employed a two-step modelling approach. First, a detailed 3D model of the campus was developed using Rhinoceros 3D. This allowed for precise solar irradiation analysis based on surface orientation, tilt, and potential shading.

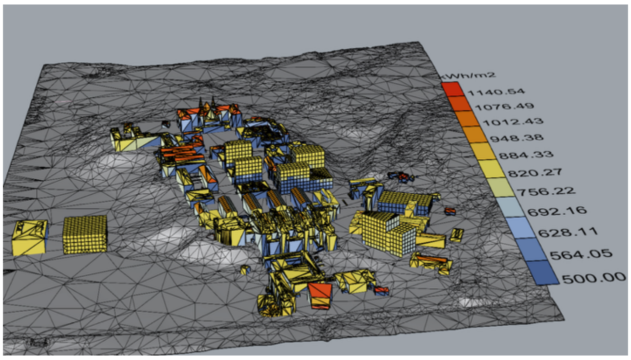



*Figure 1: Solar Mapping of the existing and planned buildings of the Gløshaugen campus.*

Next, the identified surfaces were imported into PVsyst, a specialized simulation tool for photovoltaic systems. Here, simulations were conducted using actual meteorological data from Trondheim, and various PV configurations were tested. Both rooftop and facade-mounted systems were analyzed, including conventional, dual-oriented, and bifacial panel arrangements. Performance was assessed in terms of annual energy output and specific yield. A variety of building-integrated and building-applied designs were included to reflect both practical feasibility and aesthetic integration. The buildings and surfaces evaluated are shown in the pictures below.

*Table 3.1: Overview of all Cases in the Thesis*

| Case | Building | PV System(s) | Simulated Scenarios |
|---|---|---|---|
| **1** | P1 | Rooftop | 9 |
| **2** | P2 | Facades | 2 |
| **3** | P6 | Rooftops & Facades | 4 |
| **4** | Central Building | Facades | 4 |
| **5*** | Central Building | Facades | 2 |
| **6*** | Chemistry Blocks | Rooftops | 2 |

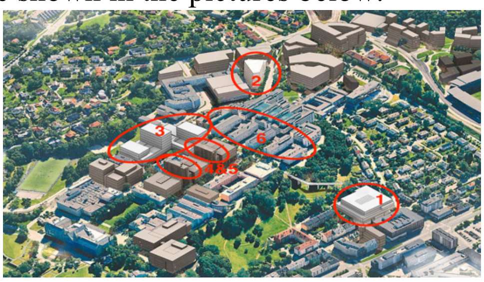



*Figure 2: The selected buildings for PV system evaluation*

### Calculations

The simulation results revealed that several buildings at Campus Gløshaugen offer excellent conditions for solar energy production. Among the most promising were the rooftops of the new P1 and P6 buildings, the sloped roofs of the Chemistry Blocks, and the facades of the P2 and P6 buildings. Dual-oriented and bifacial systems, especially those installed on rooftops, demonstrated the highest annual energy outputs and favorable cost-efficiency.

Facade-mounted systems showed lower total production but maintained high specific yields and stable wintertime performance, particularly valuable in Trondheim’s low-sunlight season. By replacing traditional facade materials with PV modules, some of the additional costs could be offset. Collectively, the most feasible systems are estimated to generate approximately 1,270 MWh annually. This figure represents a significant contribution to the university’s total energy consumption and aligns well with NTNU’s sustainability strategy.

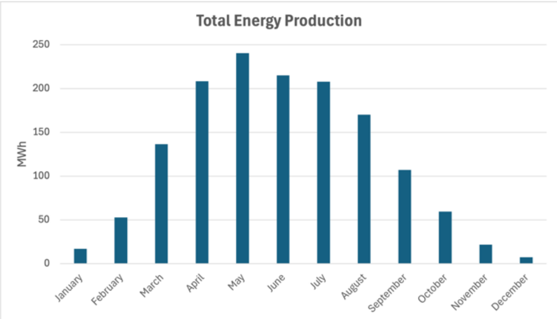



*Figure 3: The total energy production from the evaluated cases in this thesis*

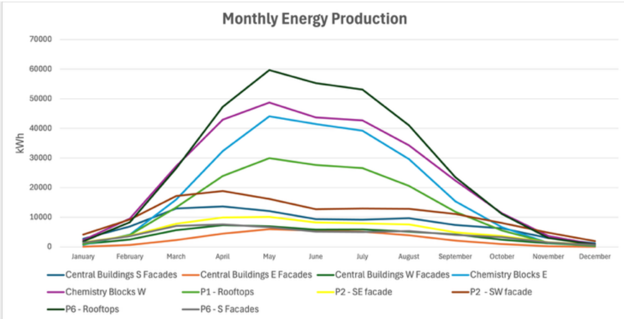



Figure 4: Monthly energy production from each PV system

### Conclusion

This thesis demonstrates that strategic deployment of photovoltaic systems on rooftops and facades at NTNU’s Gløshaugen campus can make a meaningful contribution toward the university’s sustainability and energy self-sufficiency goals. The most effective solutions combine high energy yield, cost-efficiency, and architectural integration.

Key recommendations include prioritizing dual-oriented rooftop installations and leveraging facade-mounted PV systems where visual and structural integration is feasible. These efforts can serve as a blueprint for similar installations across the campus. Further work should focus on implementing the most promising PV systems and monitoring their performance to validate simulation results. The analysis method can be expanded to other NTNU buildings to map broader solar potential. Additionally, energy storage solutions like batteries could be explored to manage possible overproduction and improve on-site energy utilization.

# High power and high frequency induction heating application

Student: **Langelid, Magnus**
Supervisor: **Weiss, Beatrix Veronika**

**Abstract**
This master's thesis explores the development of a high-power, high-frequency induction heating system, with a focus on the selection, simulation, and testing of advanced semiconductor devices suitable for such demanding applications.

The work begins with a comprehensive theoretical foundation outlining the principles of induction heating, as well as key considerations in designing converters capable of operating efficiently at power levels up to 25 kW and frequencies in the MHz range. The theoretical part of the thesis focuses on the comparison on suitable semiconductor switching devices for the investigated application. Two specific devices were selected for detailed analysis: the Qorvo Silicon Carbide (SiC) cascode Junction Field-effect Transistor (JFET) UJ4SC075018L8S and the P2 Series 650 V/25 mΩ enhancement-mode Gallium Nitride (GaN) High Electron Mobility Transistor (HEMT) with ICeGaN gate CGD65D025SP2 from Cambridge GaN Devices (CGD).

These devices were evaluated in a simulation environment where their switching performance was analyzed under various commutation conditions. The performance on the chosen semiconductors are then further investigated in converter simulations. Both devices demonstrated low switching losses under ideal conditions, although the GaN HEMT showed a slight advantage in terms of efficiency and switching speed, making it a strong candidate for high-frequency applications.

Even though both investigated devices were found to be suitable for the application only the GaN HEMT was investigated and analyzed in the practical part of this thesis due to its availability at ENRX as well as time constraints. For this purpose, custom printed circuit boards(PCBs) were designed and fabricated, including both a gate driver board and a full-bridge inverter. These were assembled and tested at ENRX's facilities. The converter underwent extensive validation to rule out layout or assembly errors and was successfully operated at a switching frequency of approximately 1.55 MHz under low-voltage conditions.

However, during testing at voltages above 15 V, abnormal switching behavior was observed, specifically one of the transistors exhibited a premature turn-off at elevated voltage, which raised safety concerns. Despite the gate signals appearing correct, this issue prevented safe operation at the intended 20–25 kW power level. The fault was suspected to be due to capacitive coupling between the gate signals from the transistors laying on opposite sides of the PCB, which were later verified by testing the system as a half-bridge converter. Overall, the thesis contributes to the growing body of knowledge on applying wide bandgap(WBG) semiconductors in MHz- range induction heating systems and offers practical insights into their integration and real-world challenges.

# Data-driven Adaptive Control of a Converter using Online Impedance Identification

Student: **Marie Lerstad**
Supervisors: **Olimpo Anaya-Lara, Raymundo Torres-Olguin, Sjur Føyen, Atle Rygg**
Contact: **marielerstad@hotmail.no**
Collaboration with: **SINTEF and Equinor**

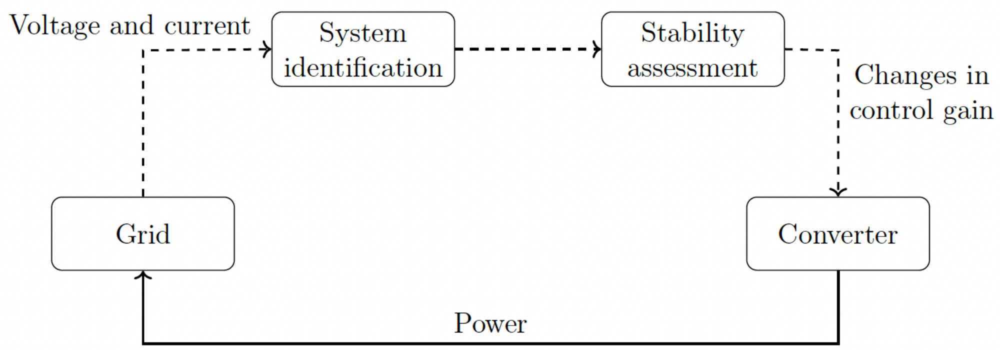
**Problem description**

As the power system transitions toward renewable energy sources like wind and solar, power electronic converters are replacing traditional synchronous generators. These converters typically use phase-locked loops (PLLs) for grid synchronization. However, fixed PLL settings can cause instability under weak-grid conditions, leading to low-frequency oscillations and controller interactions.

This challenge has been observed in real-world scenarios, such as an instability event at an offshore wind farm in the UK, which was traced back to a poorly designed PLL. Traditional control strategies typically assume static operating conditions, making them poorly suited for the dynamic behaviour of modern power systems.

**The task**

This thesis explores a data-driven approach to improve converter stability by enabling real-time adaptation of PLL parameters. The method relies on estimating the converter and grid impedance during operation, allowing the converter to tune itself in response to changing conditions. This essentially creates a feedback loop around its own behaviour.




**Model/ measurements**

A simulation model of a grid-connected voltage source converter (VSC) is developed in MATLAB/Simulink. The grid is represented using a Thevenin equivalent with variable impedance to emulate strong and weak grid scenarios.

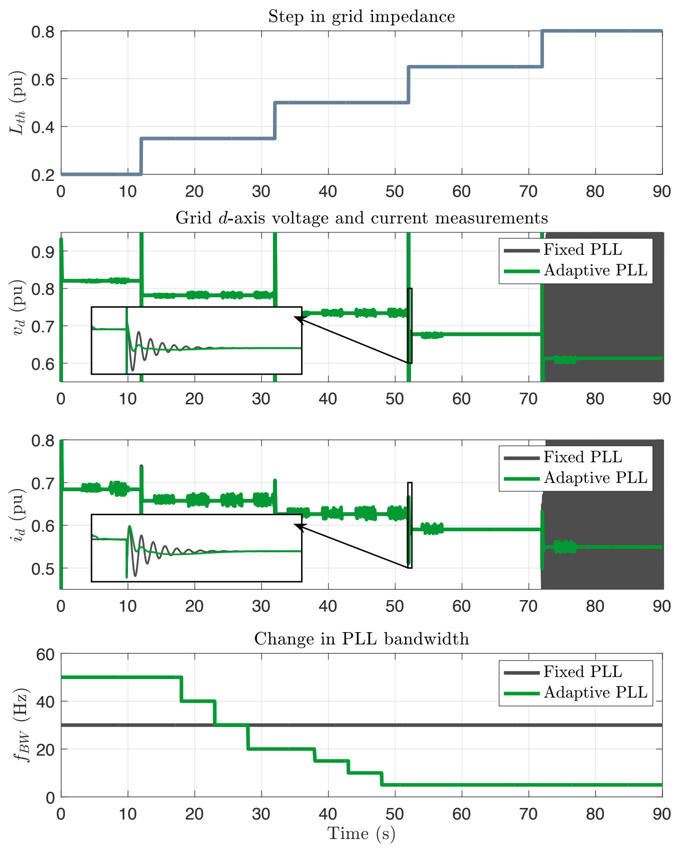
During operation, the converter continuously measures terminal voltage and current. These signals are processed using the Eigensystem Realization Algorithm (ERA), a time-domain system identification method, to estimate the surrounding impedance. The resulting impedance model feeds into a control algorithm that adjusts the PLL's PI gains in real time based on stability metrics.

## Results

The impedance estimate is used to calculate the sensitivity function, which indicates the system's stability margin. When the sensitivity peak exceeds a predefined threshold, the PLL bandwidth is reduced to maintain stable operation.

A case study with stepwise increases in grid inductance showed that:

- A fixed-parameter PLL became unstable as the grid weakened.
- The adaptive PLL responded by lowering its bandwidth and maintained stability.
- The ERA-based impedance estimates aligned well with analytical models in the mid-frequency range, validating the approach.




## Conclusion

The study demonstrates that real-time impedance identification using ERA, combined with adaptive PLL control, can effectively stabilize converters under changing grid conditions. This makes the converter self-tuning, able to adapt without prior knowledge or offline tuning.

While the concept was successfully proven in simulation, future work should explore:

- Robustness to measurement noise and disturbances
- Implementation on real-time embedded hardware
- Strategies for safely triggering system perturbations

The work contributes to the development of more robust, intelligent control strategies for future converter-dominated power systems.

## Enhancing Solar Power Simulation Quality by Analysing Key Parameters

Student: **Hans Martin Lie**
Supervisor: **Steve Völler**
Collaboration with: **Aneo and Pareto**

**Problem description**
This thesis tries to analyse and compare real life production data from an operational solar system with the results given by the same system modelled in the simulation software PVsyst. The chosen operational solar system is a roof mounted system at Malvik Fryselager AS in Trøndelag, Norway. Two different weather data sources will be used in PVsyst. One using Meteonorm which generates synthetical weather data for a median year, and the second using real recorded weather data from Malvik 2024. The resulting monthly and yearly totals from PVsyst will be compared to real production from 2024. In addition, singular days throughout the year will be chosen for further hourly inspection.

**Method**
A PVsyst model of the solar system at Malvik Fryselager was provided by Aneo to conduct simulations. It uses Meteonorm as a weather source that uses historical weather data from the last 30 years to create a median year. In addition real weather data from 2024 will be imported into PVsyst to run a second simulation. This real data was collected from Værnes Airport 9 km north east of Malvik Fryselager using Seklima, a web portal by «Meterologisk institutt».

Monthly and yearly results from PVsyst using the two different weather data, will be compared with the actual production data gathered from the inverters at Malvik Fryselager. The accuracy of monthly soiling factors in the winter months to simulate loss in irradiance due to snow cover will be investigated. In addition the daily production profile during sunny days throughout the year will be analyzed and compared.

**Results**
Table 4.1 shows the main results from PVsyst using Meteonorm data and Seklima data. The real production in 2024 is also shown.

| | Meteonorm | | | Seklima | | | Malvik |
|---|---|---|---|---|---|---|---|
| **Month** | **GHI [kWh/m²]** | **Temp. [°C]** | **Energy [MWh]** | **GHI [kWh/m²]** | **Temp. [°C]** | **Energy [MWh]** | **Energy [MWh]** |
| January | 5,9 | -1,20 | 0,6 | -0,2 | -2,59 | 0,4 | 2,65 |
| February | 22,8 | -1,15 | 8,2 | 18,4 | -0,30 | 7,8 | 16,75 |
| March | 66,7 | 0,76 | 37,7 | 61,0 | 3,57 | 36,4 | 80,45 |
| April | 111,5 | 5,14 | 133,4 | 110,8 | 4,78 | 137,0 | 141,83 |
| May | 151,0 | 9,42 | 198,1 | 164,0 | 14,89 | 212,5 | 221,66 |
| June | 159,5 | 12,20 | 207,2 | 136,7 | 14,03 | 176,4 | 183,58 |
| July | 154,8 | 15,52 | 197,8 | 135,2 | 15,83 | 174,2 | 171,26 |
| August | 116,1 | 14,75 | 148,6 | 97,1 | 15,75 | 126,4 | 130,74 |
| September | 67,6 | 10,85 | 85,5 | 58,6 | 11,45 | 75,5 | 88,22 |
| October | 29,4 | 6,08 | 33,4 | 22,4 | 6,73 | 26,2 | 32,66 |
| November | 8,0 | 1,97 | 5,9 | 5,3 | -3,51 | 5,6 | 6,91 |
| December | 2,7 | -0,49 | 0,5 | -1,7 | -5,11 | 0,3 | 0,21 |
| **Year** | **896,0** | **6,20** | **1057,0** | **807,5** | **6,33** | **978,8** | **1076,92** |

Table 4.1: Main monthly results for PVsyst using Meteonorm and Seklima aswell as the real results from Malvik

The yearly production is more accurate using Meteonorm than Seklima, but the monthly production, especially during the summer months, where the majority of the production occurs, is more accurate with Seklima data. The main differences are the higher GHI and lower temperatures using Meteonorm, than Seklima. Higher GHI leads to higher production, while the efficiency of the solar cells also increases at lower temperatures. This leads to much more production during summer than in reality, when using Meteonorm data.

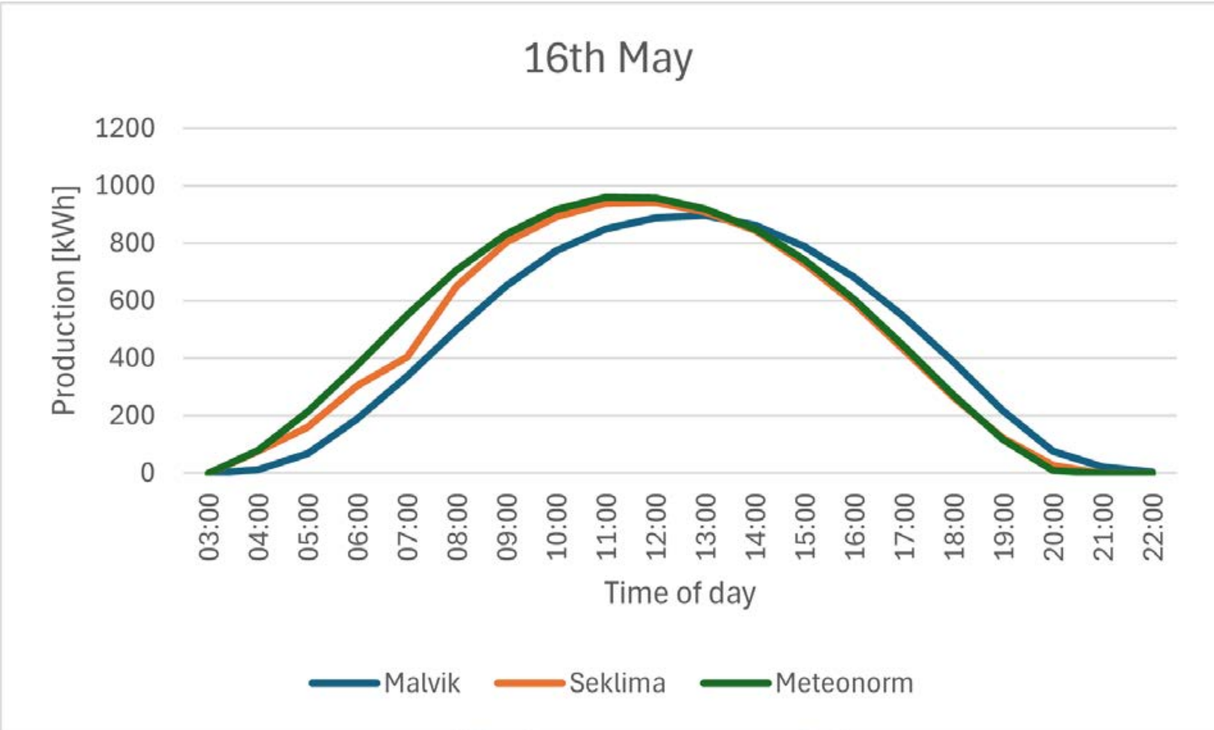



**Figure 1: Hourly production profile of 16th of May 2024**

The figure above shows the hourly production profile of 16th of May 2024 for both simulations in PVsyst as well as the actual production. It is interesting to see the time shift throughout the day, where PVsyst reaches the peak at 12:00, with even production in the morning and afternoon. While the real production peak is at 13:00 and slightly more production in the afternoon and evening than during the morning.

**Conclusion**

Even though Seklima data is taken from 2024 and should result in a very similar energy production compared to actual 2024 production, the Meteonorm data provides a more accurate yearly total production. However, on a monthly basis and singular day basis, Seklima is more accurate. The hourly time shift seen i singular days in PVsyst compared to real life is very interesting, and could affect the pricing of the solar energy when sold on the spot price market.

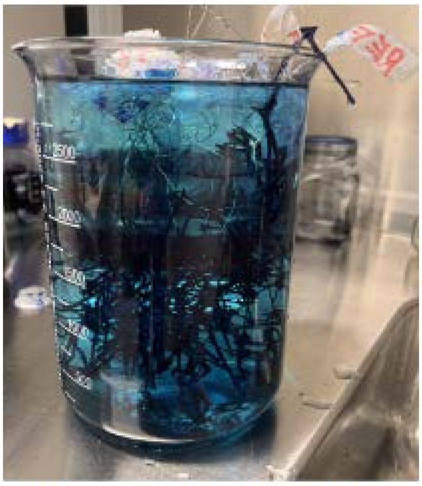
# Water Tree Initiation and Growth in XLPE Insulation: The effect of aluminium alloys and corrosion

Student: **Leander Lilleli**
Supervisor: **Øystein Leif Gurandsrud Hestad**
Collaboration with: **SINTEF Energy**

Traditionally, subsea cables have used copper conductors with a lead sheath to prevent water intrusion. However, with the rapid expansion of offshore wind farms, there is a growing demand for subsea cables that are lighter, more flexible, and cost-effective. In addition, EU regulations are pushing for the removal of lead sheaths due to environmental concerns, creating a need for wet cable designs that can tolerate limited moisture exposure. There is also an increasing interest in using aluminum as a conductor material due to its lower weight and cost. However, this introduces new challenges, as aluminum combined with wet designs creates favorable conditions for water tree growth within the insulation, potentially compromising the cable's long-term reliability.

