NTNU
Institutt for elkraftteknikk

Masteroppgaver 2020

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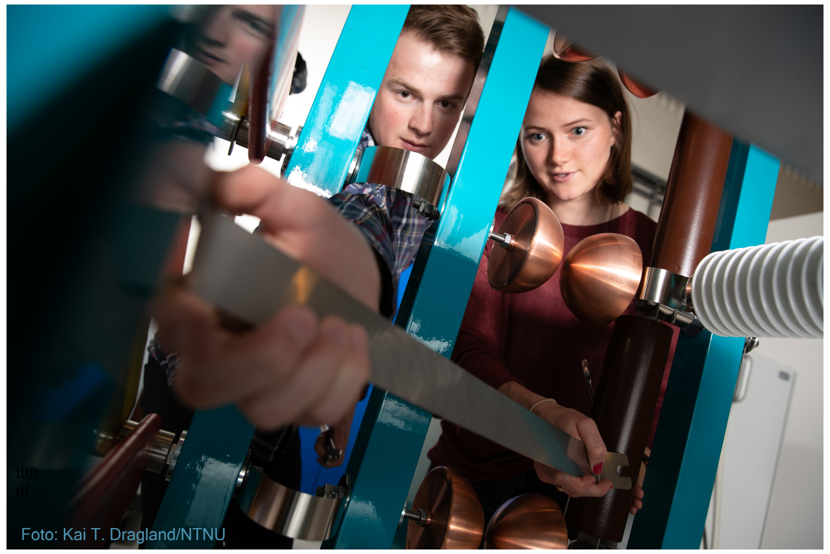
Summary of Master's Theses 2020

Department of Electric Power Engineering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Fakultet for informasjonsteknologi og elektroteknikk
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Summary of Master's Theses 2020

We are proud to present this pamphlet, which gives a summary of the 93 master's theses that were submitted to the Department of Electric Power Engineering in 2020, most of them in June. The Department's vision is to be "At the Centre of the Digital, Green Shift," and our master's students make important contributions to this vision.

This year, a special ***Thank you!*** goes to all our master's students and all our supervisors, who found ways to continue working on and supervising master's theses during the Covid-19 lock down in the spring semester. I am impressed and grateful for the high quality of work and learning that took place under difficult circumstances. The general high quality of the theses submitted speaks volumes of the high caliber and spirit of our students. I congratulate them for their successful completion of their studies and wish them the best for their future endeavors.

The master's thesis is independent, research-oriented work undertaken by the student under the guidance of academic staff as a finalization of a master's degree. The topic is most often chosen from a set composed by the Department's 5 research groups. The topics offered are closely related to the core research being conducted in the groups, often in cooperation with our industry partners and our neighbor institution SINTEF Energy Research. Thus, this folder also gives an impression of the general research activity at the Department. Our 5 research groups are: *Power Electronic Systems and Components (PESC), Electricity Markets and Energy System Planning (EMESP), Electrical Machines and Electromagnetics (EME), High Voltage Technology (HVT), Power System Operation and Analysis (PSOA)*.

A master's thesis at the Department corresponds to a workload of 30 ECTS in the final semester of our programmes, and is performed within a timeframe of 20 weeks. It is most often based on a specialization project with a workload of 15 ECTS, submitted in the previous semester. In this way, the students dedicate ¾ of a study-year to get in-depth knowledge on a specific topic within their discipline, and at the same time, they give valuable contributions to projects for external partners, and to research projects within the department. This is real value creation, both through the innovations that are direct results from the work performed, but most importantly, through the candidates themselves, who get a first-class research-based education.

We are sure that the candidates that we educate from our department will continue to shape the future, especially within the fields of Electric Power Engineering and Energy, as they have done in the past. We also take the opportunity to invite existing and new partners to contact us to discuss topics for future master's theses. Read more about our department here: https://www.ntnu.edu/iel.

NTNU, October 2020

Ole-Morten Midtgård (sign)
Head of Department

High-Power Electric Charging in the Norwegian Distribution Grid

Student: **Tormod Habbestad Aarnes**
Supervisor: **Magnus Korpås**
Contact: **Bendik Nybakk Torsæter**
Collaboration with: **SINTEF Energi AS**

Problem description

This master's thesis is written in collaboration with and is a part of KPN FuChar. FuChar is a KPN project funded by The Research Council of Norway and industry partners (grant no. 295133/E20). The aim of the FuChar project is to minimise investment and operating costs related to the grid integration of electric transport.