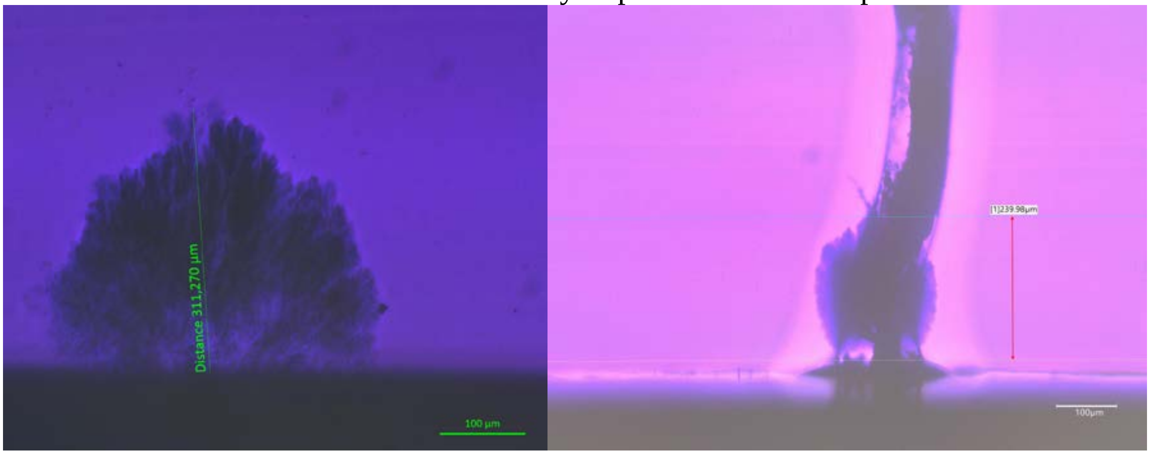
This thesis presents an aging study of two different aluminum alloys (1370 \& 6082) using molded Rogowski cup samples to simulate the insulation system of a high voltage cable. The study also investigated whether the application of a corrosion accelerator (NaCl) on the conductor surface influenced the growth of water trees. The aging process was carried out by applying an electric field of 5 kV/mm using a central electrode inserted into the Rogowski cup. To replicate operating conditions, the samples were placed in a climate-controlled heating cabinet maintained at 70 °C.

**(a)** Methylene blue solution before stirring

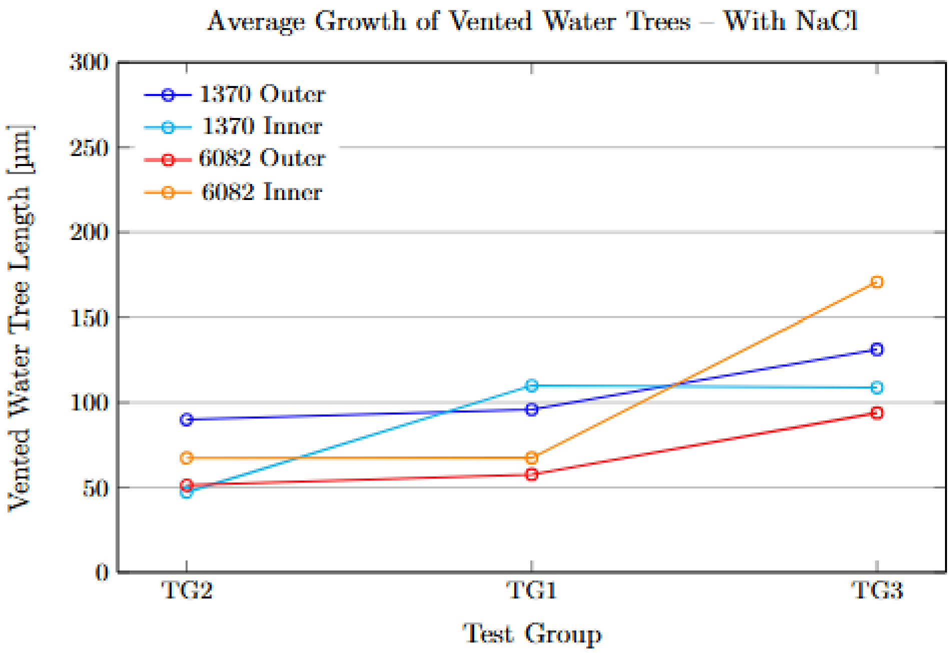


**(b)** Samples after dying in water

After the aging period, the Rogowski cups were subjected to breakdown testing to determine the dielectric strength of the insulation. Following this, the cups were sectioned into smaller samples and dyed using methylene blue to enhance the visibility of water trees. The samples were then examined under a microscope, and the water trees were measured. These measurements formed the basis for the analysis presented in this report.




The results indicate a clear trend of longer vented water trees originating from the inner semiconductor in samples where a corrosion accelerator (NaCl) was applied to the conductor. Conversely, there is a weaker trend suggesting slightly longer vented water trees from the outer semiconductor in samples without NaCl.




A distinction was also observed between the two aluminum alloys: 6082 appears to promote more water tree growth in the presence of NaCl compared to 1370. Whereas 1370 tends to support more growth in the absence of the corrosion accelerator compared to 6082.

## Evaluating Frequency Stability Mitigation Strategies in a Low-Inertia Nordic Power System

Students: **Nora Si Jia Beck Lillelien and Jørgen Kjøpstad Sørhaug**
Supervisor: **Kjetil Obstfelder Uhlen**
Co-supervisor: **Knut Styve Hornnes**
Collaboration with: **Statnett SF**

### Problem description

The increased share of Converter-Interfaced Generation (CIG) in the Nordic power system reduces system inertia, posing new challenges for grid stability. As inertia contributes to slowing Rate of Change of Frequency (RoCoF) immediately after a disturbance, its reduction raises concerns among Transmission System Operators (TSOs) as it gives them less time to enact countermeasures.

### The task

The thesis investigates frequency stability in low-inertia power systems, following large disturbances. The focus is on evaluating how different technologies and control strategies can mitigate frequency instability in future grid scenarios dominated by Convert-Interfaced Generation (CIG).

### Model/ measurements

To analysing a low inertia version of the Nordic grid, the Nordic 45 model developed by M. G. Teignes was updated with Voltage Source Converters (VSC) to capture CIGs effect on the power system. Figure 1 below shows the updated Nordic 45 2.0 model.

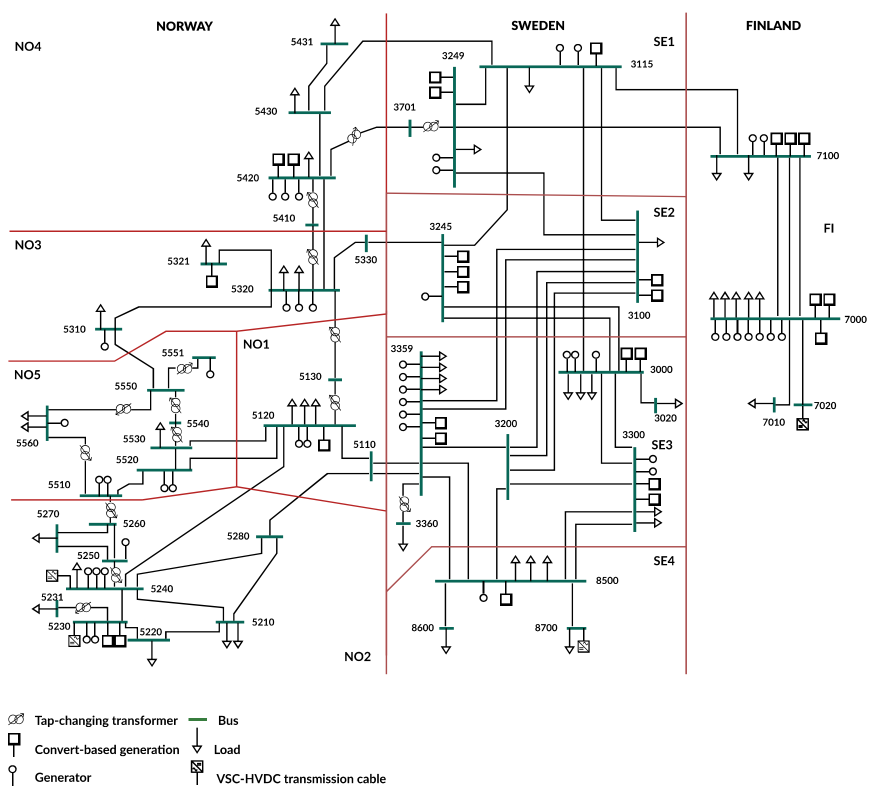



Figure 1: Updated version of the Nordic 45 model referred to as Nordic 45 2.0.

The dynamic simulations in this thesis were made possible through the Tiny Open Power System Simulator (TOPS) developed by Hallvard Haugdal at NTNU. In addition to updating the model with VSC, the HYGOV model was updated and Power System Stabilizers were added, then both were tuned.

**Results**

The validation case was compared to data from a real scenario and showed similar results. Compared to the base-case, which are a future scenario with less inertia and more CIG, shows that the integration of CIG has a big impact on the frequency response as seen in Figure 1. In Figure 2 the impact of the different mitigation can be seen. Fast Frequency Reserves (FFR) and frequency support from wind heightens the nadir, without slowing the RoCoF. FFR causes a second dip when the contract time is finished. Both the synthetic inertia (SI) and the inertia from synchronous condensers (SC) can be seen to slow the RoCoF but have a lesser impact on the nadir as less energy is injected.

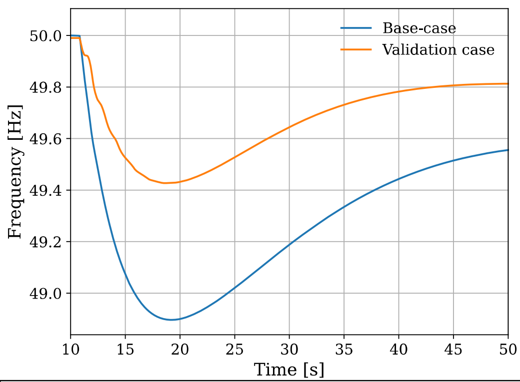



Figure 2: Comparing the validation case (2023) with a future base-case (2031) with lower inertia.

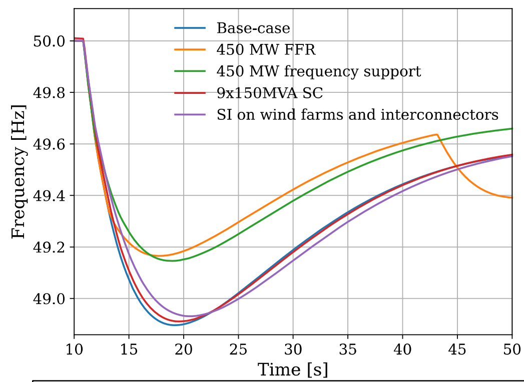



Figure 3: Comparing the different mitigation when added to the base-case.

**Conclusion**

The frequency mitigation works in all the different cases. Synthetic inertia is especially interesting as it shows CIG can provide something similar to real inertia. It is hard to directly compare the different mitigation as the goals and activation strategies are different. Synchronous condensers inject less power than the synthetic inertia case and therefore seems less effective. They both have the goal of decreasing the RoCoF and does so. FFR and frequency support from wind on the other hand aims to lessen the power deficit and heighten the frequency nadir, by significant contributions of power. The FFR has a second dip in frequency, while frequency support from wind does not. Therefore, frequency support wind is to be preferred, but the market structure for the procurement of this is not in place and should be further investigated.

# The Impact of Demand Response in a Net Zero 2050 Northern European Power System

Student: **Nora Lindman and Sina Haugland Myhrsveen**
Supervisor: **Hossein Farahmand, Arild Helseth, Amund Bergset**
Contact: **Hossein Farahmand**
Collaboration with: **SINTEF Energy**

**Problem description**

Decarbonizing the energy system through large-scale integration of VRES introduces greater operational uncertainty and volatility due to their weather-dependent nature. It makes hydropower scheduling more complex and highlights the need for advanced tools capable of handling such uncertainty. In addition, the volatility associated with VRES makes it increasingly difficult to match supply and demand - especially during low-output (Dunkelflaute) or surplus periods. These conditions lead to price volatility and reduced investment incentives due to the cannibalization effect.

This study examines the Northern European power system under a 2050 net-zero scenario, using the dataset **expanded_dem-h2pris45_headcorr_fansi-batt_increase50** obtained from the HydroConnect project.

**The task**

The analysis explores both the annual impact of DR and two specific system stress scenarios: Dunkelflaute and VRES surplus. The goal is to assess how load shifting can help mitigate price spikes during supply shortages and reduce zero-price events during periods of excess generation. To illustrate these conditions, week 19 (characterized by low wind and solar) and week 30 (marked by high solar production and low demand) from the year 1996 are used as representative cases. In addition, this study will investigate to what extent DR can reduce electricity price volatility, improve VRES capture rates and reduce total operational costs in the interconnected regions of Norway (hydropower-dominated), and Denmark and Germany (VRES-dominated).

**Model/ measurements**

This study applies the hydropower scheduling model ReSDDP, a stochastic optimization model developed by SINTEF Energy in the RES100 project, to analyze how DR through load shifting can mitigate and respond to these pronounced price fluctuations. ReSDDP uses the SDDP framework to estimate a long-term strategy of water values and an integrated ReSIM model in to simulate short-term operations. The plot shows the convergence of the SDDP algorithm.

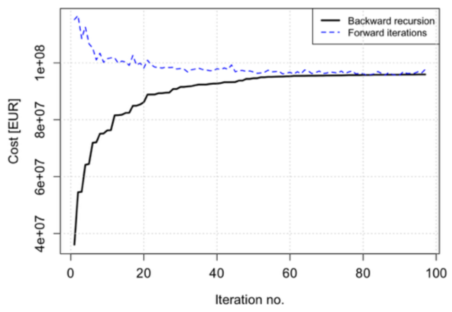



**Figure 4.3.1:** Convergence plot over 100 iterations. Backward iterations are shown in black, and forward iterations are shown as blue dashed lines.

## Calculation

The results of this study show that demand-side flexibility can reduce average electricity price peaks in Southern Norway by between 0.51% and 61.45% during a Dunkelflaute week, depending on the level of load-shifting flexibility. In Northern Germany and Western Denmark, the maximum observed average price reduction exceeds 55%, achieved with a 4-hour load recovery time and 50% load-shifting capability.

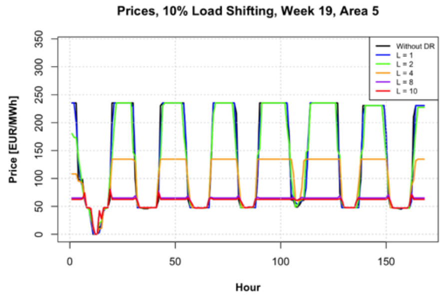



**Figure 5.2.19:** Hourly electricity prices in Area 5 (Southern Norway) during Week 19 under different load recovery time with 10 % load shifting.

| Scenario | Relative Price Reduction [%] Area 5 | Area 20 | Area 22 |
|---|---|---|---|
| L = 4, 10 % | 31.73 | 10.17 | 10.60 |
| L = 4, 20 % | 60.57 | 27.90 | 28.50 |
| L = 4, 30 % | 62.35 | 45.30 | 45.81 |
| L = 4, 40 % | 61.56 | 54.11 | 54.59 |
| L = 4, 50 % | 61.45 | 55.04 | 55.48 |

**Table 5.2.7:** Reduction relative to average price in Areas 5 (Southern Norway), 20 (Western Denmark), and 22 (Northern Germany) in week 19 under different load shifting percentage limits at 4 hours load recovery time, compared to the baseline without DR.

During a VRES surplus week, the highest number of zero-price hours eliminated was 47 hours and observed in Western Denmark under the same DR configuration (4-hour load recovery time and 50% load-shifting capability), with the increased load shifting capability being the most effective to mitigate zero-prices. While this level of flexibility may be somewhat optimistic, the results illustrate the potential of DR as an effective tool for managing price volatility in a 2050 scenario with high VRES penetration.

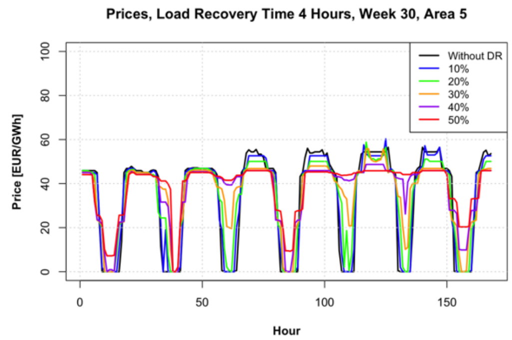



**Figure 5.2.29:** Hourly electricity prices in Area 5 during Week 30 under different load shifting percentage limits at 4 hours load recovery time.

| Scenario | Hours Price Raised from Zero Area 5 | Area 20 | Area 22 |
|---|---|---|---|
| L = 4, 10 % | 11 | 13 | 10 |
| L = 4, 20 % | 24 | 26 | 20 |
| L = 4, 30 % | 34 | 36 | 31 |
| L = 4, 40 % | 40 | 42 | 35 |
| L = 4, 50 % | 45 | 47 | 39 |

**Table 5.2.8:** Number of hours during week 30 where electricity prices increased from zero in the baseline (without DR) to non-zero values in the DR configurations.

Over the full year, the results show an increase in wind and solar capture rates, highlighting DR as an effective tool to reduce the projected decline in VRES capture rates. In Germany, the solar capture rate increases by nearly 40% at the highest level of flexibility. However, hydropower capture rates decline as load-shifting capability increases, suggesting that DR alters the dispatch balance in favor of VRES during high-output periods.

## Conclusion

Overall, the findings demonstrate that DSF is a powerful and essential strategy for improving the performance of a future net-zero power system. By shifting electricity consumption in time, DR contributes to lower operational costs, reduced price volatility, enhanced resource utilization, and improved capture rates for VRES. It helps mitigate extreme price spikes during low renewable output events and reduces the frequency of zero-price hours during surplus periods.

# A Case Study on DER Deployment for Energy Sharing and Congestion Management in an Energy Community

Student: **Hanna Lofnes**
Supervisor: **Karen Byskov Lindberg**
Co-supervisor: **Josh Eichman**
Collaboration with: **Institut de Recerca en Energia de Catalunya (IREC)**

## Problem description

To meet the European Union's target of becoming climate-neutral by 2050, increased deployment of renewable energy sources (RES) to replace fossil fuels is vital. However, the increasing penetration of RES and other distributed energy resources (DERs) into the distribution grid poses operational challenges for distribution system operators (DSOs), including line congestion. Utilizing local energy generation and demand-side flexibility presents a promising solution to such issues. In line with recent EU regulatory developments, emerging market frameworks, such as peer-to-peer energy trading, energy communities, and local flexibility markets, can offer opportunities to deliver grid services to DSOs while also generating value for participating agents.

## The task

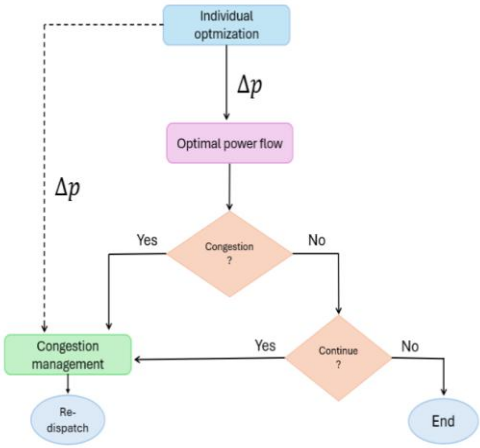
This thesis aims to examine how various configurations of DERs, including photovoltaic (PV) panels, electric vehicles (EVs), and battery energy storage systems (BESS), impact the performance of an energy community, focusing on energy costs and independence from the main grid. Furthermore, it aims to analyze how the configurations can help the DSO manage congestion in the distribution network while preserving individual user preferences.

## Model

| Case | Users w/ PV | Users w/ BESS | Users w/ EV |
|---|---|---|---|
| Base | 31 | 16 | 6 |
| PV-all | 55 | 16 | 6 |
| PV-all-10kW | 55 | 16 | 6 |
| PV-only | 55 | 0 | 0 |
| BESS-all | 31 | 55 | 6 |
| BESS-only | 0 | 55 | 0 |
| EV-50 | 31 | 16 | 28 |
| EV-all | 31 | 16 | 55 |
| EV-only | 0 | 0 | 55 |
| DERs-all | 55 | 55 | 55 |

The model used in this thesis is based on the framework presented by García-Muñoz et al. The deterministic three-stage optimization model is used to self-manage congestion arising within an energy community through P2P trading and an LFM. In this thesis, EVs are incorporated into the model, reflecting their rapidly growing share in the global vehicle fleet and their potential to provide flexibility through load shifting and vehicle-to-grid. A case study including 10 cases with varying levels of DER penetration, considering PVs, BESS, and EVs, is developed and applied to the model.