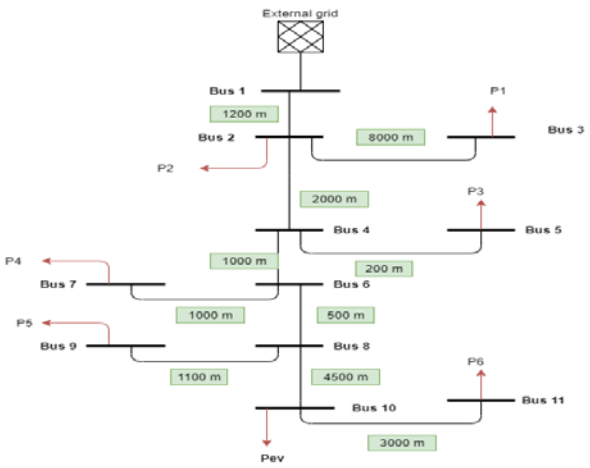
The purpose of this thesis is to investigate the grid impacts of a large charging demand from high-power charging in the medium-voltage (MV) grid, and also to investigate problems that could interfere with an optimal charging infrastructure. In addition to that, strategies that could be implemented to mitigate the impacts of high-power charging will also be examined.

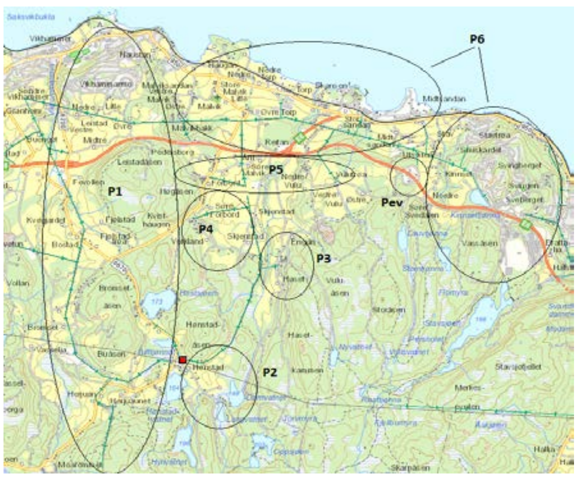
The task

- Develop a MATLAB-based simulation model for analysing different scenarios related to the future grid intergration of high-power chargin interfaces
- Investigate potential challenges related to to grid integration of high-power charging of electric cars
- Investigate different measures to mitigate the supply voltage variations

Model/ measurements

The power system that will be examined in this thesis is illustrated below. As shown, the network is an 11 bus system with one feeder and seven loads and is visually represented as a radial network of 24kV. The system is developed based on the MV grid overview from NVE of the rural area Vikhammer-Hommelvika, outside of Trondheim. From NVEs data of the electrical grid in the respective area, the area that is being investigated is based on the location starting off from the transformer station with ID 14757 close to Hønstad. This transformer is fed from the regional power lines of 132kV and is transformed down to 24kV, which is the voltage level for this network.





There are two different types of loads in this given network. Pev is represented as the only charging station that will be used throughout this study. All the remaining loads from P1-P6 are loads represented general loads, including households, agriculture, schools, and department stores.

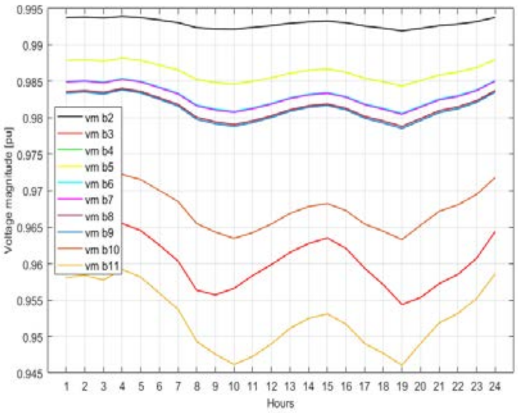
The general load profiles P1-P6 are created by using of a model made by SINTEF, general FASIT load profiles. These profiles are hourly-resolution profiles used to indicate the hourly demand for specific load groups throughout different seasons and different levels of demand.