The three stages include an individual optimization problem, followed by an optimal power flow (OPF) problem, and lastly a congestion management problem. In the first stage, each agent individually optimizes their energy dispatch and use of DERs to minimize their total energy costs. In stage 2, the DSO evaluates the aggregated user schedule using an OPF model to detect possible line congestion. In the third stage, the congestion model utilizes DER flexibility and P2P trading to relieve congestion while minimizing the deviation from the original user preferences. The optimization problems in stages 2 and 3 employ a second-order cone programming (SOCP) formulation to relax the nonlinear optimal power flow constraints.




$$\min z_{1,i} = \sum_{t \in T} \lambda_t^{bg} \Delta p_{i,t}^{-} - \lambda_t^{sg} \Delta p_{i,t}^{+}$$

$$\min z_2 = \sum_{t \in T} \sum_{i \in A} \lambda_t^{bg} pk_{i,t}^{bg} - \lambda_t^{sg} pk_{i,t}^{sg}$$

$$\min z_3 = \sum_{t \in T} \sum_{i \in A} \lambda_t^{bg} pk_{i,t}^{bg} - \lambda_t^{sg} pk_{i,t}^{sg} + |\delta p_{i,t}^{+}| + |\delta p_{i,t}^{-}|$$

**Calculation**

Some selected results are presented, including the congestion heatmap in the EV-all case and the Figure showing the aggregated power flows across all cases.

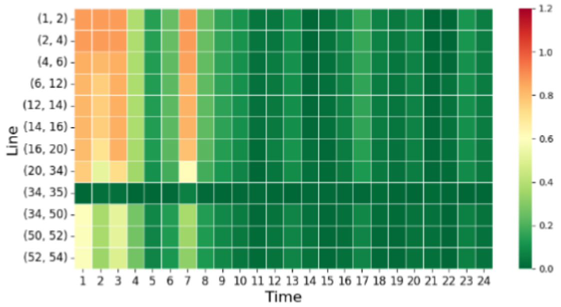
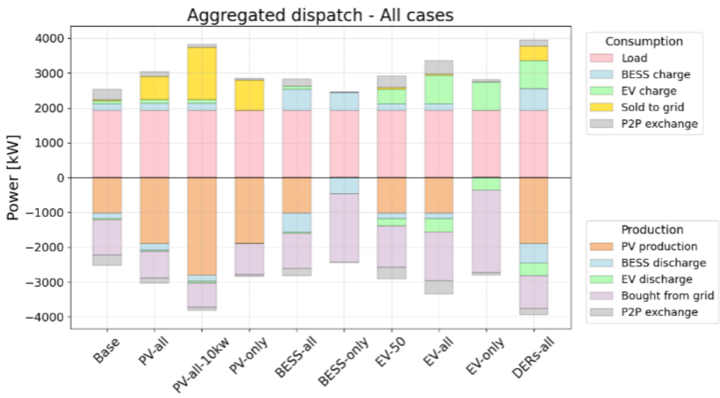



Figure 50: Congestion heatmap for stage 3 in the EV-al




**Conclusion**

The study highlights the effect that various DER deployments have on energy costs, energy autonomy, and congestion in energy communities. It is found that increasing the share of PVs and BESS generally reduces the energy costs compared to the base case, whereas cases with higher deployment of EVs increase the energy costs. The EV cases are less cost-efficient due to their constrained charging behavior, which leads to a high reliance on the grid in the morning when there is little to no local generation. All cases with a high penetration of EVs show an increased level of line flow in the mornings, due to simultaneous charging among agents. This congestion is mitigated in the congestion management model by re-dispatching the DER schedules set by the users in the individual optimization problem, while minimizing the deviations from user preferences. These results demonstrate the importance of collective coordination in avoiding congestion that can occur with a high share of EVs in the distribution network.

One of the highest self-sufficiency rates is seen in the case where the energy community is fully equipped with all DERs, underscoring the value of combining local generation and storage systems to reduce dependence on the main grid. This case also resulted in lower energy costs compared to the base case, however, congestion is detected when the agents act without coordination. This highlights the need for local market structures in an EC with high shares of DERs, as uncoordinated behavior can overload the network.

# Comparison of Current Controller Strategies for Active Front End Converters

Student: **Meløysund, Kristian**
Supervisor: **Nilsen, Roy**


## Abstract

PI controller with pulse width modulation is commonly used as a current controller for the Active Front End converter. In this thesis, four alternative current controllers with improved bandwidth are analyzed through numerical calculations and simulations: the hysteresis current controller, the deadbeat current controller, and two types of model predictive current controllers, CS-MPCC and FS-MPCC. The current controllers without a modulator, the hysteresis controller, and FS-MPCC, have been demonstrated to have better bandwidth than the PI controller, but the PI controller had better steady-state performance. The deadbeat controller and CS-MPCC exhibited the same steady-state performance as the PI controller but showed significant oscillations in their dynamic response.

# Recurrent Neural Network-based Optimization of Hydropower Scheduling in Competitive Electricity Markets

Student: **Miskeen, Rashid**
Supervisor: **Farahmand, Hossein**

**Abstract**

Global energy demand is growing rapidly. This leading to a greater focus on renewable energy sources. Hydropower is an integral part of the global renewable energy sector, which provides reliability, flexibility and storage capability in power generation. However, with growing market competition and the integration of variable renewable energy sources, optimizing hydropower scheduling has become a complex challenge. Traditional scheduling techniques suffer from computational inefficiencies, making them less responsive to real-time market conditions. In this research, we are using the application of machine learning models, including recurrent neural network (RNN) and long-short-term memory (LSTM) network, to better predict inflow, electricity prices, production and demand. The results indicate that the LSTM model is better at predicting for long-term trends and seasonal changes, which leads to more accurate forecasts and takes less time to calculate, based on the evaluation of various performance metrics such as NSE, MAE, MSE, RMSE and MAPE. These results support the integration of advanced machine learning methods for more economical and operationally efficient hydropower management in competitive electricity markets.

## Vurdering av 2D-modellers nøyaktighet ved beregning av luftledningers serieimpedans ved fjordkryssing – en 3D-basert FEM- analyse

Student: **Niklas Mjelde**
Faglærer: **Bjørn Gustavsen**
Veileder: **Martin Hovde**

### Problemstilling

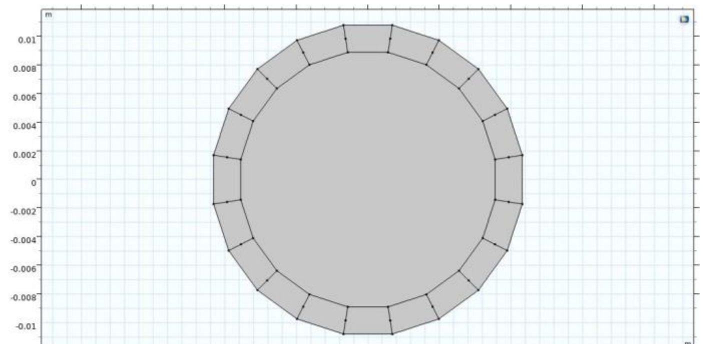
Både nettets størrelse og kompleksitet vil øke betraktelig i årene som kommer. Flere norske nettselskaper vurderer derfor å endre dagens systemjording fra spolejording til direktejording. Dette åpner for automatisk utkobling av jordfeil basert på målinger av nullsekvensstrøm i tilknyttede nettstasjoner. For å sikre korrekt innstilling av jordfeilvern er det avgjørende å beregne serieimpedansen til luftlinjer med høy nøyaktighet. I dag benyttes i stor grad analytiske metoder som forutsetter homogen eller lagdelt jord. I praksis er dette sjelden tilfelle, spesielt ikke i det norske landskapet der luftlinjer ofte krysser fjorder eller områder med store variasjoner i jordens elektriske egenskaper.

### Oppgaven

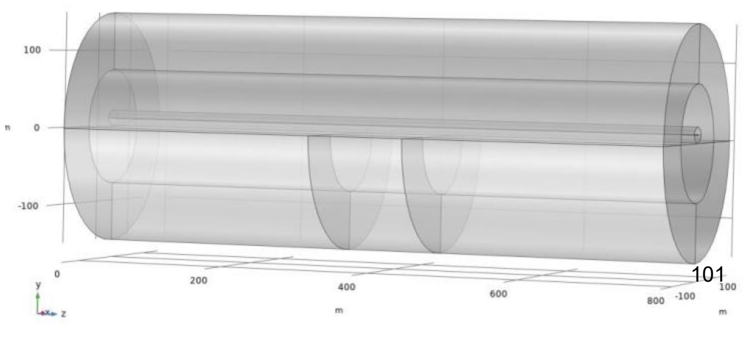
Denne masteroppgaven utvikler en 3D-modell i COMSOL Multiphysics som representerer en høyspentlinje over en jord-sjø-jord konfigurasjon. Målet er å undersøke hvordan en fjordkryssing påvirker returstrømmen og nullsekvensimpedansen til en høyspentlinje ved en jordfeil. Nullsekvensimpedansen fra 3D-modellen sammenlignes med en kaskade av 2D-modeller for å undersøke hvilke avvik som oppstår når overgangseffekter mellom jord og sjø neglisjeres.

### Modell/målinger

3D-modellen bygger på en enkel 2D-geometri som er ekstrudert 800 meter i z-retningen og som har en jord–sjø–jord-konfigurasjon. For å muliggjøre ekstruderingen er faselederne modellert som 20-sidede polygoner. Sjøseksjonen utgjør 125 meter, og modellen har en radius på 150 meter. Ledningsevnen i jord og sjø er henholdsvis 0,01 S/m og 3 S/m. For å ivareta riktige grensebetingelser til tross for begrenset modellstørrelse er Infinite Element Domain benyttet. Beregningene er utført ved 2500, 1000, 500 og 250 Hz. Dette skyldes numeriske hensyn, ettersom modellen ikke konvergerer ved lavere frekvenser.

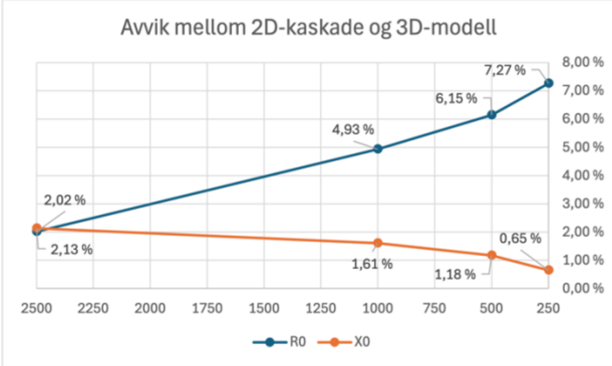


**Figur 1: Faseleder representert som et 20-sidet polygon i COMSOL**




**Figur 2: Oversikt over 3D-modellen i COMSOL med fjordseksjonen i senter**

**Beregninger**
Resultatene viser at det prosentvise avviket mellom 3D-modellen og kaskaden av 2D-modeller er økende for R0, men avtakende for X0 ved synkende frekvens. Ved 250 Hz er avviket i R0 7,27%, mens avviket i X0 er 0,65% og anses som neglisjerbart. Basert på utviklingen til R0 antas det et avvik på rundt 10% ved 50 Hz.



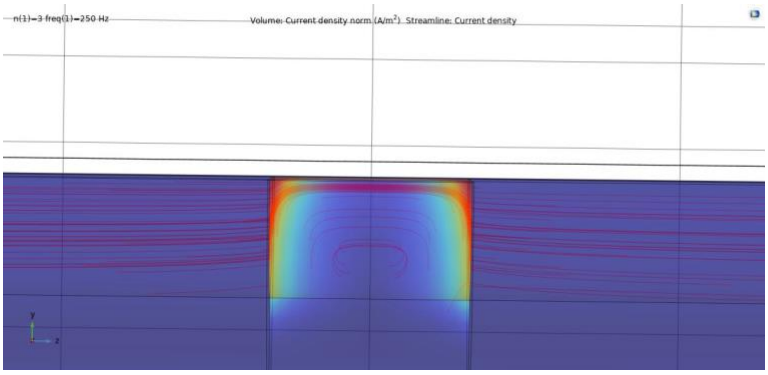

**Figur 3: Prosentvis avvik i R0 og X0 ved ulike frekvenser**

Tabell 1 viser beregnet R0 og X0 ved 250 Hz. Det observeres at X0 er omtrent syv ganger større enn R0. Avviket i R0 vil dermed ha liten betydning for Z0, både i størrelse og fasevinkel. Dette antas også å være tilfellet ved 50 Hz.

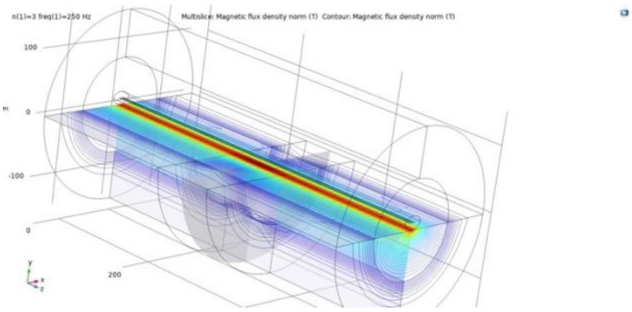
| | R0 | X0 |
|---|---|---|
| 2D | 0,6263 | 4,6916 |
| 3D | 0,6754 | 4,6611 |
| Diff [Ω] | 0,0491 | 0,0305 |
| Diff [%] | 7,27 % | 0,65 % |

**Tabell 1: R0 og X0 for 3D-modellen og kaskaden av 2D-modeller, ved 250 Hz**

Visualiseringene viser at den største endringen i strømbanen ved overgangene skjer i sjøen. Returstrømmen stabiliserer seg også betydelig langsommere i jord enn i sjø ved overgangene. Plott av magnetisk flukstetthet viser de samme tendensene hvor det er større tetthet i fjordseksjonen, men differansen er ikke like markant.



**Figur 4: Strømfordeling ved en fjordkryssing, ved 250 Hz**



**Figur 5: Oversiktsbilde av den magnetiske flukstettheten, ved 250 Hz**

**Konklusjon**
Ved beregning av nullsekvensimpedans gir neglisjering av overgangseffekter et målbart avvik i R0 som øker ved lavere frekvenser. Ved 250 Hz er avviket 7,27%, mens avviket i X0 er neglisjerbart. Denne utviklingen indikerer at avviket i R0 kan være rundt 10% ved 50 Hz. Likevel vil dette ha liten praktisk betydning ettersom X0 er klart dominerende og den totale nullsekvensimpedansen Z0 forblir tilnærmet uendret i både størrelse og fasevinkel. Dette antas også å være tilfellet ved 50 Hz til tross for at Z0 da vil være noe mindre dominert av X0.

På bakgrunn av dette indikerer resultatene i denne masteroppgaven at avviket mellom en 3D-modell og en kaskade av 2D-modeller, som ser bort fra overgangseffekter, er av liten betydning og kan anses som neglisjerbart. Fremtidig arbeid bør likevel prøve å utvide modellen til mer virkelighetsnære scenarier for å bekrefte dette.

# Modeling Harmonic Distortion and Resonance in an Offshore Windfarm- Effects of Harmonic Phase-Angle and Sensitivity Analysis

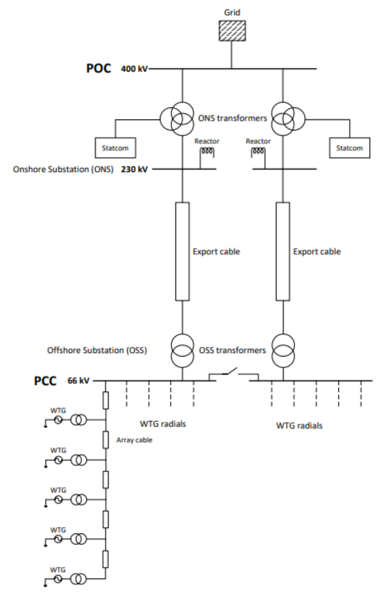
Student: **Albertin Rafuna & Magnus F. Moan**
Supervisor: **Sjur Føyen**
Contact: **Atle Rygg**
Collaboration with: **Equinor**

## Problem description

The development of offshore wind farms presents major opportunities for sustainable energy production, but also introduces challenges related to harmonic distortion and resonance. These challenges are caused using power electronic converters and long submarine cables, which generate harmonic components and create resonant conditions. This interaction can lead to power quality issues and violations of standard limits. However, these limits are often based on worst-case assumptions that neglect phase-angle variations in harmonic sources. Such variations can lead to cancellation effects and lower distortion levels. This suggests that current standards may be conservative. This can lead to overly conservative designs and unnecessary costs.

## The task

Develop a Python-based model of a wind farm using realistic data for resonance and harmonic analysis. Analyse harmonic distortion and identify potential resonance conditions within the system. Perform a sensitivity analysis to evaluate how the phase angles of harmonic sources and variations in component parameters influence harmonic voltages. Compare results with the limits specified in current IEC standards. Finally, investigate possible mitigation measures using passive filters.

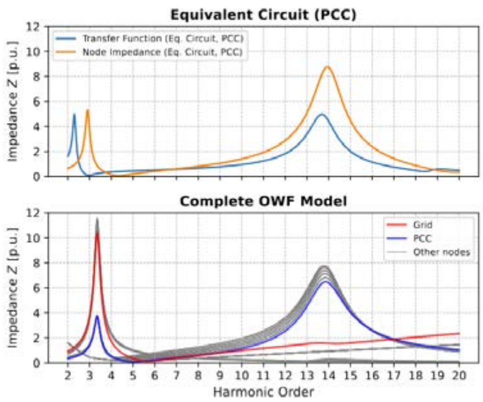


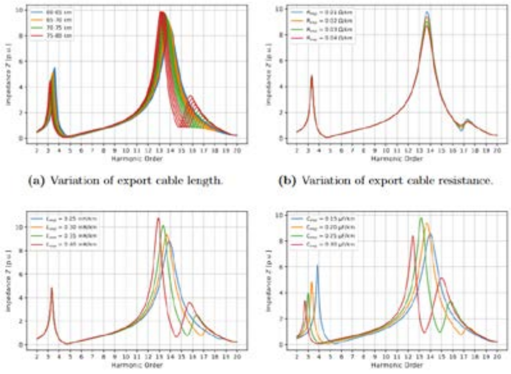

## Model/ measurements

Components parameters were provided by Equinor. Cables were modelled using a cascaded lumped π-model with interpolation to capture frequency-dependent effects. Transformers were represented using the Funk-Hantel model. Resonance conditions were analysed through frequency scans of transfer functions and nodal admittance matrices. Harmonic voltages were studied using the current source method, allowing for variation in phase angels of injections and component parameters. "The study is conducted in the frequency domain".

## Results

The resonance analysis showed resonances around the $13^{th}$ and $14^{th}$ harmonic orders. Both the simplified equivalent circuit and the complete OWF showed resonances at the same points. To assess the influence of harmonic sources and evaluate the impact of phase angle variation on harmonic voltages, a full-scale model was required. The results show that cable capacitance, transformer reactance, and cable length are key factors influencing resonance frequencies. Accurate cable modelling proved important due to its strong influence.

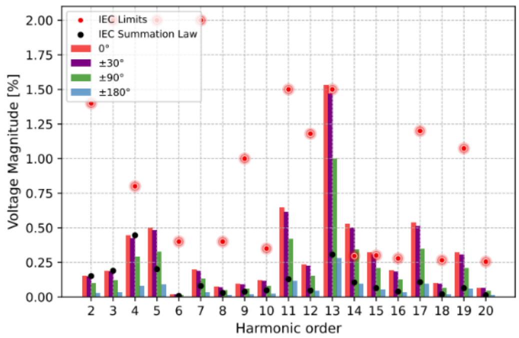


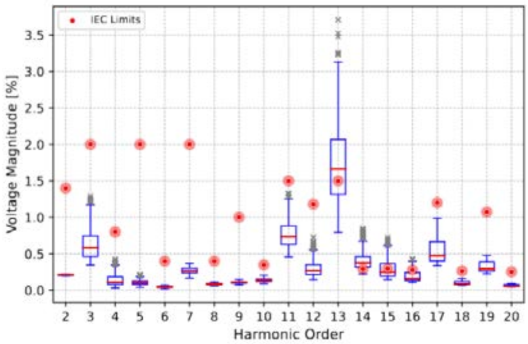



(a) Variation of export cable length. (b) Variation of export cable resistance.

(c) Variation of export cable inductance. (d) Variation of export cable capacitance.

Sensitivity analysis demonstrated that small variations in component parameters change resonance frequencies, thereby influencing whether harmonic voltages comply with IEC limits. Including phase angle variation reduced the distortion levels due to cancellation effects. A comparison with the IEC 61000-4-7 summation law revealed limitations of the standard method as it may over- or underestimate harmonic levels, depending on the harmonic order.




Both series trap and C-type filters effectively mitigated critical harmonics, with the C-type offering a more balanced response and practical benefits for offshore use.

**Conclusion**

The highest harmonic distortion was observed at resonance points, resulting in IEC limit violations. Variation in phase angles led to cancellation effects that reduced distortion, suggesting that worst-case assumptions may overestimate actual levels. Passive filters installed at the PCC successfully reduced harmonic voltages at the tuned frequency. The sensitivity analysis showed that small changes in parameters can shift resonance points and cause other harmonic orders to impact compliance with IEC standards. This highlights the importance of accurate cable modelling. In offshore wind farms, including phase angle variation gives more realistic results and may reduce the need for mitigation and overly conservative design limits. This should be considered in future harmonic studies.