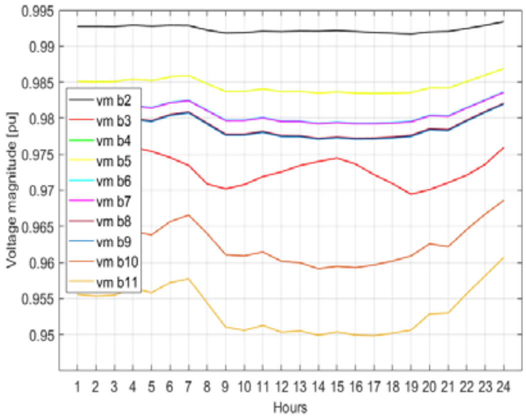
The four study cases that have been examined in this thesis are:

- Case zero: Initial condition (no EV charging)
- Case one/two: Two/Four charging outlets
- Case three: Six Charging Outlets Connected and Increased Traffic Flow of 40%
- Case four: Twenty Charging Outlets Connected and Increased Traffic Flow of 335%
- Case five: Measures for Grid Improvement

Calculation

The most significant results are presented below. The first figure shows how the voltage is distributed under normal operation condition (case zero). How the system responds to a large scale of EV charging and with measures for grid mitigation (case five), is shown in the second figure.





Conclusion

By implementing battery storage and increasing the cross section of some transmission lines, the voltage was kept within the boundaries of ±5% throughout the whole day, with the exceptions of two hours where it was barely underneath the limit. It is concluded that even with a large EV scale and with its high power consumption, the supply voltage variations can be improved by a considerably amount by using smart and already developed strategies for grid improvements.

Modelling and Validation of Energy Storage Components for Dynamical Analysis of Offshore Energy Systems

Student: **Jeffery Selorm Adorkor**
Supervisor: **Elisabetta Tedeschi**
Contact: **Salvatore D'Arco**
Collaboration with: **SINTEF Energy Research**

Problem description
The exponential growth in renewable energy integration and the expansion of transmission and distribution networks in offshore energy systems necessitates an optimal level of system stability and reliability. The efficient operation of these interconnected systems requires an understanding of each subsystem to facilitate dynamical analysis of potentially sophisticated electrical systems. An important focus in this regard is maintaining generation-demand balance to mitigate the effects of intermittency of renewable sources and variations in load demand. Energy storage is an effective grid-support solution with the potential to enhance grid resiliency by compensating for power mismatch due to the factors mentioned above.

The task
This master's thesis investigates the contribution of energy storage, specifically hybrid energy storage systems (HESS), to the improvement of grid resiliency against load variations. The power system under study is made up of a HESS connected to an AC offshore remote area power system (RAPS) via a two-stage power converter. The focus of this project is the utilisation of the HESS to improve DC bus voltage stability by reducing the load-transient recovery time and mitigating deviation magnitudes. A battery-supercapacitor HESS is implemented considering the complementary energy density and power density characteristics of the constituent storage elements. Its effectiveness in achieving the stability objective is compared with that of a battery in the same application.

Control employed for the hybrid storage converters relies mainly on the response time of the HESS elements. System net power due to load demand variation is decoupled into high and low-frequency components. Due to the difference in the control bandwidths, the supercapacitor compensates high-frequency peak variations, within the first few milliseconds of a transient event, and the battery responds to slower system variations. Consequently, the battery is protected from fluctuating peak currents, improving its lifetime. Furthermore, the supercapacitor's volumetric efficiency is increased, operating within a broader voltage range.

Description of model
All modelling and simulation tasks are carried out in Simulink. The power system is made up of DC and AC sections. In the DC section, the battery and supercapacitor are modelled as DC voltage sources with corresponding bidirectional DC/DC converters. These converters are modelled as duty cycle-controlled 2-quadrant DC/DC converters. The outputs of the converters are connected in parallel to the DC bus. Interfacing the DC bus to the AC system is an average model two-level voltage source converter with an LCL filter. The studied variables for the final simulations are the DC bus voltage and total converter output current. The first criterion for determining the effectiveness of both energy storages in maintaining voltage stability during a transient is load-transient recovery time. This is the time taken for the output voltage, i.e. DC bus voltage, to return and remain within the recovery/settling band (selected as 0.25%=1V) around its nominal/steady-state value (400V) after a step change in load current. The other criterion is the magnitude of voltage deviation from the nominal value.