# Revisiting Nuclear Power in Denmark's Energy Transition: A Scenario-Based Analysis Using EnergyPLAN and PyPSA-Eur

Student: **Moen, Kamilla Aarflot**
Supervisor: **Nøland, Jonas Kristiansen**

**Abstract**
As Denmark aims for a carbon-neutral energy system by 2045, the potential role of nuclear power remains highly debated. While previous studies have generally concluded that nuclear is too costly compared to wind and solar power, this thesis finds that nuclear power, especially with district heating integration, can represent a cost-optimal pathway. This thesis revisits the role of nuclear power in Denmark's energy transition by reproducing and extending a prominent reference study using two complementary modeling tools: EnergyPLAN and PyPSA-Eur.

The analysis introduces updated cost assumptions for onshore and offshore wind CAPEX, nuclear OPEX, and hydrogen storage capacity. Additional scenarios and sensitivity analyses are conducted to capture the effects of investment and uncertainty, system flexibility, and weather variability. A custom implementation of nuclear combined heat and power (CHP) is also integrated into PyPSA to account for potential district heating applications.

The results show that under updated assumptions, nuclear power with district heating integration becomes cost competitive in several scenarios. However, the findings are subject to limitations, including simplified CHP modeling, perfect foresight, simplified planned downtime for nuclear technology, and non-optimized trade prices.

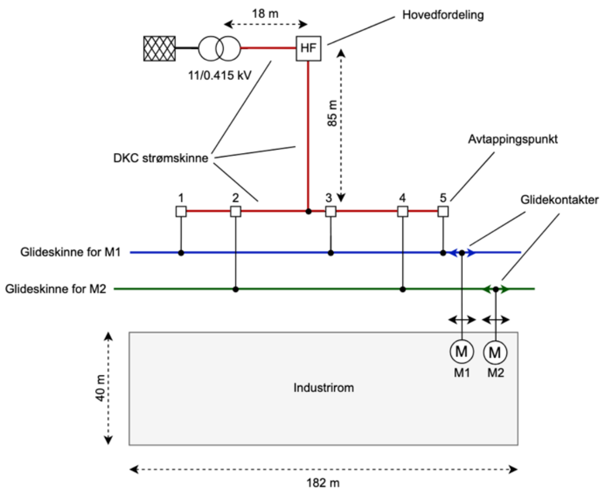
Overall, the thesis highlights that nuclear power consistently emerges as a robust, cost-optimal, and valuable part of Denmark's future energy mix. Its importance becomes even greater in high electrification scenarios or under limited interconnection expansion, where its stable power output and contribution to system reliability offer significant advantages.

# Dimensjonering av STATCOM i et industrielt lavspentanlegg med motorlaster

Student: **Eirik Andreas Mortensbakke**
Veileder: **Bjørn Gustavsen**
Utføres i samarbeid med: **Magtech og Statsbygg**

**Problemstilling**
I oppgaven gjøres det beregninger på spenningsfall og -stigning i lavspentnettet til et industrielt bygg som er under oppføring av Statsbygg. To motorlaster som står plassert på skinner og beveger seg på tvers av et industrirom forsynes fra en fordelingstransformator plassert over hundre meter unna. Akselerasjon og regenerativ bremsing av motorene vil føre til stort spenningsfall og -stigning i anlegget. Statsbygg er bekymret for at spenningen havner utenfor grensene satt av byggherren på ±0.05 per unit av referansespenningen og vil undersøke hvilke tiltak som kan gjøres for å bedre spenningen.

**Oppgaven**
Det skal bygges opp en simuleringsmodell av anlegget for å undersøke om spenningsfallet/stigningen mellom fordelingstrafoen og motorene blir for stort i forhold til kravene. Dersom dette er tilfellet, er målet å dimensjonere et Static Synchronous Compensator (STATCOM)-anlegg som ved hjelp av reaktiv effekt-kompensering kan holde spenningen ved motorene innenfor de definerte grensene. Motorene forsynes gjennom Active Front End (AFE)-drivere, og dette har innvirkning på effektfaktoren til motorene.



**Figur 1: Industrianlegget**

**Modell/målinger**
Modellen ble laget i simuleringsprogrammet PowerFactory, og brukt til å gjennomføre stasjonære lastflytanalyser. Simuleringene tar utgangspunkt i det mest kritiske tilfellet, som er når begge motorene akselerer eller bremser samtidig, helt fra enden av skinnene de står på. Effektfaktoren (PF) på lastene ble satt til PF = 0.95 induktivt og PF = 1.0. Fire hovedscenarioer, og to tilleggsscenarioer ble analysert. I tilleggsscenarioene ble det sett på alternative tiltak, uavhengig av STATCOM.

**Beregninger**
Resultatet fra hovedscenarioene viste at bremsing ga de verste spenningsforholdene. En av grunnene til dette er at fordelingstransformatoren skal være trinnet til 415 V på sekundærsiden, som er svært nærme den øvre spenningsgrensen på 420 V (1.05 p.u.) satt av byggherren. For å få spenningen innenfor grensene, var det i det verste tilfellet (PF = 0.95, bremsing) behov for totalt 3.0 MVAr reaktiv effekt absorbert fra STATCOM. Ved å ta utgangspunkt i produkter fra Magtech, kan dette løses med fem STATCOM-moduler, hvor hver modul har en kapasitet på 0.6 MVAr.

Tilleggssimuleringene viste at det finnes alternative tiltak som kan bidra til å forbedre spenningen ved motorene, men de er ikke alene nok til å komme innenfor spenningsgrensene i alle tilfeller.

**Konklusjon**

Analysene konkluderer med at kompensering er nødvendig for at anlegget skal tilfredsstille kravene til byggherren, og at bruk av STATCOM kan være et effektivt og fleksibelt verktøy for å oppfylle kravene.

## Congestion Management Using Optimal Power Injections for Power System Planning

Student: **Mulder, Arun**
Supervisor: **Oleinikova, Irina**

**Abstract**

Due to the rapid electrification, congestion has become a critical challenge in modern power systems, particularly in the Dutch grid. Capacity limitations are negatively affecting existing and new grid connections. Flexibility, represented by the ability to adjust power injections and withdrawals, offers a potential solution.

This thesis investigated the optimal distribution of congestion-relieving power injections in terms of time, location and quantity for energy system planning purposes. A methodology was developed to assess congestion and determine optimal power injection locations using a DC Security-Constrained Optimal Power Flow (SC-OPF) formulation. Where congestion was defined as a state in which an increase in power flow on one or more network branches would lead to the violation of operational security limits. The approach was based on Power Transfer Distribution Factors (PTDFs) and Line Outage Distribution Factors (LODFs) to model the effects of power injections, which represent flexibility. A 73-bus system was used to test with a year of hourly timesteps, considering both N-0 and N-1 security constraints.

According to the results, buses close to overloaded lines and at the end of radial lines are optimal to manage the congestion under N-1 constraints. The radial lines appear to be optimal due to the reduction of system losses. Under N-0 constraints, only buses close to overloaded lines were found to be optimal. The system experienced overloading for 67.4\% of the hours and needed 2,995,225 MWh to manage the congestion under N-1. By contrast, under N-0 constraints, overloading occurred in only 17.1% of the hours, requiring 279,264 MWh. Limiting optimal injection locations under N-0 increased energy needs by 58.2%, while N-1 constraints allowed multiple near-optimal solutions. Scenario comparisons also indicated that increasing branch limits reduced the required corrective energy, whereas imposing additional constraints on injections increased it.

These findings provide insights into the role of flexibility in congestion management for system planning and emphasize the location sensitivity of optimal solutions under different constraints. Future work should explore the sensitivity, uniqueness, and feasibility of solutions, as well as apply the methodology to real system data and location-dependent costs to enhance practical applicability.

# Short-circuit analysis of different winding layouts in a permanent magnet synchronous motor

Student: **Ola Nordvik Myrstad**
Supervisor: **Robert Nilssen**
Contact: **Andrea Bocchese**
Collaboration with: **Rolls-Royce Electrical Norway**

**Problem description**

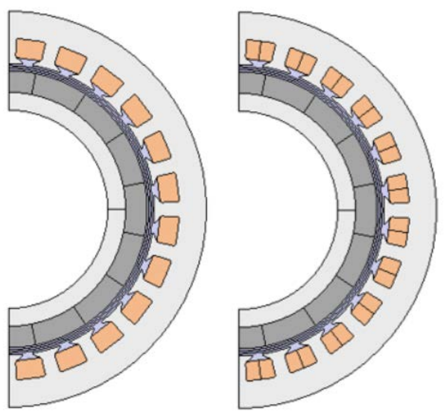
In recent years, advancements in permanent magnet technologies and high performance have made permanent magnet synchronous machines (PMSM) a suitable choice for many applications within aviation. The aircraft sector is consistently moving towards more electrification, and this drive towards electrification is heavily dependent on performance and reliability of electrical machines. In aviation, electrical machines have strict requirements for both power density and torque density. Specific requirements vary from case to case, but are generally demanding. Other requirements include efficiency, availability and cost-effectiveness. In addition to these design requirements, one of the most important aspects of an electrical machine intended for aviation is safety and reliability. Machine failure can have fatal consequences, and short-circuit testing is an important part of aviation design in order to ensure that a machine is safe to operate.

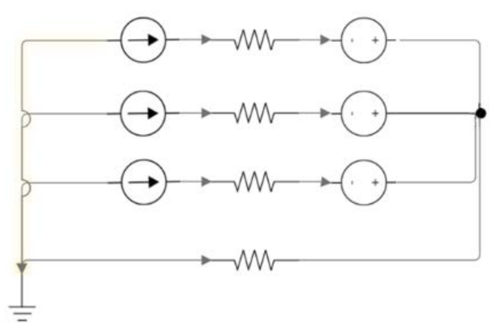
**The task**

In this master thesis, the goal is to observe the effects that different winding layouts have on the short-circuit currents.

**Model/ measurements**

A permanent magnet synchronous machine (PMSM) intended for aviation, originally designed in my specialization project, has been short-circuited in the FEA software COMSOL. The winding layout of the machine is changed from a single-layer distributed layout to a double-layer distributed winding layout, after which it is also short-circuited and evaluated for single-layer and double-layer concentrated windings. For concentrated windings 2 different versions were tested, one with changed stator slot sizes.

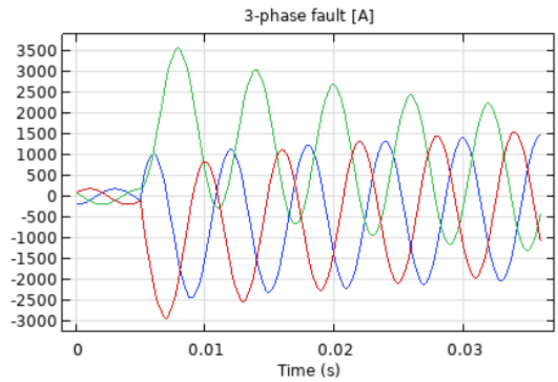


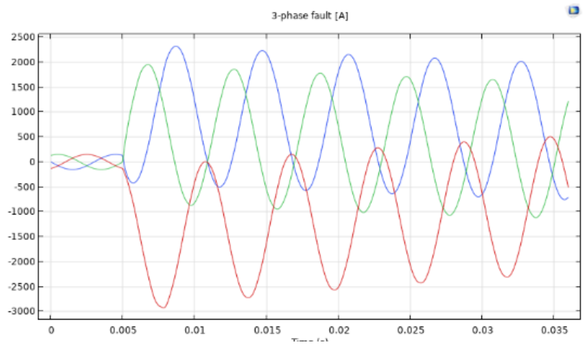


The figures above show the model implemented in COMSOL with single-layer distributed windings (left) and double-layer distributed windings (right), as well as the equivalent circuit that was used to short-circuit the machine.

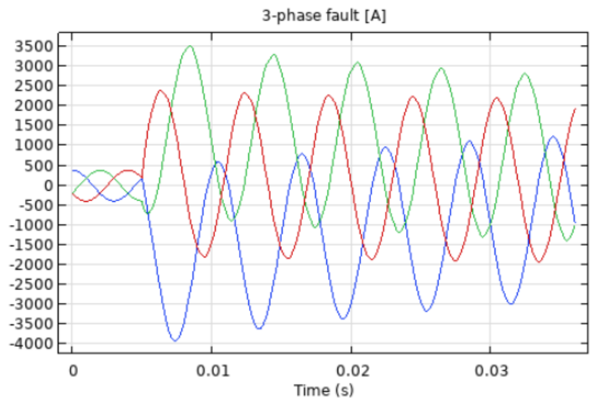
The model is short-circuited by linking the model to an equivalent circuit in COMSOL. It is tested for both 3-phase fault and 2-phase fault.

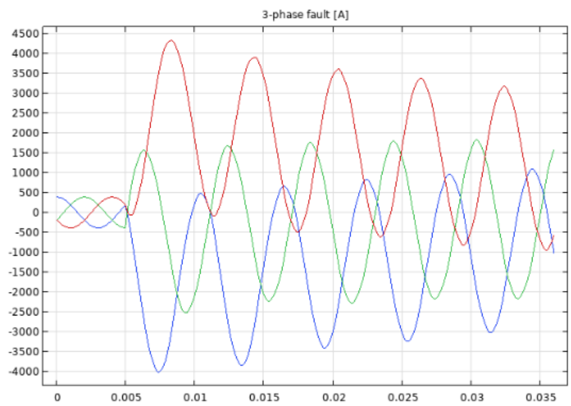
## Calculation




Short-circuit fault currents for 3-phase faults in single-layer distributed windings (left) and double-layer distributed windings (right).




Short-circuit fault currents for 3-phase faults in single-layer concentrated windings (left) and double-layer concentrated windings (right).

| Winding layout | 3-Φ [p.u.] | 2-Φ [p.u.] |
|---|---|---|
| Single-layer, distributed | 19.10 | 16.21 |
| Double-layer, distributed | 15.55 | 11.84 |
| Single-layer, concentrated | 8.96 | 6.23 |
| Double-layer, concentrated | 10.08 | 6.58 |
| Single-layer, concentrated (new slot size) | 10.10 | 6.60 |
| Double-layer, concentrated (new slot size) | 11.27 | 8.27 |

## Conclusion

The concentrated windings produced a lower peak fault current compared to the distributed windings due to a higher inductance. In order for the different winding layouts to achieve the same performance, the concentrated windings demanded a higher number of turns per coil. N 2/R = L shows the relationship between coil turns and inductance and can be used to explain the higher inductance in concentrated windings, and consequently a lower short-circuit. Double-layer have a higher fault value than single-layer. Since double-layer have different phases in the same slots and both phases cannot have max. current at the same time, the double-layer winding layouts will have a lower leakage reactance.

## Computation of Stator Core Losses in Synchronous Machines

Student: **Mølmen, Trygve**
Supervisor: **Nysveen, Arne**

**Abstract**
In this report a FEM model of a 100 kVA SM with 114 slots had its stator divided into 114 equal sections. Simulations showed that the core loss was similar with rated load or no load. With rated load the core loss deviated by a maximum of 5.1 % in one section compared to the average loss, due to the fractional slot winding. With no connected load, the core loss was the same in all 114 sections. This allowed for limiting the flux density investigation and core loss computation to only one such section. The presence of rotating flux density was investigated for a 105 MVA SM using FEM software. There were varying degrees of rotating and non-sinusoidal flux in the 24 points sampled in the stator section. There was more rotating B in the yoke, and more non-sinusoidal B in the teeth. The core loss density for the 24 points was computed using the Bertotti method in the frequency domain. The Bertotti coefficients were curve fitted in the FEM software, based on BP-data from the steel manufacturer. The loss density was highest in the teeth compared to the yoke, where the loss density decreased radially outwards. The radial and tangential B-data for one stator section was then extracted from the FEM software. The data included the coordinates of each mesh node. The loss density in each node was analyzed using the Bertotti method in both the frequency and time domain. The loss densities were integrated over the stator section using the coordinates to calculate the area of each mesh-element. The post-processing loss calculation was performed on both machines using a Matlab script. The loss in the stator section was extrapolated to the entire stator, and compared with measured/documented values. Both the time and frequency domain methods underestimated the losses. The loss density for each odd harmonic was plotted on the surface of the stator section. The harmonics contributed 13.2 % of the total losses for the 105 MVA SM. The Bertotti coefficients were investigated and curve fitted using a Matlab script. Loss calculations with new coefficients showed that the total loss is sensitive to the curve-fitting process. The separation of losses is poorly implemented when the coefficients are freely curve fitted. The implementation of the Bertotti method in this report could not predict stator core losses with an acceptable degree of accuracy for either machine. The likely sources of error were rotating B and material defects from manufacturing.

# Galvanisk korrosjon i driftsbygninger som følge av utjevningsforbindelser

Student: **Per William Dahl Måløy**
Veileder: **Eilif Hugo Hansen**

## Problemstilling

I driftsbygninger kombineres gjerne et fuktig og korrosivt miljø med bruk av metaller med ulike elektrokjemiske egenskaper. Samtidig fører skjerpede krav til potensialutjevning til elektrisk forbindelse mellom disse metallene. Dette skaper en krevende balanse mellom elsikkerhet og korrosjonsrisiko. Tiltak som skal beskytte mennesker og dyr mot elektrisk sjokk, kan samtidig øke faren for galvanisk korrosjon på metalliske komponenter som innredning og armering. Oppgavens overordnede problemstilling er definert som følger:

Hvordan påvirker kravene til potensialutjevning i driftsbygninger risikoen for galvanisk korrosjon, og hvilke tiltak kan redusere korrosjonsfaren uten å svekke elsikkerheten?

For å forsøke å besvare problemstillingen, er oppgaven delt inn i følgende delmål:

- Redegjøre for hvorfor driftsbygninger er spesielt utsatt for korrosjon.
- Analysere ulike galvaniske celler som kan oppstå i driftsbygninger.
- Forklare hvordan berøringsspenninger oppstår, og hvordan husdyr påvirkes av strømgjennomgang.
- Vurdere relevante tiltak for å redusere korrosjon i både eksisterende og nye driftsbygninger.
- Undersøke hvorvidt dagens krav til potensialutjevning av innredning er nødvendige, eller om de kan tilpasses uten å redusere elsikkerheten.

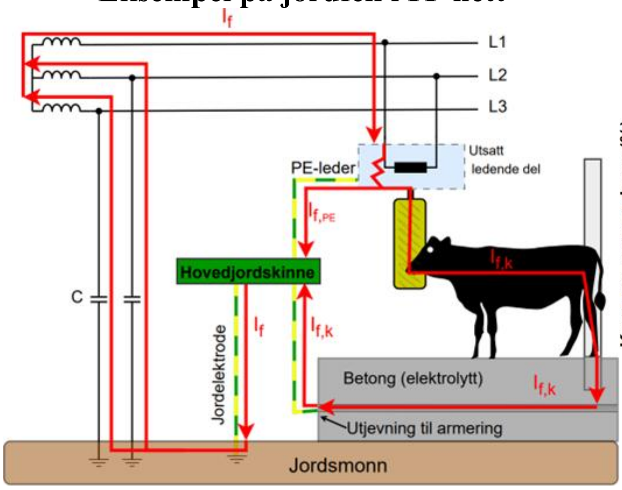
## Oppgaven

Oppgaven analyserer ulike galvaniske celler som kan oppstå mellom innredning, utjevnings-ledere og armering i nærvær av elektrolytter som husdyrgjødsel og fuktig betong. Det vises hvordan enkelte montasjeløsninger og feil utførelse av utjevning kan forsterke korrosjonsfaren betydelig. Samtidig vurderes risikoen for berøringsspenning hos husdyr, inkludert terskelverdier for atferdsendringer, ubehag og unnvikelsesatferd ved strømgjennomgang.

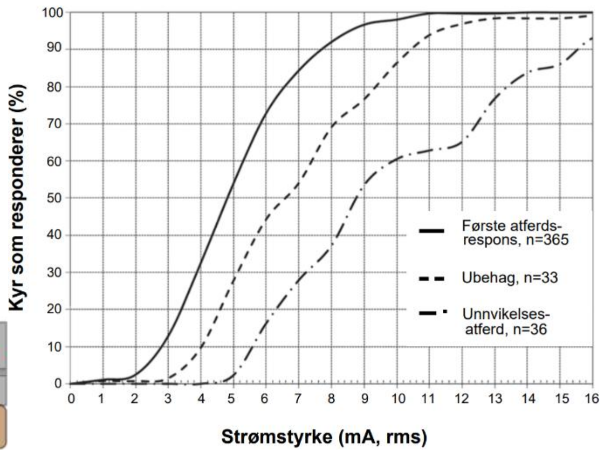
## Metode

Oppgaven er gjennomført som en litteraturstudie med mål om å undersøke sammenhengen mellom galvanisk korrosjon og krav til potensialutjevning i driftsbygninger. Arbeidet er rent teoretisk, ettersom det verken er utført målinger eller simuleringer. Det er likevel forsøkt å ha en praktisk tilnærming ved å trekke inn dokumenterte eksempler og erfaringer fra norske landbruksinstallasjoner der det har vært mulig, samt å beskrive konkrete tiltak som kan redusere korrosjonsfaren i slike bygg. Det er også utarbeidet en rekke figurer for å illustrere sentrale prinsipper, feilsituasjoner og anbefalte tiltak. Figurene er utviklet for å visualisere og tydeliggjøre ulike problemer og løsninger.