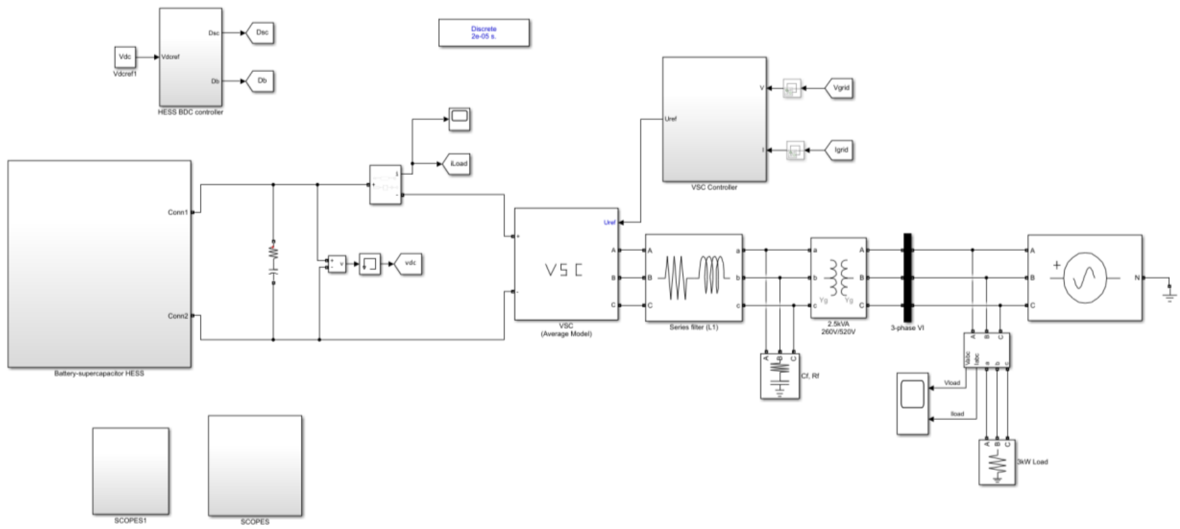


Fig.1: Simulation model of power system under study

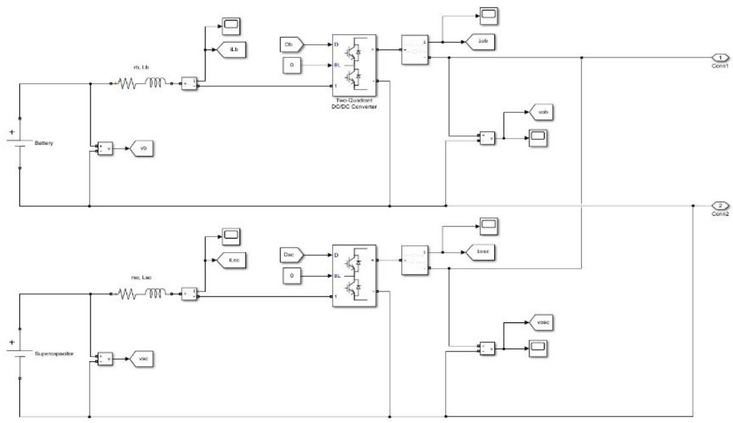


Fig.2: Parallel topology of hybrid battery and supercapacitor with full active configuration

Simulation results and analysis

The influences of energy storage on the DC bus voltage are analysed for two cases: a step increase in load demand and a step decrease in load demand. The two scenarios considered are connections to a DC standalone system and a full power system (hybrid DC/AC).

DC System

	Step increase in load demand		Step decrease in load demand	
	Battery	**HESS**	**Battery**	**HESS**
Transient recovery time[s]	0.012	0.006	0.014	0.004
Voltage deviation[%]	0.425	0.325	0.4	0.3

Full Power System

	Step increase in load demand		Step decrease in load demand	
	Battery	**HESS**	**Battery**	**HESS**
Transient recovery time[s]	0.075	0.027	0.047	0.02
Voltage deviation[%]	3.43	3	2.62	2.28

Conclusion

It is established that energy storage has the potential to increase grid resiliency against variations in system load demand. Further adopting a more advanced configuration such as hybridisation makes the energy storage more effective in providing grid support, as shown in the results of the comparative performance evaluation between battery and HESS.