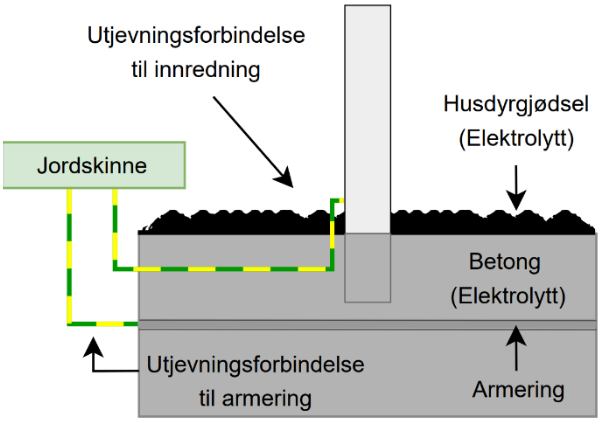
**Eksempel på jordfeil i IT-nett**



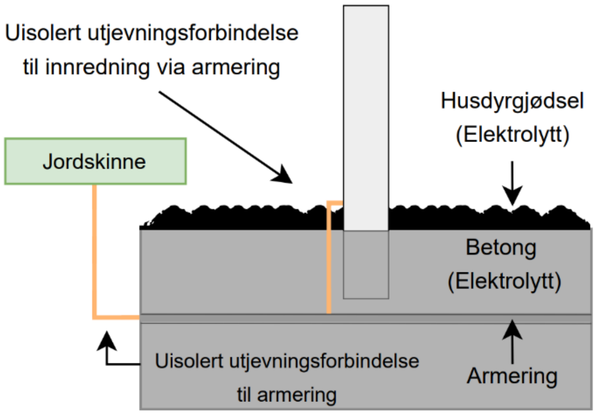

**Kyrs respons på strømgjennomgang**




**Korrekt utførelse av utjevning**




**Feilaktig utførelse av utjevning**




## Konklusjon

Oppgaven viser at galvanisk korrosjon i driftsbygninger kan reduseres vesentlig gjennom god planlegging og tverrfaglig koordinering, uten at det går på bekostning av elsikkerheten. Strømstyrte jordfeilvern gir effektiv beskyttelse mot elektrisk sjokk, men lave lekkstrømmer kan fortsatt føre til vedvarende berøringsspenninger som påvirker dyrevelferden negativt. Kravet om tilleggsutjevning av metallisk innredning vurderes som fornuftig, men må tolkes korrekt. Unødvendig utjevning, spesielt i fuktige miljøer uten tilstrekkelig isolasjon, kan øke risikoen for korrosjon.

I eksisterende bygninger bør utjevningsforbindelser gjennomgås og fjernes der det er faglig forsvarlig, samtidig som uisolerte ledere bør erstattes med isolerte og beskyttes mot elektrolytter. Ved direkte metallisk kontakt mellom innredning og armering anbefales det å etablere isolerende montasjeløsninger. I nybygg bør man minimere behovet for utjevning ved å bruke ikke-ledende materialer der det er mulig, eller beskytte metallisk innredning med isolerende belegg som bitumenmaling eller krympestrømpe. God ventilasjon og regelmessig renhold bidrar i tillegg til å redusere elektrolyttenes ledningsevne og dermed risikoen for korrosjon.

## The role of Small Modular Reactor in Decarbonizing Hydrogen Production

Student: **Davide Nevodini**
Supervisor: **Jonas Kristiansen Nøland**

### Abstract

This thesis investigates the integration of Small Modular Reactors (SMRs) with Solid Oxide Electrolyzer Cells (SOECs) to produce sustainable hydrogen for applications within the aviation sector. The research encompasses both thermodynamic and economic analyses, focusing on the feasibility, efficiency, and cost-effectiveness of such systems.

A MATLAB-based model was developed to calculate the Levelized Cost of Hydrogen (LCOH) for SOECs, considering electricity prices and capacity factors, and sensitivity analyses were performed to evaluate the system's economic robustness. Furthermore, an SMR-integrated hydrogen production model was designed using the HEEP software to incorporate the costs of nuclear energy and electrolyzer operation. Thermodynamic simulations in Simulink provided insights into the thermal coupling between SMRs and SOECs, with particular attention to optimizing energy flows and minimizing system instability.

The results highlight the potential of the SMR-SOEC system to achieve competitive LCOH values, approaching $1/kg by 2050, under favorable technological and economic assumptions. The thermodynamic matching analysis demonstrated that hydrogen extraction before the high-pressure turbine does not destabilize the system, ensuring stable operation and high cogenerative efficiency. Moreover, the system's co-location at airports was found to offer significant advantages by reducing transportation costs for hydrogen and electricity and minimizing infrastructure investments.

While the scientific feasibility has been established, economic challenges remain the primary obstacle to immediate implementation. The study concludes that further research into cost reductions for SOECs and SMRs, regulatory frameworks, and the potential for hydrogen as an aviation fuel is essential. If these challenges are addressed, the SMR-SOEC system could become a cornerstone for sustainable energy and hydrogen production, significantly contributing to the decarbonization of the aviation industry.

# Assessing the Impact of Capacity Reserve Dimensioning Methods on a Future Hydro-Dominated Power System


Student: **Eline Norvik and Julie Kathrine Wilborn**
Supervisor: **Gro Klæboe**
Contact: **Per Arne Vada and Bjørn Bakken**
Collaboration with: **Hafslund and Statnett**


## Problem description

As the share of intermittent energy sources such as wind and solar continues to grow, new challenges for the future power system are introduced. Unlike conventional dispatchable generation from hydro and thermal plants, the production from wind and solar is highly weather-dependent and less predictable, leading to greater variability and uncertainty in the power system. To ensure grid stability, the TSOs are responsible for reserving enough capacity that can be activated during real-time operation to manage unforeseen events. The European Union legislation enables the TSO's to adapt their systems and bidding zones to meet these capacity requirements. However, the regulation provides room for interpretation regarding how the reserve capacity should be dimensioned. This flexibility allows for different national or regional approaches, which may result in varying outcomes in terms of system stability, market efficiency, and cross-border coordination. It is therefore of interest to explore how these methodologies function in practice, as it is crucial that both the TSOs and the market design are adequately adapted to future system conditions.

## The task

This master's thesis aims to investigate the implications of different methodologies for capacity reserve dimensioning in a future power system. The analysis is structured around three scenarios with different levels of coordination, to highlight how varying approaches to reserve dimensioning may affect system outcomes. By applying identical assumptions across all other input parameters, the study isolates and compares the impact of the different dimensioning methodologies on future power system performance relative to the current situation. The impact of the dimensioning methods is evaluated through key indicators such as hydropower utilization and energy and reserve price development. This thesis contributes to current research by addressing a gap in the literature concerning how reserve requirements and market outcomes may evolve in hydropower-dominated systems.

## Model

To assess the impact of different capacity reserve dimensioning methods, a market-clearing model was developed for the Norwegian and Swedish power systems. The model minimizes operational costs while meeting hourly energy demand and reserve requirements, under constraints for production, transmission, and reservoir levels. Three scenarios with varying levels of cross-zonal coordination were implemented, each based on a shared reserve calculation framework incorporating reference incidents, normal imbalances, and a dynamic scaling factor reflecting voluntary bids. Input data for 2024 is based on historical values, while data for 2050 reflect predictions in generation mix and demand. The model, built in Python using Pyomo, was solved on an hourly resolution for a full year in both 2024 and 2050.

**Calculation**
Model simulations show that in 2050, the least cooperative dimensioning approaches result in infeasible solutions due to strict local reserve requirements. This particularly evident in SE4, which relies on slack variables for nearly 25% of the year to meet up- and down-regulation needs in the most conservative approach . In contrast, the coordinated approach allows flexible reserve sharing, leading to feasible operation and a 642 GWh increase in annual hydropower production compared to the current approach, despite identical inflow conditions.

Hydropower operation shifts toward more selective and efficient patterns in 2050, with increased use of the most efficient operating point and, in the coordinated scenario, more frequent operation at maximum capacity. Average energy prices increase from 2024 to 2050 in both scenarios, but remain consistently lower in the coordinated case. Reserve prices increase sharply in the current approach, while the coordinated scenario sees a more moderate rise, demonstrating the benefits of system-wide flexibility.

**Conclusion**
The results indicate that increased coordination in capacity reserve dimensioning leads to more efficient use of hydropower, as well as lower energy and reserve prices. In contrast, approaches with less coordination fail to meet future system requirements under the given assumptions, highlighting limitations in systems with a growing share of intermittent generation. At the same time, the thesis concludes that the assumptions behind the fully coordinated approach are unrealistic, and that a hybrid solution combining elements of both coordinated and uncoordinated approaches is both necessary and beneficial for the future power system.

## Surrogate Modeling of Electrical Machines in COMSOL

Student: **Nyhavn, Bendik**
Supervisor: **Nilssen, Robert**

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

**Student: Aleksander Gussøy Paulsen**

**Supervisor: Karen Byskov Lindberg**

**Contact: +47 46959196**

**Collaboration with COOP & Frigi/Aneo**

## Abstract

In recent years, Norway has given financial subsidies for buying electric vehicles (EVs) to reduce road transport emissions. This has effectively increased the number of private EVs, resulting in reduced greenhouse gas emissions (GHG) from this sector. However, GHG emissions from trucks and vans continue to rise due to a lack of investments in electric trucks, which have faced logistical challenges such as limited driving range, few charging stations, and high investment costs.

The thesis aims to optimize the logistical routes of COOP's logistics center in Trondheim, reducing annual driven distance by the truck fleet and the required number of trucks to operate the routes. Additionally, the thesis aims to minimize the total cost of ownership (TCO) of the operating truck fleet by evaluating the optimal mix of electric trucks with various battery capacities and biogas trucks. The simulated cases in the master thesis are tested with both depot-only charging and depot + mid-route charging of the electric vehicles.

The results demonstrate that the annual distance of the new optimal routes is reduced by 7% and the number of required vehicles is reduced from 19 to 15. This leads to a more efficient utilization of the truck fleet as the average distance by each truck increases by 17.8%.

The cases including depot-only charging demonstrate a composition of 53% to 73% electric trucks, resulting in average TCO of between 15.74 to 16 NOK per kilometer driven. The majority of these electric trucks are chosen to be Scania trucks, which have the largest battery capacity, and can therefore do longer trips without needing to charge. By introducing depot and mid-route charging for the same cases with reduced battery capacity, the truck composition of electric trucks increases to between 93% and 100% of the truck fleet. This results in a TCO cost from 14.98 to 15.16 NOK per km. Also, the results demonstrate that transitioning to a truck fleet consisting of around 80-90% electric trucks reduces Well-to-Tank (WTT) emissions by about 75% - 80%.

The results of this master's thesis conclude that optimizing the routes can reduce the number of required trucks and the annual distance covered by the truck fleet. Additionally, the results

indicates that the composition of the truck types should be aligned individually based on the specific routes, meaning an electric truck should not have an enormous battery capacity if the routes do not require it. Overall, Depot-only charging and depot + mid-route charging demonstrate a pathway for transitioning to electric trucks with reduced TCO cost, which also reduces GHG emissions. However, the results illustrate that the most efficient way to reduce emissions and total cost of ownership of the truck fleet is to invest in trucks with lower battery capacity to reduce CAPEX and charge the vehicles at the depot and mid-route. Additionally, this strategy allows for easier adjustments for potential route changes in the future.

## Model Predictive Control for Switching Power Converters in Hybrid AC/DC Microgrids

Student: **Rahman,Tanjida**
Supervisor: **Tedeschi, Elisabetta**

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

# Model Predictive Control with Adaptive Droop for Power Sharing in DC Microgrids

Student: **S M Sakiul Islam Ripon**
Supervisor: **Professor Elisabetta Tedeschi**
Co-Supervisor: **Dr Spyridon Chapaloglou**
Contact: **ripon.sakiul@gmail.com**
Collaboration with: **SINTEF Energy Research**

**Problem description**

DC microgrids will play an important role in sustainable energy transition because of their efficiency, flexibility, and reliability. One of the key challenges they face is to ensure proportional power sharing, which involves two conflicting objectives: (i) achieving accurate current sharing among sources; and (ii) maintaining voltage regulation within ±5% of the nominal voltage. Conventional control strategies often fail to achieve both objectives simultaneously under practical conditions, such as nominal voltage mismatch and uneven load distribution. They often adapt a hierarchical control strategy to ensure proportional power sharing, where primary layer uses decentralized droop control and secondary layer uses distributed controller with communication. However, lower droop resistance results in tighter voltage regulation, while current sharing remains inaccurate. In contrast, current sharing improves at high droop gain, whereas the voltage regulation drops below the acceptable voltage level. To address this, secondary layer is added with the primary high droop gain. This approach compensates for the impact of the droop resistance by injecting a voltage shift term ($k_j$) and improved the voltage regulation to the acceptable range. However, achieving precise current sharing and parameter tuning remains challenging. This necessitates an effective method to ensure efficient, reliable, flexible, and dynamically adaptive power sharing.

**The task**

This thesis aims to implement model predictive control (MPC) as an effective alternative to traditional controllers. The work was carried out in two phases. In the first phase, conventional primary droop control and the secondary distributed control were implemented to validate the performance under two practical conditions: unequal nominal voltage and uneven load distribution. To address the limitations of them, an MPC algorithm using adaptive droop was proposed in the final phase of this thesis. The control algorithm was designed in MATLAB using the nonlinear MPC toolbox.

**Model and Measurements**

The test system consists of two DGs ($V_1$ and $V_2$), each supplying power to its respective local load ($R_1$ and $R_2$), shown in Figure 1. The manipulated variables are $R_{d1}$ and $R_{d2}$. The main goal of the MPC algorithm is to ensure $I_1$-$I_2$ is small (ideally zero) and to regulate $V_{C1}$ and $V_{C2}$ within ±5% of $V_1$ and $V_2$, respectively. (where, $V_1 = V_2 = 48$V).

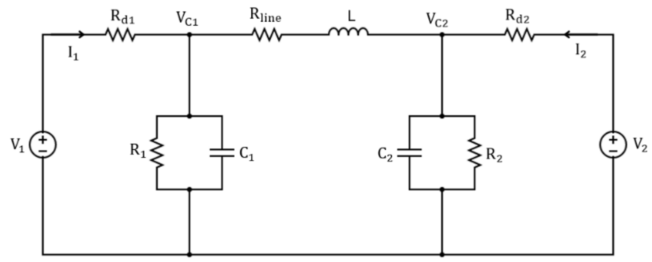



Figure 1 Equivalent Circuit of DC Microgrid Test System

For evaluating conventional control strategies, low droop gain of $R_{d1} = R_{d2} = 0.25\ \Omega$ and high droop gain of $R_{d1} = R_{d2} = 2\ \Omega$ were considered. The shift gain $k_j$ was selected as 1.9 Ω. To overcome the limitations of these methods, an MPC algorithm was implemented using a quadratic cost function that includes both current sharing and voltage regulation. In the formulation, constraints were imposed to the droop inputs, output voltages, and currents. Only the first control input of $R_{d1} = R_{d2} = 1\ \Omega$ was applied, which was then automatically adjusted based on system requirements, as shown in Figure 2.

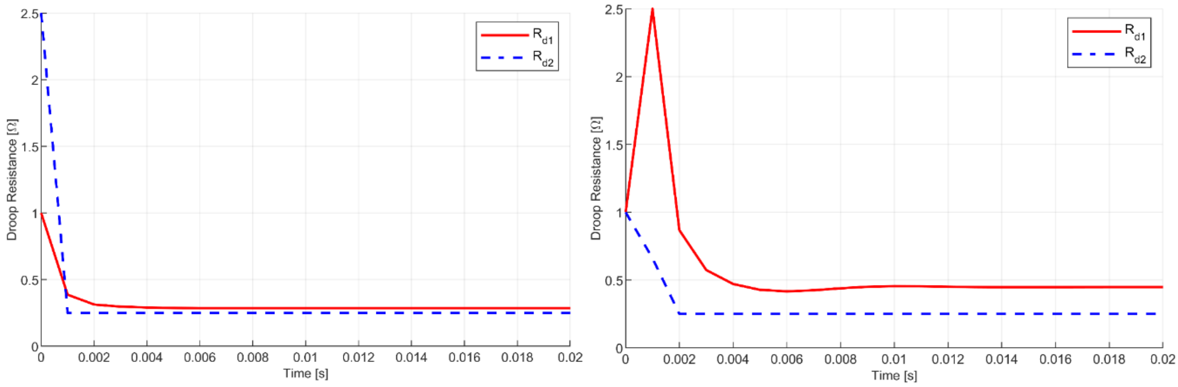



Figure 2 Dynamic adjustment of droop resistances using MPC under
(a) Unequal Nominal Voltages (b) Uneven Load Distribution

## Results

The performance comparison of different control methods is shown in Table 1 and Table 2.

**Table 1: Performance Comparison of Different Control Methods for Power Sharing under Nominal Voltage Mismatch**

| Parameter | Primary Decentralized Droop Control | | Primary Decentralized Droop + Secondary Distributed Control | MPC (Replacing primary and secondary) |
|---|---|---|---|---|
| Droop Settings | $R_d = 0.25\ \Omega$ | $R_d = 2\ \Omega$ | $R_d = 2\ \Omega + k_j = 1.9\ \Omega$ | Adaptive gain $R_{d1}$=0.30 Ω, $R_{d2}$=0.25 Ω |
| Voltage Regulation | ~2.8% | ~22.2% | ~1.3% | 2.3% |
| Current Sharing Error | 0.57 A | 0.09 A | 0.09 A | ~0 |
| Voltage Regulation within ±5% | Yes | No | Yes | Yes |
| Current Sharing Performance | Moderate | Good | Good | Best |
| Real-time Adaptability | No | No | No | Yes |

**Table 2: Performance Comparison of Different Control Methods for Power Sharing under Uneven Load Distribution**

| Parameter | Primary Decentralized Droop Control | | Primary Decentralized Droop + Secondary Distributed Control | MPC (Replacing primary and secondary) |
|---|---|---|---|---|
| Droop Settings | $R_d = 0.25\ \Omega$ | $R_d = 2\ \Omega$ | $R_d = 2\ \Omega + k_j = 1.9\ \Omega$ | Adaptive gain $R_{d1}$=0.45 Ω, $R_{d2}$=0.25 Ω |
| Voltage Regulation | ~0.97-1.76% | ~10.34-11.52% | ~0.02-1.07% | ~0-2.56% |
| Current Sharing Error | 2.43 A | 0.23 A | 0.23 A | ~0.04 A |
| Voltage Regulation within ±5% | Yes | No | Yes | Yes |
| Current Sharing Performance | Poor | Good | Good | Best |
| Real-time Adaptability | No | No | No | Yes |

In Table 3, the constraint handing capability of MPC is illustrated.

**Table 3: Constraint Handling by MPC During Simulation**

| Variable | Defined Limits | Observed Range | Constraint Violated |
|---|---|---|---|
| Capacitor Voltage ($V_{C1}$) | 45.6 V – 50.4 V | 46.8 V– 46.9 V | No |
| Capacitor Voltage ($V_{C2}$) | 45.6 V – 50.4 V | 46.9 V– 48 V | No |
| Source Current ($I_1$) | 0 A – 5.21 A | ~2.6 A – 5.2 A | No |
| Source Current ($I_2$) | 0 A – 5.21 A | ~2.6 A – 5.2 A | No |
| Droop Resistance ($R_{d1}$) | 0.25 Ω – 2.5 Ω | 0.30 Ω – 0.45 Ω | No |
| Droop Resistance ($R_{d2}$) | 0.25 Ω – 2.5 Ω | 0.25 Ω | No |

## Conclusion

Simulation results showed that the droop resistance adjusted automatically under both test conditions, which demonstrated the controller's ability to adapt to system conditions without relying on predefined gain values. The controller maintained acceptable voltage regulation without any deviations, and precise current sharing performance, outperforming conventional control methods. Furthermore, all system constraints were satisfied properly.

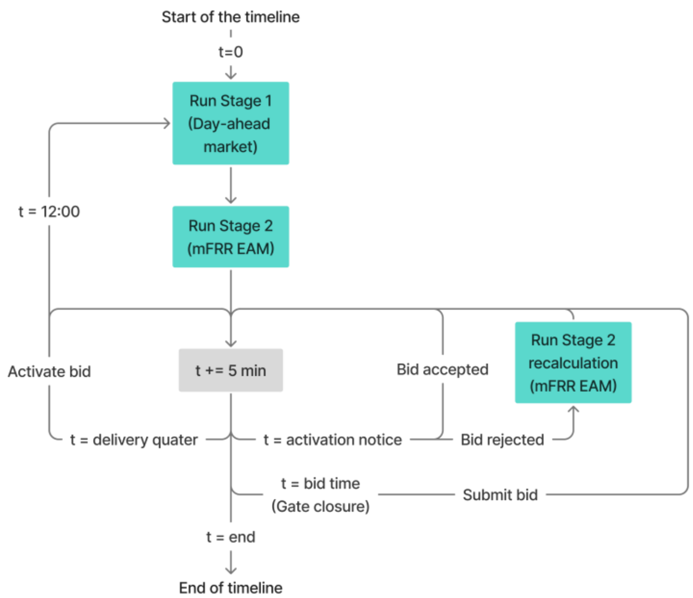
# Optimal scheduling and operation of a BESS in the mFRR market

Student: **Sander Rogndokken**
Supervisor: **Jayaprakash Rajasekharan**

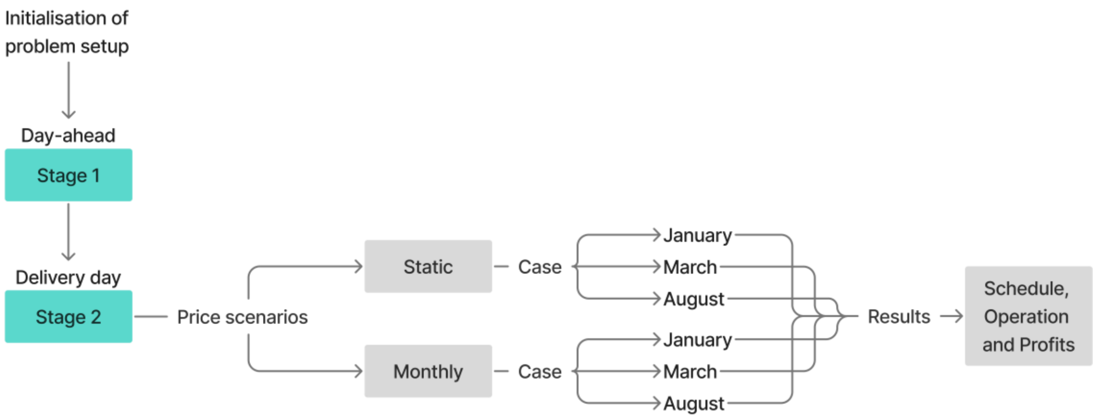
**Problem description**
The central analytical question guiding this research is: "How can batteries be optimally scheduled and operated in the day-ahead and mFRR energy activation markets?" To address this question, three main inquiries were examined. The first question investigated was: "What opportunities for scheduling and operating batteries in the reserve markets have been identified in existing research?" Additionally, the question "How can we manage the uncertainty of reserve market prices when incorporating them into an optimisation model?" was considered. Finally, the thesis answers the question: "Is a stochastic optimisation model suitable for managing the operation of a battery?" By answering these questions, a clearer understanding of the role and effectiveness of batteries in the reserve markets can be gained.

**The task**
To answer these questions, a literature review on the utilisation of batteries in reserve markets is presented first. Then, a two-stage stochastic optimisation model is developed to investigate the optimal scheduling and operation of batteries in the mFRR energy activation market.

**Model/ measurements**
The two-stage stochastic optimisation model is integrated into a rolling horizon timeline to operate over a week.




To different type of mFRR price estimations is developed, one static price distribution and one monthly dynamic price distribution. Each of these price distributions is used in three different runs, one week in January, March and August each, resulting in six different simulations.




**Calculation**
The results show that there is potential for profits by participating in the mFRR markets. The most amount of profits is gained in the January months. The monthly dynamic price estimations do not guarantee more profits but seems to use the battery less in markets with lower prices and usage that time of year. This will result in less strain on the battery for similar revenue gains.

**Conclusion**
The research questions were answered trough a literature review of relevant research, development of two different mFRR price estimation approaches and by developing a two-stage stochastic optimisation model and running six different cases. Future work should focus on expanding the reserve markets used and the types of flexible resources used. As well as, investigating more dynamic approaches to mFRR price estimations.

## Induced canning losses in FRAMO´s SX1000

Student: **Sandal, Karoline Løtvedt**
Supervisor: **Nilssen, Robert**

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

# Cost Modelling of Pink Hydrogen Production from Small Modular Reactors

Student: **Tomine Lysaker Sanden**
Supervisor: **Jonas Kristiansen Nøland**
Co-supervisor: **Martin Hjelmland**

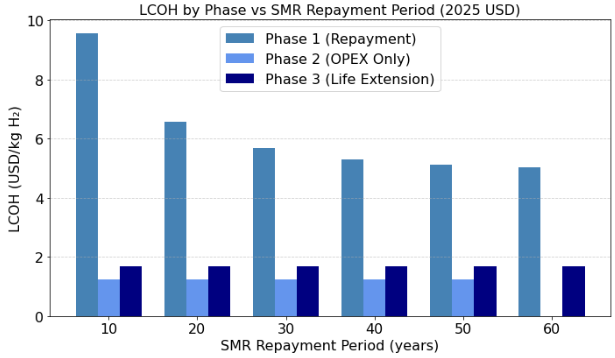
**Problem description**
The global transition toward a low-carbon energy system requires the development of clean hydrogen production methods. While electrolysis powered by renewable energy is a widely studied option, its intermittency poses challenges for large-scale, reliable supply. Nuclear energy, particularly in the form of small modular reactors (SMRs), has emerged as a potential low-carbon. Source of electricity and heat for continuous hydrogen production, commonly referred to as pink hydrogen. However, the capital-intensive nature of SMRs introduces economic uncertainty, particularly regarding how financing strategies affect the long-term cost of hydrogen. This creates a need for systematic cost modelling tailored to nuclear-electrolysis systems, with focus on investment recovery strategies.

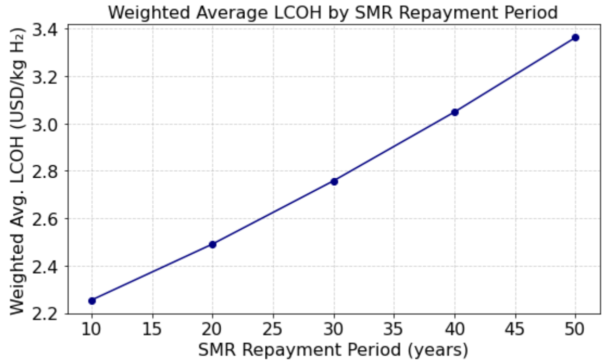
**The task**
This thesis aims to quantify how the choice of repayment period for SMR investments affects the levelized cost of hydrogen (LCOH) over the full lifetime of the system. The work focuses on cost dynamics across three operational phases: initial capital recovery, steady-state operation, and reinvestment for lifetime extensions. In addition, the model is benchmarked against external studies and applied to a Norwegian policy context, where nuclear energy is not yet part of the electricity mix, but where electricity demand is expected to grow substantially in the coming decades.

**Model/ measurements**
A custom techno-economic model was developed in Python to calculate LCOH as a function of SMR repayment time, system lifetime, operational expenditure (OPEX), reinvestment cost, and hydrogen output. The model uses annuity method for capital recovery and incorporates discounted cash flow logic to evaluate costs across all time periods.

The SMR capital cost is based on NREL's 2024 projections for nuclear in the United States, while OPEX includes fixed and variable components for both the reactor and the electrolyser. Lifetime extensions of the SMR are modelled at years 60 and 80, using cost estimates from IEA. The electrolyser is assumed to be replaced every 25 years, and the stack every 7 years. All future values are discounted at a 6% real rate, consistent with Norwegian investment guidelines.

**Calculation**
The LCOH is computed by dividing the present value of total cost by the present value of hydrogen produced over the full project horizon. Annuity-based capital recovery is used to reflect realistic financing. The model accounts for reinvestment in the SMR after 60 and 80 years based on a 100-year project lifetime, and periodic stack replacement of the electrolyser every 7 years. The cost evaluation is tracked on an annual basis to distinguish the effects of financial structure over time.




## Conclusion

This thesis shows that the choice of repayment period is a key driver of long-term hydrogen production cost in SMR-based systems. While pink hydrogen can be economically competitive over the full lifecycle, realising such projects in Norway would require fundamental policy and regulatory changes, as well as infrastructure development for both nuclear power and hydrogen. The model provides a forward-looking tool for exploring financial strategies in the planning of low-carbon hydrogen systems.

# Long-Term Partial Discharge Behavior of Protrusion and Free Metallic Particle Defects in Air-Insulated HVDC Gas-Insulated Substations

Student: **Sculac, Luka**
Supervisor: **Mauseth, Frank**

**Abstract**

High-voltage direct current (HVDC) has established itself as the leading technology for long-distance transmission, particularly for interconnections between countries and offshore wind farms. Sulfur hexafluoride (SF6) has traditionally been the preferred insulating medium in gas-insulated substations (GIS) due to its excellent dielectric properties; however, its high global warming potential (GWP) remains a significant drawback. Partial discharge (PD) detection serves as a critical diagnostic tool for ensuring the operational reliability of GIS systems. This study investigates the long-term PD behavior of protrusion and free metallic particle defects in HVDC GIS filled with technical air. The PD apparent charge magnitude and repetition rate evolution are analyzed using pulse sequence analysis (PSA) plots. Results indicate that PSA plots evolve and vary depending on the defect type, posing challenges for human experts and machine learning models in defect classification. Furthermore, most existing PSA plots are derived from test conditions using SF6, highlighting the need for research in alternative insulation gases such as technical air. Both conventional and unconventional PD detection methods were employed within a full-scale GIS test cell. The two defect types were subjected to voltage application for one week. The free metallic particle defect exhibited a 20% change in PD apparent charge magnitude over the test duration but showed minimal alterations in weight and physical structure. In contrast, the protrusion defect experienced a 30% increase in PD apparent charge magnitude, accompanied by significant physical changes, as revealed through microscope imaging. The observed changes in PD behavior after just one day of voltage application suggest that long-term testing in technical air is unnecessary. Similarly, PSA patterns from SF6 were successfully used to classify defects in technical air, demonstrating that knowledge transfer is possible. Finally, the similarities between certain patterns of free metallic particles and protrusion defects in technical air highlight the need for further investigation in different test environments to refine defect classification in future studies.

# Absolute Stability of a DC Networked-Controlled Microgrid


Student: **Sigurd Nordby Skeide**
Supervisor: **Gilbert Bergna-Diaz**
Contact: sigurdskeide@hotmail.com, gilbert.bergna@ntnu.no


**Problem description**

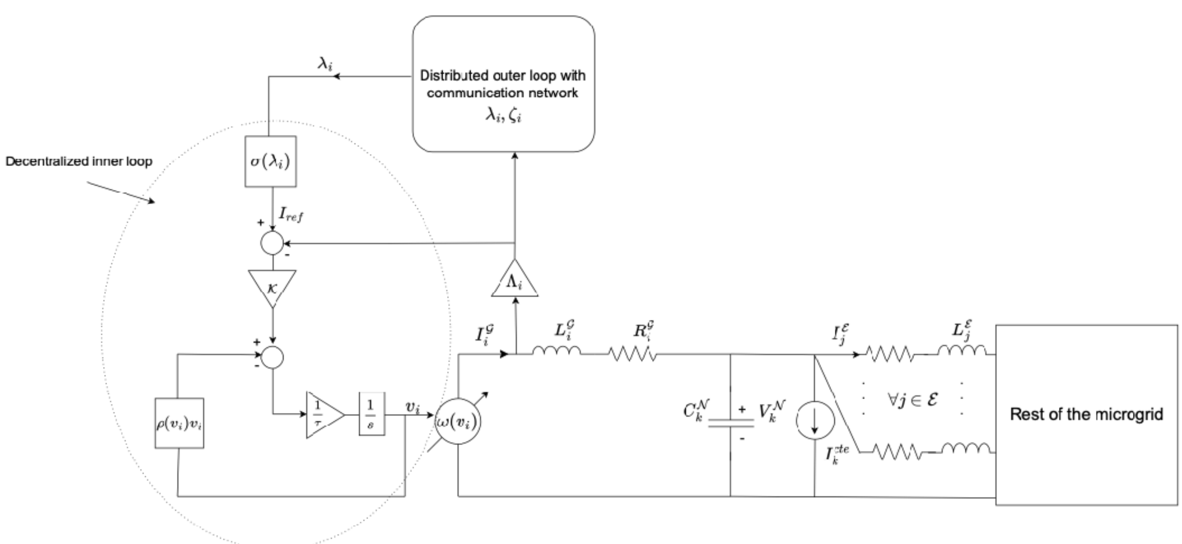
Establish conditions for absolute stability in a DC network-controlled microgrid using the Popov criterion, based on two case-specific scenarios. The first scenario analyzes a single DC converter to determine conditions for absolute stability, while the second extends the analysis to a small-scale microgrid with two interconnected units.

**The task**

The task of this master's thesis is to investigate absolute stability of DC microgrids using the Popov criterion, with a particular focus on systems incorporating multiple nonlinearities and outer-loop communication dynamics. Motivated by the limitations of traditional small-signal methods and the conservatism introduced by time-scale separation in singular perturbation theory, the thesis aims to establish a frequency-domain framework for proving large-signal stability. This is achieved through a two-step approach: first, by analytically applying the Popov criterion to a simplified single-converter system under voltage saturation, and second, by extending the analysis to a more complex MIMO system representing a microgrid with interconnected converters. The work seeks to both develop theoretical understanding and provide practical stability conditions and controller tuning recommendations.

**Model/ measurements**

The microgrid model used in this thesis is based on an established framework from the literature. However, as the focus of the thesis is on developing a frequency-domain approach for assessing absolute stability, no time-domain simulations have been conducted. Instead, the analysis relies on frequency-domain plots and stability assessments derived from state-space models and system matrices, evaluated using MATLAB.



## Calculation

The absolute stability calculations in this thesis are carried out using the Popov criterion, applied within a frequency-domain framework. The analysis begins with a simplified SISO Lur'e system representing a single DC converter subject to voltage saturation, where loop transformations and frequency-domain conditions are used to verify strict positive realness (SPR) of the system transfer function. This enables the construction of a suitable Lyapunov function, thereby confirming absolute stability on an arbitrarily large domain. The methodology is then extended to a more complex MIMO system modeling a small-scale DC microgrid with multiple interacting nonlinearities and outer-loop communication dynamics. Here, numerical tools in MATLAB are employed to assess the SPR condition of the system's transfer function matrix. Eigenvalue analysis and frequency-domain plots are used to derive tuning constraints that guarantee absolute stability under certain parameter values, without relying on time-scale separation assumptions.

## Conclusion

This thesis concludes that the Popov criterion is well suited for verifying absolute stability in fixed, small-scale DC microgrid architectures. Its strength lies in providing a frequency-domain framework that avoids conservative assumptions such as time-scale separation, making it a valuable tool for analyzing systems with known topology and parameters. However, due to the sensitivity of the transfer function matrix to changes in system configuration, the Popov criterion does not offer plug-and-play stability guarantees and is therefore less applicable to scalable or reconfigurable microgrids. Despite this limitation, the methodology developed in this thesis lays a foundation for an iterative design process, where controller parameters can be systematically tuned to satisfy frequency-domain stability conditions. Specifically, the results indicate that absolute stability in the MIMO system is achieved by slowing down both the decentralized inner control loops and the outer communication-based controllers. Thus, the Popov criterion not only enables formal stability verification but also provides practical insights into controller tuning for fixed microgrid configurations.

# Optimization of Export System for Offshore Wind Parks

Student: **Jo Emil Spakmo**
Supervisor: **Irina Oleinikova**
Collaboration with: **Equinor**

**Problem description**
When the power generated in an offshore wind park is exported to shore using high voltage alternating current (HVAC), as a transmission technology, the shunt capacitance of the submarine cables generates large amounts of reactive power. This reactive power causes issues with efficiency and violations of the system's operational limits. By strategically implementing reactive power compensation (RPC) and on-load tap changing (OLTC) transformers, this reactive power can be effectively managed.

**The task**
The task for this master's thesis is to investigates the impact of using RPC and OLTC transformers in HVAC export systems for offshore wind parks as well as how these technologies can be optimized such that the system wide losses are minimized.

**Model**
A wind park and its export system is modeled to investigate the effects placing RPC and OLTCs at various locations. Seven different configurations are investigated and optimized. To minimize the active power losses the system, an iterative gradient descent optimal power flow (OPF) algorithm is used. This algorithm is used to optimize the magnitude of RPC and tap-ratios for OLTC transformers for a range of power generation levels from the wind park. Optimal fixed reactances for passive RPC devices, that minimizes losses across all the generation levels, are also identified. This is found by using quadratic interpolation together with the equivalent reactances from the RPC found using the OPF.

**Findings and concluding remarks**
The optimization results show that the optimal operating points for RPC are higher when the generation from the wind park is low, and lower when the generation is high. Using multiple RPC devices in the export system shows to be the most efficient practice to reduce the losses, as this limits the magnitude of the generated reactive power and how far it needs to flow on the export cable. Additionally, utilizing the reactive power capabilities of the wind turbine generators (WTGs) proves advantageous at low generation levels, but is limited as the efficiency of the WTGs' converters and transformers are sensitive to low voltage levels. By implementing OLTC transformers into the export system, additional control over the voltage levels and the reactive power generated is achieved. The optimal operating points for the OLTC transformers shows to reduce the voltages on the export system at lower power generation levels, from the wind park, to reduce the reactive power generated by the export cable.

# Determination of External Thermal Resistance of Buried Power Cables by Interpolation of Lookup Tables Generated by FEA

Student: **Sivert Røyset Spalder**
Supervisor: **Bjørn Alfred Gustavsen**
Co-supervisor: **Martin Hovde**

**Problem description**

The current capacity of buried power cables is in large part decided by the thermal resistance of its surroundings. There exist standard equations for calculating this value for many cases, but for touching cables with unequal loading, such as bundled HVDC cables with Metallic Return, the use of Finite Element Analysis is generally recommended. This usually requires the use of software as for example COMSOL Multiphysics, which is both time consuming and seldom used by technical personnel.

**The task**

The goal is to create a way of determining this external thermal resistance for every cable in the bundle in an accessible and reliable way, given a set of parameters.

**Model**

2D cable models were created in COMSOL, including three cables in flat formation and a HVDC/MR bundle. Calculation of the thermal resistance was performed for a vast array of combinations of parameters. This data was used as a base on which to apply interpolation to calculate values that were not directly simulated. In addition a simplified model of the HVDC/MR bundle was created in an effort to generalise the power cable and make it applicable to any power cable. A simplified model has fewer parameters and is less computationally demanding, making it easier to work with when varying parameters of the cables.

**Conclusion**

Three main points made the interpolation of the values extremely accurate: Firstly, the logarithmic parameter spacing made the model accurate in parameter regions with high thermal sensitivity. Secondly, the choice of interpolation method (either cubic or radial basis function) interpolation. Thirdly, the logarithmic transform of the values pre interpolation, and the exponentiation post interpolation. In combination with the large data sheet created by simulation, this allowed for determination of any thermal resistance for a large spectrum of parameter combinations.

The simplified cable model showed promising results for when the internal cable structure was had similar ratios between cable layers, but struggled to replicate results for different models. Though some headway was made into how best to create a simplified cable model.

## Efficiency of Motor Drive Systems for Brunvolls Marine Propulsion

Student: **Steilbu, Henrik**
Supervisor: **Matveev, Alexey**

**Abstract**
This thesis investigates how different input power types, variable frequency drive (VFD) types, and PWM switching frequencies influence the efficiency of a 1 kW induction motor under varying load conditions. Two profiles were examined: a load curve and a propeller curve. Measurements were conducted using a sine wave supply from the grid and a programmable AC power supply(Itech) as well as three different VFDs (Schneider, Parker, and ABB). The results show that the grid supply performed better than the Parker VFD at partial loads (10–50%), likely due to lower iron losses. The Schneider VFD outperformed the sine wave from grid, contradicting the theory on the subject. Among the VFDs, the Schneider drive achieved the highest average efficiency (72.5%), outperforming both Parker (67.8%) and ABB (66.8%), possibly due to its superior control system.
Tests on the Schneider VFD further revealed that increasing the PWM switching frequency marginally improved efficiency. For the propeller curve case, the sine wave supply from the Itech achieved the highest efficiency (80.3%), slightly ahead of the Schneider VFD (79.0%), highlighting the impact of resistive and iron losses associated with VFD use.
These findings contribute to a better understanding of energy efficiency in electric propulsion systems and support the development of more sustainable maritime and industrial applications.

# Design and Life Cycle Assessment of an Insulation System for a Marine PMSM

Student: **Sophie Lægland Sundberg**
Supervisor: **Pål Stabel Keim**
Contact:
Collaboration with: **Kongsberg Maritime**

**Problem description**
Marine electric propulsion systems are a key part of the maritime industry's transition toward sustainability. While the reliability of electric machines is heavily dependent on the quality of their insulation systems, these systems are often overlooked in both design and environmental assessments. In particular, there is limited understanding of how insulation system design and material selection influence both operational performance and overall environmental impact.

**The task**
The primary aim of this thesis was to evaluate both the technical and environmental performance of an insulation system designed for a marine permanent magnet synchronous motor (PMSM). This included the development of a representative reference machine, analytical and simulation-based evaluation of the insulation system, and a life cycle assessment (LCA) of its environmental footprint.

**Model/ measurements**
A base case PMSM, based on a rim-driven azimuth thruster from Kongsberg Maritime, was analytically designed to provide a foundation for insulation system assessment. The insulation system was dimensioned using analytical models accounting for the electrical stresses induced by inverter-fed operation. Electrostatic simulations were performed in COMSOL Multiphysics to assess electric field distributions and identify critical stress regions.

**Calculation**
Analytical calculations determined the required insulation thicknesses for both mainwall and turn insulation, while simulation results quantified electric field distributions within the system. The environmental performance was analyzed using a cradle-to-gate LCA, with emission factors sourced from established databases.

- The electrostatic analysis showed that while average electric field strengths were within acceptable limits, local peaks at conductor corners exceeded the theoretical design threshold, highlighting the need for detailed geometric modeling and simulation-based verification.
- The LCA estimated the total carbon footprint of the insulation system at 77.9 kg $CO_2e$, with the impregnation resin identified as the dominant source of emissions and volatile organic compounds (VOCs).

**Conclusion**
The study demonstrates that material selection, particularly for impregnation resins, is critical for both technical reliability and minimizing environmental impact. Although insulation systems constitute a modest share of the total environmental footprint of a marine PMSM, they play a vital role in operational durability and regulatory compliance. A holistic approach that combines analytical modeling, simulation, and LCA is essential for the development of robust and sustainable insulation systems.