Dynamic thermal modelling of power transformers

Student: **Selassie K. Agbodza**
Supervisor: **Erling Ildstad**
Co-supervisor: **Dejan Susa**
Collaboration with: **Statnett**

Problem description

To meet the energy demands of tomorrow, methods are being researched to optimize utilization of the already existing infrastructure in the electrical grid. The power transformer is one of the most important and expensive components in the power grid. As such, it forms a considerable part of the research on the power system components. The power transformer's capacity is currently set conservatively, to static thermal limits based on simulations of the most critical loading and weather conditions. Since the loading and weather conditions are changing variables, it results in the power transformer’s capacity also constantly changing. This means that the power transformer can be regulated in line with the conditions, such that the component is utilized in the most efficient way at all times.

To reach this goal information about what determines these thermal limits are needed, as well as methods that can be used to calculate them.
The thermal limits are set after the power transformer's winding hottest-spot temperature, which is one of the most critical parameters that limits its capacity, by degrading the insulation.

The task

The thesis presents a dynamic thermal model (NTNU model) that can be used to calculate the hot-spot temperature. The model is based on the bottom-oil temperature in the transformer, and is developed by combining the works of Swift and Pierce. To verify the developed model, it is compared to the STET model and IEC's model from 2018, which are both based on the top-oil temperature. The models are compared by using general data, and real data from an ABB power transformer.

Model/ measurements

The three models are based on empirical modelling. With empirical modelling, a thermal-electrical equivalent is used to describe the complex heat transfer modes in a power transformer, with simple differential equations. The solution of these equations gives the change of the hot-spot temperature over time.

Results and conclusion

The figures below show the results from the use of the real data from the power transformer. The hot spot temperatures are calculated using the three models and compared to the measured hot-spot temperatures. Figure 1 shows this comparison when the models are first used to calculate the oil temperatures, and then these values are used to calculate the hot-spot temperatures.
Figure 2 shows this comparison when the correct, measured oil temperatures are used as input in the hot-spot temperature models, to calculate the hot-spot temperatures.

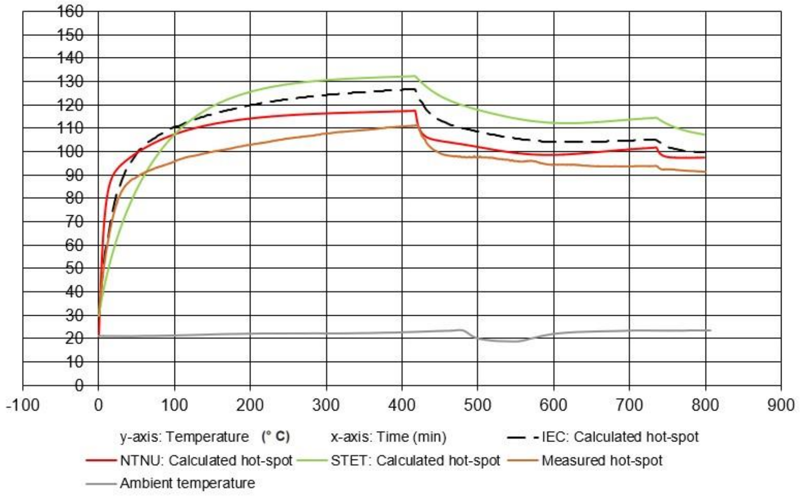


Figure 1: Comparison of the hot-spot temperatures using the calculated oil temperatures

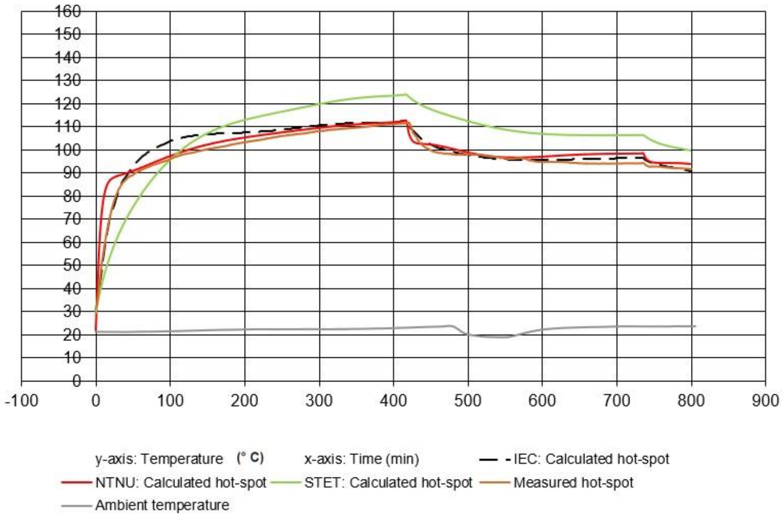


Figure 2: Comparison of the hot-spot temperatures using the correct, measured oil temperatures