# Restoring Hydropower Flexibility Under Environmental Constraints: A Local Medium-Term Perspective

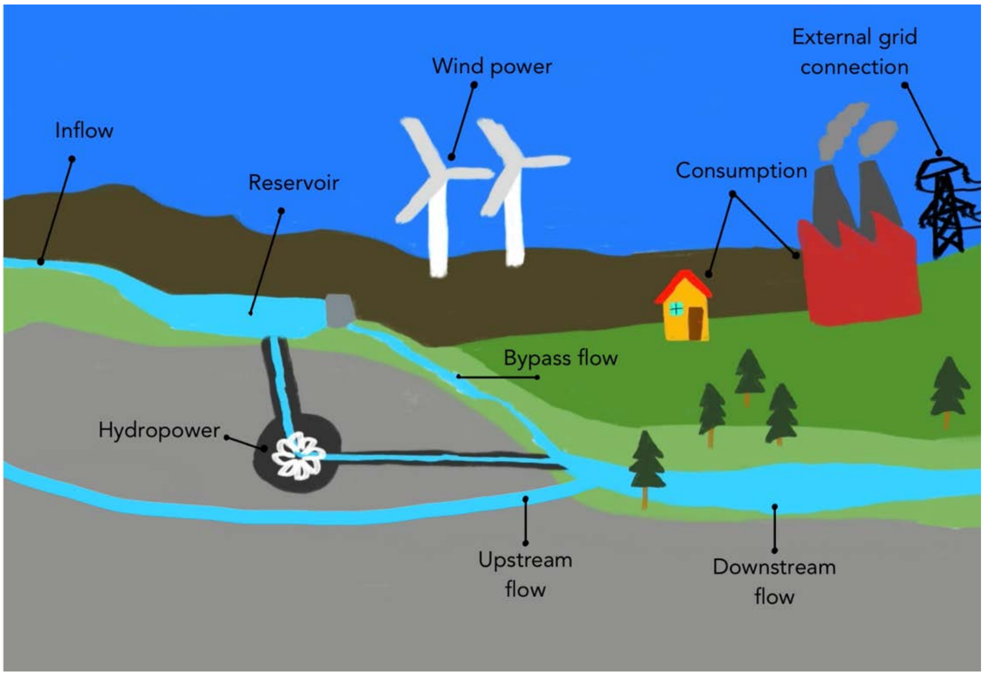
Student: **Jon Thore Mogen Thorset**
Supervisor: **Gro Klæboe**
Co-Supervisor: **Vivian Aubin**
Contact: jonthore@yahoo.no

**Problem description**
Norwegian hydropower plays a crucial role in ensuring energy security and flexibility in a renewable-based power system. However, the implementation of the EU Water Framework Directive imposes environmental constraints such as minimum environmental flows, ramping restrictions, and minimum turbine dispatch limits, which can significantly reduce the operational flexibility of hydropower plants. This poses a challenge to maintaining energy system adaptability while preserving aquatic ecosystems. The problem addressed in this thesis is how to restore flexibility in regulated river systems affected by such environmental constraints, without violating ecological requirements.

**The task**
This thesis investigates how lost hydropower flexibility due to environmental constraints can be restored. The study focuses on a specific case: a regulated river outlet hydropower plant inspired by the Svartelva system in Norway. The main tasks include:

- Modeling hydropower operations under likely combinations of environmental constraints.
- Implementing flexibility measures such as replaced turbine impeller and pumped storage hydropower
- Determining feasible methods for quantifying flexibility restoration by evaluating the ability of Flexibility Factor (FF), Equivalent Electrical Storage (EES) and Price Volatility Index (PVI) to accurately quantify flexibility restoration.
- Quantifying the effects using novel and established flexibility metrics

**Model/ measurements**
A Mixed-Integer Linear Programming optimization model was developed to model the operation of a hydropower-dominated system over a one-year horizon. The model includes key components such as reservoir inflows, power demand, wind production, bypass requirements, ramp constraints, and spot prices. A visual overview of the model structure is provided in the illustration below.




**Calculation**

Several scenario variants were constructed: Constraint sets (A, B, C) represent different levels and types of environmental restrictions. Flexibility measures (1: impeller replacement 2: pumped storage hydropower (PSH)) are tested across these constraint sets. The results are compared to eachother and the baseline scenario across the flexibility metrics and other key metrics that describe the system operation.

**Conclusion**

This master's thesis demonstrates that environmental constraints imposed by the EU Water Framework Directive significantly reduce the operational flexibility and production capacity of Norwegian hydropower systems. However, the research successfully identifies and evaluates viable strategies to restore this lost flexibility. The study highlights that technical upgrades can effectively compensate for these reductions. The findings emphasize the critical importance of balancing ecological preservation with system-level operational needs in a regulated environment.

For quantifying flexibility restoration, the combination of a modified version of EES and the PVI proved well-suited and insightful, capturing both operational and economic dimensions of system performance. While the Hydropower-specific Flexibility Factor (Hydro FF) and System-wide Flexibility Factor (System FF) offered less direct insights in isolation, their interpretation alongside total energy generation provided a clearer picture. The case study, focused on the Svartelva power plant, offers practical insights into how hydropower flexibility can be regained within a regulated framework. The work underscores that careful planning and strategic technical investments are essential to navigate the trade-offs between environmental stewardship and the increasing demand for grid flexibility.

# Learning by Doing in the Global Race for Clean Energy Dominance

Wright's Law Cost Modeling for Nuclear and Floating Offshore Wind from First Principles

Student: **Kristian Tibaldi**
Supervisor: **Jonas Kristiansen Nøland**
Co-supervisor: **Martin Hjelmeland**

**Problem description**

Projecting the future costs of clean energy technologies is a critical yet often oversimplified aspect of long-term energy planning. Most existing models assume that all capital cost components improve uniformly with scale, typically applying a single learning rate across the entire cost structure. This overlooks the reality that learning-by-doing primarily affects labor-intensive and process-related costs, whereas material inputs, such as steel, concrete, and specialized components, are governed by physical constraints, market prices, and regulatory standards. As the world pursues clean energy dominance, understanding where true cost reductions are achievable becomes essential, especially for complex technologies like nuclear energy and floating offshore wind (FOW).

**The task**

The aim of this thesis is to address these modeling gaps by developing a refined, learning-based cost forecasting framework that better aligns with the original principles of Wright's Law. Instead of treating capital costs as a monolithic figure, the model isolates learning effects to the overhead portion of construction, i.e. labor, engineering, and project management, while keeping material input costs unchanged.
This framework is applied to three strategically important technologies:

- **Large-scale nuclear power**
- **Small modular reactors (SMRs)**
- **Floating offshore wind (FOW)**

Together, these technologies offer complementary paths to clean energy security: nuclear power provides dispatchable baseload energy, while FOW opens up access to wind resources in deepwater areas beyond the reach of fixed-bottom turbines.

**Model/ measurements**

The analytical model separates total overnight capital costs into two categories:

- **Material input costs (MIC):** Determined from component-level quantity estimates and unit prices
- **Overhead costs (OH):** Representing labor, planning, and site-specific services

Two learning scenarios are modeled:

- **Fixed Learning Rate (FLR):** Applies a constant learning rate to the overhead share
- **Overhead-Weighted Learning Rate (OWLR):** Dynamically adjusts learning based on the relative size of the overhead component

Monte Carlo simulations are used to capture uncertainty in material prices, learning rates, and deployment trajectories from 2030 to 2050. Figures in the thesis visualize these simulations, comparing cost distributions under different modeling assumptions.

**Calculation**

Simulations show clear divergence in cost trajectories between the technologies:

- **SMRs** benefit the most from learning. Their compact design, low material intensity, and high overhead share enable significant cost reductions as deployment scales. By 2050, SMR LCOE is projected between $50–60/MWh, with some scenarios falling below $50/MWh. Overnight costs could drop below $2,000/kW through design standardization and process improvements.
- **Large-scale nuclear** has high cost-reduction potential, but this is contingent on consistent design and repeatability. Without standardization, learning is disrupted by bespoke, site-specific implementation. Nonetheless, under more uniform deployment, large reactors can approach SMR-level costs.
- **Floating offshore wind**, while scalable in theory, shows limited potential for learning-driven cost reduction. The physical layout must adapt to local seabed, depth, and weather conditions, hindering standardization. LCOE hovers around $125/MWh, with capital costs ranging widely from $4,000 to over $10,000/kW. Scenarios below $100/MWh remain unlikely under current technical and logistical conditions.

**Conclusion**

This thesis proposes a conceptual shift in how we model energy technology costs. By returning to the fundamentals of Wright's Law, where learning is linked to process and labor efficiencies rather than material inputs, it presents a more accurate, component-sensitive simulation of capital cost evolution. The results highlight that not all technologies are equally learnable: those with modular, overhead-intensive designs like SMRs are best positioned to benefit from experience and standardization. Others, like FOW, face structural limitations unless significant design convergence is achieved.

By disentangling where and how learning occurs, this work enhances the credibility of techno-economic projections and offers clearer guidance for policymakers, investors, and engineers shaping the future of the energy system.

## Current Commutation in a Mechanical DC Circuit Breaker

Student: **Anders Usland**
Supervisor: **Kaveh Niayesh**

**Problem description**

Due to the increasing need for electricity, renewable energy source is an upcoming field. Sources such as offshore-wind farms are placed a long distance from land, and the energy need to be transported over long distances. Transmission with HVDC is the best solution for long distance transmission. To integrate the offshore windfarms, a Multi-Terminal DC grid is a suitable solution. However, they contain sensitive power electronics that are vulnerable to high fault currents. Therefore, any fault needs to be interrupted fast. Additionally, due to the lack of natural current zero, where the energy in the system is zero, large DC currents can be challenging to interrupt. Therefore, current commutation can be used.

**The task**

Estimate the temperature during-, and after an electric switching arc, and determine the impact on the breakdown strength of the gas

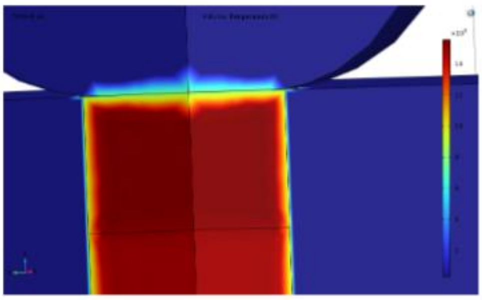
- Create a model to estimate temperature and arc radius during arcing
- Estimate heat dissipation after arc interruption
- Build a model and investigate how temperature effects the dielectric strength

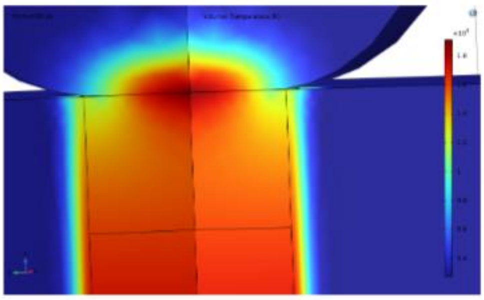
**Model**

By utilizing an already-made model that estimate the arc radius and arc temperature during arcing based on energy balance. It calculates the temperature and radius by iterations until convergence is achieved. However, the model is not time dependent. To overcome this, a newly formed equation is made that takes internal energy-changes into account, where thermal inertia is considered. The equation below presents the developed equation:

$$T_{n+1} = T_n + \frac{\Delta t}{\rho c_p}\left(\frac{I^2}{\sigma(\pi r_n^2)^2} - \frac{4kT_n}{r_n^2} - U\right)$$

The next part is to investigate the heat dissipation after successful current interruption. It is then created a COMSOL model that couple natural convection and conduction with heat transportation using non-isothermal Multiphysics. The outcome is a time-dependent heat dissipation after arc extinction. The figure represents the dissipated heat immediately after interruption until 500 um after interruption.

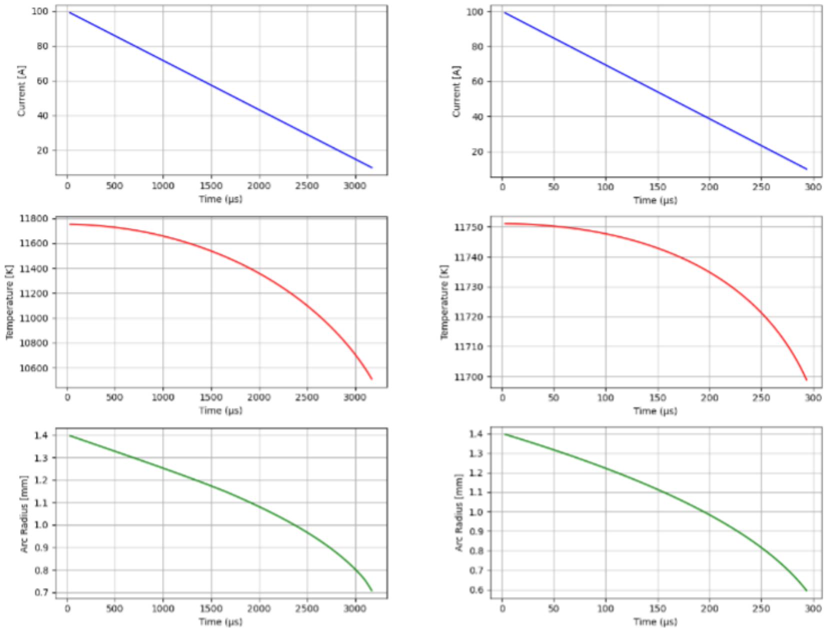




It is used Critical Field Theory to investigate the temperature after arc extinction affects the dielectric breakdown strength. This topic utilizes a reduced critical electric field that is dependent on the temperature and describes the ionization rate of the gas. It is used a simplified reduced electric field, where it is used a calculated guess to estimate the values when the temperature exceeds 6000 K. By using the values for critical electric field, and assuming a constant contact separation velocity, the critical electric field can be calculated for different scenarios.

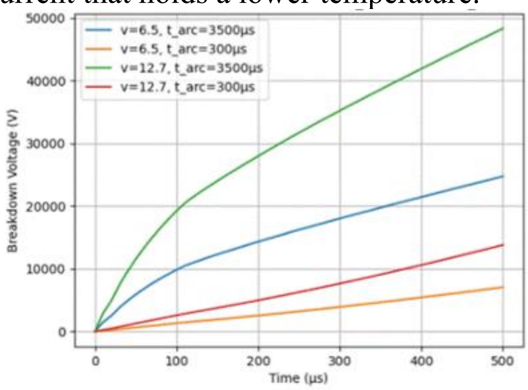
**Results**

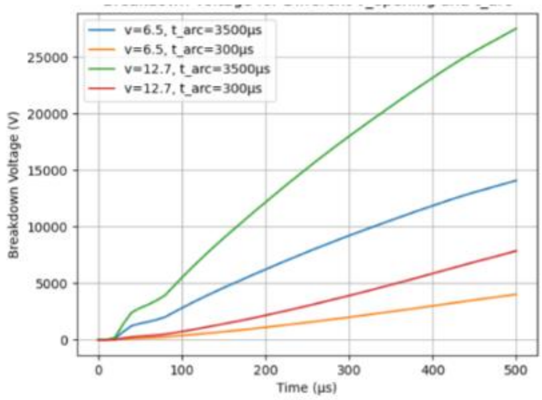
The findings of the arc temperature-, and radius model indicate that a longer arc duration has larger heat dissipation, and that the thermal inertia is more prominent for shorter arcs. This is because longer arcs come closer to the steady-state solution.




(a) 100 A current decrease over 3 500 µs    (b) 100 A current decrease over 300 µs

The breakdown voltage is highly dependent on the arc duration, and then dependent on the opening velocity of the switch. The dielectric strength is faster rebuild after a small arc current that holds a lower temperature.




**Conclusion**

The model for estimating temperature and arc radius gives an estimation of when thermal inertia and time-dependency is considered. However, it does not include the effect the arc has on the surrounding air. This propagates to the heat transfer model, that compared to experimental data estimated too rapid drop in temperature after extinction. Lastly, the calculation of breakdown voltage concludes that it is the arc duration that impacts the value the most. This is due to the inter-electrode is larger after the arc has burned for a long time.

# Value Stacking Battery Services Considering Local Voltage Support and Frequency Containment Reserves

Student: **Sigve Næss Walnum and Sigurd Sandvoll Vassmyr**
Supervisor: **Kasper Emil Thorvaldsen**

**Problem description**

Increasing electricity demand and the shift toward renewable energy generation have placed greater pressure on Norway's aging power grid. A greater penetration of Variable Renewable Energy Sources (VRES) into the power system creates challenges for both Distribution System Operators (DSOs) in terms of voltage control and Transmission System Operators (TSOs) for frequency regulation. To address these challenges, a Battery Energy Storage System (BESS) is a flexible option that can assist both the DSO through voltage support and the TSO through frequency market participation

**The Task**

The task of this thesis is to investigate how reactive power compensation can enable a grid-connected BESS to be used for local voltage support in a weak distribution grid, while simultaneously generating revenue through energy arbitrage and participation in the Frequency Containment Reserves for Normal Operation (FCR-N) market. In addition, the work aimed at providing insights into the effects of including battery degradation in the decision process to provide an accurate framework for multi-market participation.

**Model**

A mathematical model using the linear distribution flow-OPF method was developed to represent the distribution grid with a connected battery system at the outermost bus. To mitigate any potential voltage impacts from reserve activation, the model reserves capacity for reactive power compensation. This is done by simulating activation of reserves for each timestep in both directions in virtual grids to ensure that the system voltage remains within its bounds, also during activation in the reserve market. The model is tested on a medium-voltage (MV) distribution grid across several cases, first analyzing the impact of local voltage considerations in the case of activation, followed by an assessment of battery degradation effects.

## Results

4 cases were simulated where Case 1 (C1) yielded the highest revenue but would result in undervoltage in the event of reserve activation for downward frequency regulation. Figure 1 displays the voltages in the grid in the event of down regulation, meaning that the BESS absorbs active power to lower the system frequency. This is because the BESS bids close to maximum capacity in the reserve market across all hours.

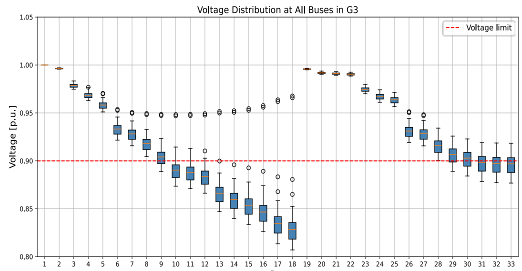



*Figure 1: Voltages Case 1 during worst-case activation*

When the battery system reserved capacity for reactive power compensation in the case of activation in Case 2 (C2), the battery system was able to maintain the voltage above the lower limit in case of activation, but total profits decreased by 28.6%. Figure 2 displays the voltages in the virtual grids, the FCR-N bid distribution and the reserved capacity for reactive power compensation in C2.

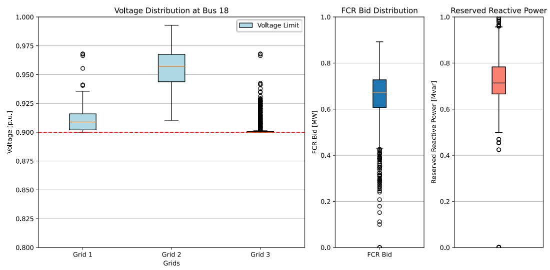



*Figure 2: Voltages, FCR bid, and reserved capacity for reactive power compensation*

When including degradation costs when cycling for energy arbitrage in Case 3 (C3), the model restricted arbitrage on smaller price differences, resulting in fewer discharging cycles and lower profits. The total profits declined by 19.06 % from C2 to C4 because of the extra degradation costs for both energy arbitrage and FCR-N market participation. Figure 3 displays the SOC of the BESS in all cases, illustrating that the battery system becomes less active when degradation is considered.

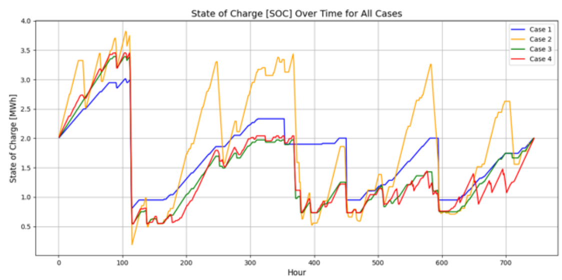



*Figure 4: SOC in all cases*

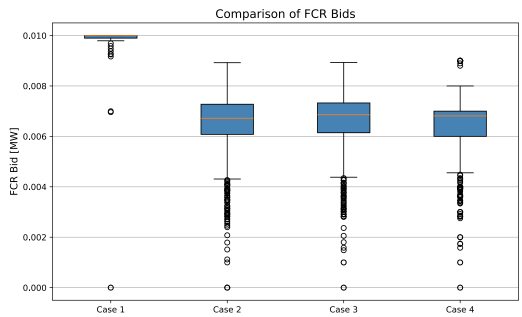



*Figure 3: FCR-N bids in all cases*

## Conclusion

The key findings reveal that by providing reactive power compensation, a BESS can participate in multiple markets while simultaneously mitigating potential local voltage issues. This thesis also highlights the importance of coordination between the TSO and DSO to ensure that activation of reserves does not cause local voltage deviations.