The NTNU model shows promising results with the use of both the real and general data. Using the real data, this model calculates the most accurate hot-spot temperatures, by estimating the most accurate oil temperatures. This trend is also apparent using the general data. When the correct measured oil temperatures are used as input in the hot-spot temperature models, it can be observed that both the NTNU and the IEC model calculate relatively accurate hot-spot temperatures. Although the IEC model requires more parameters, it does not calculate more accurate temperatures than the NTNU model. An added advantage with the NTNU model, is that one avoids modelling the time dependent overshoot function which is present in models based on the top-oil temperature. This makes the NTNU model simple and easy to use, without being less accurate.

The STET model is the least accurate of the three models. It does not consider the mechanical and thermal inertia of the oil, which causes the calculated temperatures to have too high peak values and too low bottom values. Even when using the correct measured oil temperatures, the calculated hot-spot temperatures are still not accurate enough. As a result of this the STET model should not be used to calculate the hot-spot temperature, if other models are available.

Condition Assessment of Hydro Generator Stator Bar Insulation

Examination of PD void activity versus AC voltage magnitude and frequency

Student: **Stine Arctander**
Supervisor: **Erling Ildstad**
Co-Supervisor: **Torstein Grav Aakre**

Problem description

The majority of the Norwegian hydropower generators have been in service for more than 40 years, and several have already reached their expected service lifetime. In addition, new and tougher operation conditions are expected in the future, due to more frequent starts and stops, which challenge the insulation beyond what it originally was designed for. Thus, diagnostic testing and condition assessment is needed to reduce the uncertainty regarding degree of ageing and remaining lifetime of existing and new installation.

Today, several diagnostic techniques are available to assess the insulation quality of generator rods, for example partial discharge- and dielectric response measurements. Unfortunately, wide application of these techniques is hampered by uncertain Interpretation and lack of clear assessment criteria.

The task

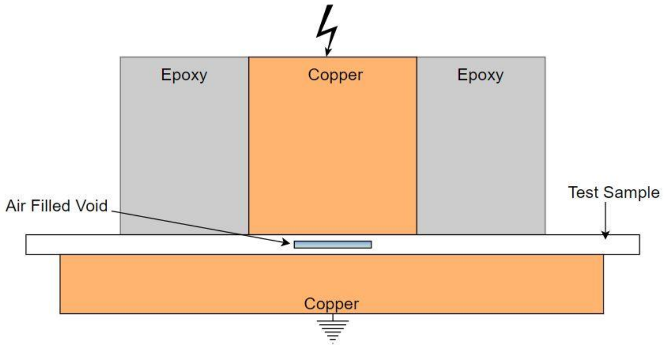
The main purpose of this thesis is to address the concerning issues using partial techniques for detection of internal critical voids in high voltage insulation. The aim is considering the effect of high voltage AC testing at very low frequencies to 50Hz both theoretically and experimentally.

The thesis is expected to constitute:

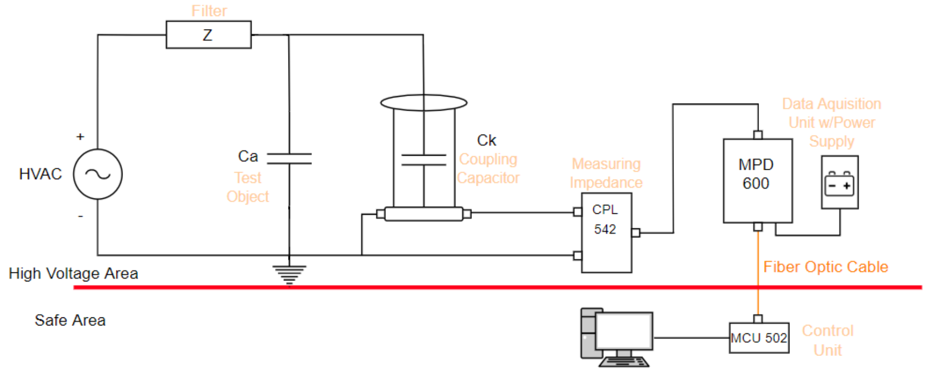
- A literature survey, including theory, forming the base for the suggested methods for estimating partial discharge inception voltage (PDIV), frequency dependence and apparent charge magnitude.
- Results from electric field calculation aiming at considering the effect of void dimensions on characteristic PD parameters.
- Results from laboratory examinations, aiming at studying the effect of ac test voltage magnitude and frequency on characteristic PD parameters.
- If possible, application of the above information regarding condition assessment and comparison of aged and non-aged generator bars.