## Jording av avløpssystem i bolig

Student: **Stian Walderhaug**
Faglærer: **Eilif Hugo Hansen**
Veileder: **Eilif Hugo Hansen**

### Problemstilling

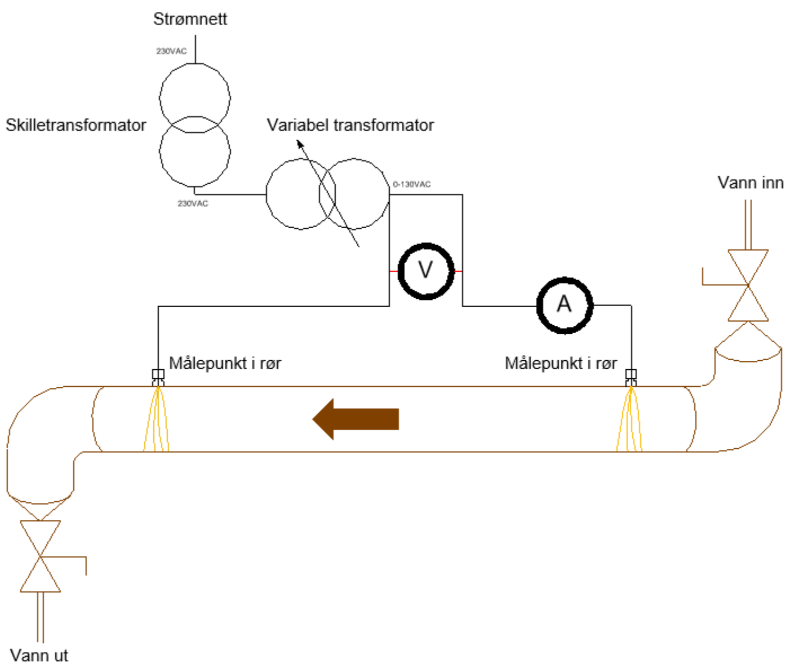
Helt siden «Forskrift for elektriske bygningsinstallasjoner» ble publisert i 1991(FEB-91) har utjevning av avløpssystem i boliger med aktuelle nettsystemer blitt utført hovedsakelig med jordingsmuffe. Løsningen med utjevning til innsiden av avløpssystemet ble innført på et begrenset teknisk underlag som ikke har vært etterprøvd i noen publisert rapport etter innføringen i 1991.

### Oppgaven

Denne rapporten er utarbeidet med tanke på å ytterligere kartlegge avløpssystemets jordfeilstrømmer opp mot dagens tiltak og eventuelt tilføre alternativer hvor dette er viser seg nødvendig. Evalueringen er bygget opp rundt teoretiske betraktninger av jordfeilscenarier og motstander, samt måling av rørføringer i lab og på aktive anlegg. Resultater er brukt for å kunne videre vurdere dagens løsning for utjevning i avløpssystemet og komme med alternativer hvor dette er nødvendig.

### Modell/målinger

Motstandsmåling av forskjellige typer avløpsvann og slam er utført i laboratorium og i et utvalg boliger. Det er brukt AC målinger med en påført målespenning på 25V-130V som er aktuelle jordfeilverdier i et 230V strømnett. Laben er utstyrt med flere lukkede horisontale røroppsett av typiske avløpsrør. Målepunkter med avstand brukes for å kartlegge resistiviteten til aktuelle medier i avløpsrørene ved måling av strømgjennomgang ved gitt spenning.




**Figur - Laboppsett for målinger av avløpsvann og slam**

Et definert område av relevante motstandsverdier har blitt kartlagt basert på resultatene. Aktuelle medier i avløpsrør er drikkevann, skittent badevann, vann med badesalt, varmt vann og varige slamavsetninger. 25V AC målinger er også brukt på aktive avløpssystem i boliger.

**Beregninger**
Målinger og beregninger viser at motstandsverdier i avløpssystemet kan variere innenfor et bredt spekter uavhengig av avløpsanleggets alder. Slamavsetninger vil kunne bidra til permanente jordfeilstrømmer i avløpssystemet, mens avløpsvannet kan bidra til vel så store strømmer i et rent avløpsrør. Begge situasjoner har sammenlignbare motstandsverdier og kan gi farlige feilstrømmer.

| | **110mm rør** | **75mm rør** | **faktor** |
|---|---|---|---|
| 2mm slambelegg(15°C) | (111,89kΩ/m) * | 165,59kΩ/m | (1,48) * |
| Rent vann(25°C) | 11,83kΩ/m | 26,70kΩ/m | 2,26 |
| Rent varmtvann(60°C) | 6,58 kΩ/m | 15,54 kΩ/m | 2,36 |
| Skittent badevann(25°C) | 10,13kΩ/m | (21,78kΩ/m) * | (2,15) * |
| Vann med badesalt(25°C) | 0,42kΩ/m | (0,90kΩ/m) * | (2,15) * |
| 1,1cm ribbefett(13°C) | (0,24kΩ/m) * | 0,35kΩ/ | (1,47) * |
| **Beregnet verdi basert på tilgjengelig måleverdi i alternativ rørstørrelse basert på omregningsformler i rapport* | | | |

**Konklusjon**
Siden den indre motstanden i avløpssystemet vil variere så mye at utjevning innvendig i avløpssystemet bare kan brukes for å hindre feilstrømmer fra andre kilder å nå utsatte våtsoner gjennom røranlegget. En lav berøringspenning under 50V AC kan ved utjevning i avløpssystemet ikke garanteres og heller ikke en høy feilstrøm over 30mA som kan sikre utløsing av jordfeilvern. Verdier for den totale isolasjonsmotstanden til jord kan kun garanteres ved utjevning av sluk ved tilstedeværelse av annen ledende del. En lokal jordingsmuffe på avløpsrøret er derfor ikke en akseptabel løsning som utjevning av avløpssystemet for våtsoner hvor utjevning er aktuelt.

Om ikke strømsmitte mellom sluker eller naboer er aktuelt. kan utjevning av avløp og sluker sløyfes siden anlegget vil ha en trygg isolasjonsmotstand til jord.

## Techno-economic study of wind energy investments in Europe

Student: **Waldum-Grevbo, Jonas**
Supervisor: **Cali, Umit**

**Abstract**

The energy market has been transforming for a significant amount of time. Climate change has necessitated the adoption of renewable energy sources (RESs); however, considerable implementation efforts remain to meet the objectives established by Europe and the European Union (EU). Wind power possesses substantial potential, and technological advancements facilitate the ongoing expansion of the wind energy sector.

This thesis performs a techno-economic analysis regarding wind energy investments in Europe. Simulated capacity factors using standard wind turbine design for onshore and offshore are used to differentiate the wind potential between various European countries. From these simulations, the lifetime cost for wind energy investments is calculated by using the Levelised Cost of Electricity (LCOE). Two cost scenarios are used for every turbine design to account for the variable costs related to wind investments, where lower Capital expenditures (CapEx) and interest rates were the differences in the scenarios. These scenarios are compared to average electricity prices to establish where wind power investments are most feasible.

The analysed wind energy potential followed the same trends for onshore and offshore, with northwestern European countries found to have the highest wind potential. Onshore wind feasibility is found to be highly cost-efficient in this analysis, achieving grid parity for the higher-cost scenario. Exceptions occur in areas with weak wind conditions or low electricity prices. Higher energy production offshore doesn't result in grid parity in most cases. It is dependent on high electricity prices and low-cost scenarios. The disparity between the technologies is demonstrated through tables and plots.

The best feasibility for wind energy investments is achieved through a combination of high electricity prices and strong wind resources. Ireland and Poland are highlighted as key locations for both onshore and offshore developments. Further research is needed to refine the cost projections and to assess the available onshore wind development areas, which could provide more incentives for offshore expansion.

# Energy Storage dimensioning tool for Lithium-Ion batteries

Student: **Jan-Ivar Flagestad Østby**
Supervisor: **Inge Nordsteien**

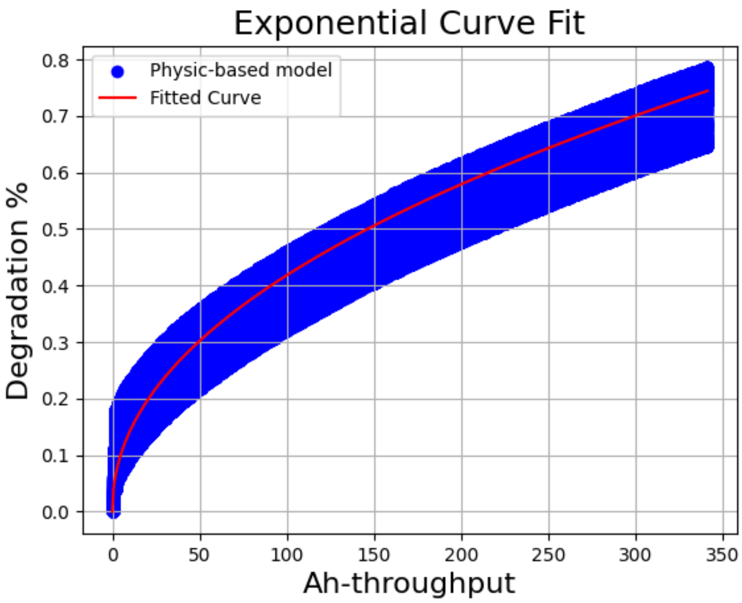
**Problem description and The Task**

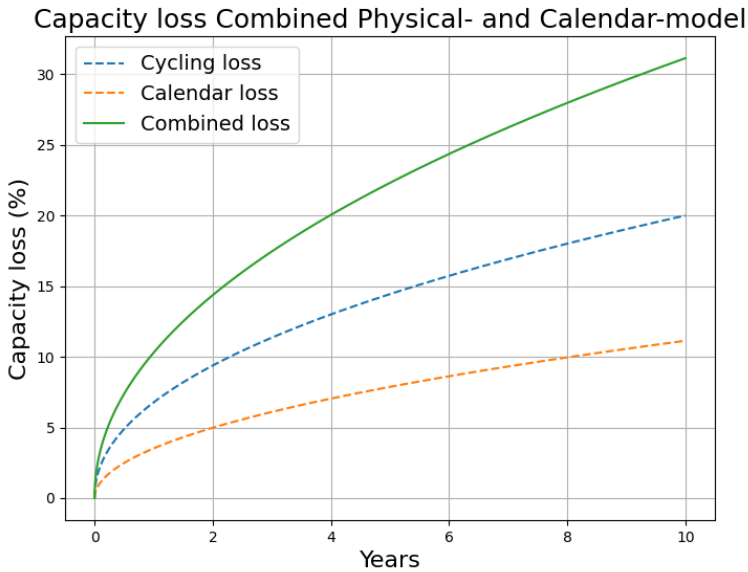
Lithium-ion batteries are a extensively used energy storage technology, and their use are only expected to accelerate in the years to come. Their high energy density, lightweight design, safety and long lifespan makes them a great choice for energy storage applications. This rapid growth bring challenges, especially in planning, development and management of battery energy storage systems. Battery manufactures and suppliers typically has their own battery dimensioning tool that allow that to optimize battery performance, but this is however not shared publicly.

The primary objective of this master thesis is to develop a energy storage dimensioning tool for lithium-ion batteries that accounts for key operational parameters. The thesis will focus on identifying and integrating essential components required to build such a tool. This includes a detailed investigation of current research, industry standards, and state-of-the-art models related to battery degradation and lifetime estimations. The outcome will be the development of a flexible, user-oriented tool that can perform early-stage calculations for energy need and projected battery lifetime. An equally important objective is to validate the tool's accuracy and reliability. To achieve this, the tool will be tested against real-world performance data from existing li-ion battery installations and against Siemens energy's dimensioning tool.

**Model/ measurements and Calculation**

A model was developed for calculating the required parameters and recommended size of the battery to reach the desired voltage and power output, while another part estimate the amount of partial cycles the battery can preform before its end of life. For calculating the number of cycles that the battery can perform before its end of life, a semi-empirical model and physics-based model are used. In addition, other models that were researched but not implemented are discussed. These models are based on different types of batteries, where the semi-empirical model is based on a LFP battery and the physics-based model uses a NCM battery. The figures attached are some of the results from the model, presenting the capacity loss of batteries after 10 years of use.




## Conclusion

The results demonstrate that the dimensioning tool provides reliable estimates for both battery size and lifespan. Validation against Siemens Energy's tool revealed that the capacity loss predicted by the tool developed in this thesis is approximately twice as high as that estimated by Siemens Energy's tool.

# Kortslutningsbeskyttelse i mikronett

Student: **Gard Bjørnar Østvold**
Veileder: **Eilif Hugo Hansen**

## Problemstilling

Økt bruk av desentralisert energiproduksjon gjør at mange lavspente elektriske anlegg og distribusjonsnett kan operere som mikronett i øydrift. Dette gir store utfordringer for kortslutningsvern, ettersom feilstrømmene reduseres og blir nær vanlige laststrømmer. Et annet problem er toveis effektflyt inne i anlegget. Hvordan kan man likevel sikre selektiv og rask utkobling?

## Oppgaven

Formålet har vært å undersøke hvordan selektivitet kan opprettholdes i lavspente mikronett med omformerbaserte energikilder. Det er utarbeidet simuleringsmodeller av et bygg (installasjon) og et lavspent distribusjonsnett i DIgSILENT PowerFactory, med simulering av ulike feilscenarier. Kortslutnings- og lastflytberegninger er utført og passende vernkonfigurasjoner er implementert.

## Konklusjon

For små mikronett og installasjoner i bygninger bør selektivitet ivaretas gjennom bevisste valg i planleggingsfasen, som å mate effekten i installasjonen inn ved en fordeling, og å velge nettverkstopologi som fordeler belastningsstrømmene over flere hovedkurser. I tillegg kan reservebeskyttelse i form av underspenningsvern benyttes for å sikre utkobling ved kortslutninger i øydrift, i bytte mot at selektiviteten reduseres.
For større mikronett vil retningsbestemte overstrømsvern kunne løse problemene knyttet til toveis effektflyt, men fremdeles kreve tilstrekkelig høye overstrømmer. Differensialvern er immune mot alle de typiske problemene, men grunnet høyere kostnader og kompleksitet brukes de sjeldent i lavspentnettet.

## Development of Open-Source Software for Reliability Assessment of Distribution Systems using RELRAD Methodology

Student: **Sondre Modalsli Aaberg**
Supervisor: **Vijay Venu Vadlamundi**

### Problem description

With increased electrification, power demand, and the propagation of renewable energy resources throughout the distribution system, assessing the reliability and adequacy of distribution systems has become more relevant and complicated. The distribution system has traditionally been a passive part of the power system. However, with the propagation of local energy resources in the distribution system, it has become a more active part of the grid. With this development, it is necessary to develop new tools for distribution system reliability analysis.

### The task

The thesis contributes to further developing the software repository at the Department of Electric Energy at NTNU for power system reliability analysis by developing generalized, open-source software for reliability analysis of radial distribution systems, utilizing the RELRAD methodology (both the analytical version and the Monte Carlo simulation version).

### Model

By simulating the switching actions of protection system elements to isolate the faulted portion from the rest of the healthy network, a step-by-step algorithm for determining the effect of a fault in a radial network has been developed. A complete, general software framework is created in Python by implementing the "Effect of Fault" algorithm into the RELRAD method and Monte Carlo simulation, together with the implementation of distributed energy resource calculations as backup power sources.

The "Effect of Fault" algorithm consists of the following general steps:

1. Trip the first available protection element
2. Open available disconnectors around the fault to isolate the fault from healthy parts of the system.
3. Assess which load points are affected by the switching action.
4. Check if the tripped protection element is still needed to isolate the fault.
5. Assess the final state of power for all load points in the system, and utilize potential sources of backup power.

The created Python software takes network data as input, in the form of buses, and the components

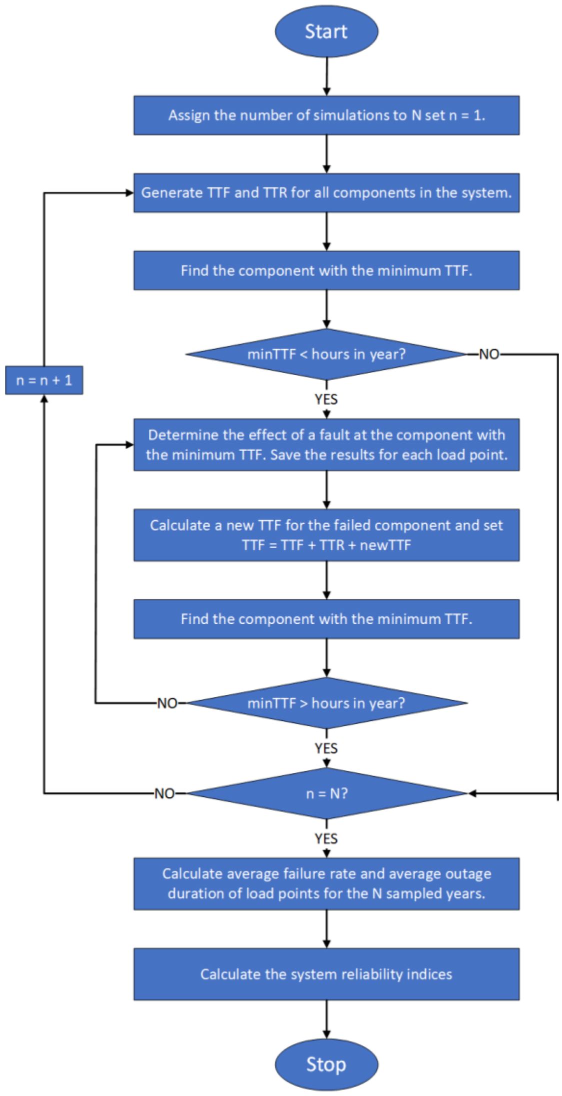



**Figure 1: Monte Carlo Simulation Flowchart**

connected between the buses. As well as customer load values, a load curve with values for every hour of the year, and data about distributed generation in the form of generation values, storage values, either as average values or as curves for every hour of the year. The software outputs average system indices and reliability data for every load point.

## Calculation

The Software is tested on multiple systems, and the results are compared with those from previously established works. The Simulation results are also compared to the analytical RELRAD results. Table 1 shows the Monte Carlo simulation results obtained by running the software for five different test systems. The “RBMC p214” and “RBTS BUS 2” systems have established analytical results that match the developed results.

**Table 1: Results from running the MCS software for five different test systems**

| System | Load level average [MW] | Load point peak [MW] | Number of customers | SAIFI | SAIDI | CAIDI | EENS | Number of simulations | Provided $\beta$ | Calculated $\beta$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Simple Test System | 2.171 | 3.517 | 631 | 2.183 | 2.417 | 1.107 | 4.999 | 1759 | 0.02 | 0.024 |
| RBMC p214 | 1.605 | 2.600 | 630 | 1.103 | 1.440 | 1.305 | 2.312 | 3177 | 0.02 | 0.0143 |
| RBTS BUS 6 | 10.715 | 20 | 2938 | 0.672 | 3.958 | 5.884 | 51.959 | 2769 | 0.02 | 0.015 |
| RBTS BUS 4 | 24.58 | 39.999 | 4779 | 0.632 | 2.173 | 3.433 | 51.616 | 16512 | 0.02 | 0.0047 |
| RBTS BUS 2 | 12.291 | 20.000 | 1908 | 0.2482 | 0.768 | 3.086 | 8.874 | 2400 | 0.02 | 0.0177 |

Figure 2 shows a comparison between developed analytical and simulation results (in gray and yellow), with analytical and simulation results from a previous study (in blue and orange), as a percentage of the established analytical results.

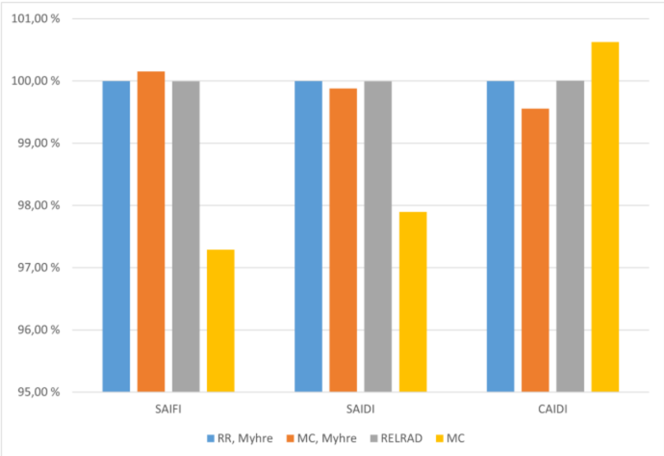



**Figure 2: Comparison between calculated and established results**

## Conclusion

The software developed in this thesis produces results similar to those of established works. It does so while requiring minimal effort in preparing the input data and no manual calculations. The software can be used in future distribution system reliability analysis studies, or be expanded upon to include new systems. Implementing ICT systems and power flow calculations in the simulation can be done without making any significant changes to the existing code.

# Non-invasive Condition Monitoring of Induction Motors Using Advanced Pattern Recognition

Student: **Mikkel August Stähr Aarnes**
Supervisor: **Robert Kristoffer Nilssen**
Co-Supervisors: **Hossein Ehya and Christoffer Sandnes Falck-Johansen**
Collaboration with: **Framo Flatøy AS**

**Problem description**

Amid continuously rising global electricity demand, induction motors remain the backbone of industrial energy consumption. Despite their durability, these machines are susceptible to numerous faults that can lead to costly downtime and potential safety hazards. Reliable monitoring of the health status of these machines is therefore becoming an essential practice.

This thesis investigates the viability of a pattern recognition-based fault detection method for induction motors using stray flux signature analysis (SFSA). Externally mounted search coils were used to capture the stray magnetic field, and various signal processing techniques were employed to extract fault-specific features.

Three types of faults were studied at NTNU: broken rotor bar (BRB), inter-turn short circuit (ITSC), and dynamic eccentricity (DE). The BRB and ITSC faults were examined both experimentally and through FEM simulations, while the DE fault was analyzed via simulation only. Additionally, a field test was conducted on a healthy induction motor at Framo Flatøy.

*Due to confidentiality, the publication of this thesis has been postponed for three years. Further presentation and discussion of the findings in the thesis can therefore not be provided at this time.*