Model/ measurements

Results from electric field calculation in various voids are preformed with the following model. Two copper electrodes surrounding the test samples. A high voltage of $V_{Peak}=\sqrt{2}\cdot 7kV$ is applied from the upper high voltage electrode, while the bottom electrode is grounded. The HV electrode is surrounded by epoxy with $\varepsilon r=4.2$. The high voltage insulation around the cavity is polycarbonate with $\varepsilon r=3$.



The experimental part of this theis is based on electrical detection of partial discharges in stator windings in hydro generators. The detection device used was from Omicron, and the measuring circuit is shown in Figure 12. A low pass filter was included in the circuit in order to sort out noise from the high voltage source. The coupling capacitor of 3.4nC is shown as Ck, and is connected to a coupling device, shown as the measuring impedance in the circuit.



Conclusion

- The electric field in a cylindrical void is found the most homogeneous at void length 2mm and gap distance 0.2mm. This is the smallest size measured in this thesis, and this results is thus expected. However, as the gap distance is only at 10% of the void length with the small are of 0.4mm it is found that the edge effect is not present due to the very high overall field in the void. The same behavior is not found for any of the other void gap to void length, and it seems like this relation is strongly increasing with the void gap also increasing.
- For spherical cavities when the insulation is increasing accordingly with the void diameter, the electric field is following the theoretical limitation for spherical field given in Eq. 7. An exception was found with a void diameter and insulation layer thickness of 10mm. This can indicate that spherical dimensions over this limit does not fit with the theory given. It was also discussed that the model was underdimensioned for this insulation size as the total insulation thickness reached 30mm, the same thickness of the HV conductor in the FEM Model.
- In the experimentally laboratory test conducted, 2 backup rods together with 2 service aged rod near HV was tested for PDIV and PDEV. For service rod S2, a clear deviation, from the average inception values of the other rods, was observed. S2 yielded a PDIV of 50% lower than for all the other rods, which was 500V under the generator operating conditions. From the rod data given, the rods had been in service for 40years, but it is not known if that rod have been replaced along the road. From a visual inspection of the rod, it was clear that some restoration have been conducted by the looks of the diamond connection of the bar-end. There were clearly large air gaps between the conductors, and some air was observed in the cross section into the groundwall insulation. However, it is hard to conclude that these voids go deep enough to pass the field grading paint into the rod. Hence, it is not known if these void affects the PDIV. When fitting the experimental measured PDIV to the ABC-model, the lowest PDIV found was at 2.9kV with a void distance of 1.9mm. This is close to equal to the PDIV of the 3 rods yielding the same PDIV while the model did not fit for service rod S2.

Real-Time Parameter Identification for Reliable Operation of Synchronous Generators

Student: **Sophie Seehuus Berg**
Supervisor: **Jonas Kristiansen Nøland**

This master thesis explores the online identification methods for synchronous machine parameters using online measurements. The central concept of the online parameter estimation algorithm is to use the dynamic measurements from the machine in combination with the manufacturer's estimates of the parameters to make the machine model agree with the measurements. The goal is to use already available measurements to improve upon manufacturers estimates of the synchronous machine parameters which may be obtained from stand-still tests decades ago.

The model of the generator is based on Park's model of the synchronous machine with an observer for the damper winding currents. The generator modelled was a ten pole salient pole synchronous generator from Voith situated in a German hydropower-plant. Three hundred seconds of voltage and current measurements was received from the generator during steady-state running on rated load connected to the grid. Inductances and resistances of the generator were calculated from the available data from the datasheet. The model for the parameter estimation is built in MATLAB Simulink. To estimate the rotor position of the generator, a phase-locked-loop control system was implemented on the signal from the phase a voltage. A Kalman Filter was used as an optimal observer to filter and correct the measurements by using previous knowledge about the synchronous generator and its parameters. The method for parameter estimation uses the recursive least squares (RLS) algorithm to create an estimate for the inductances and resistances of the machine using available measurements.

However, due to disturbances and noise present in the measurements of the field voltage and current, results from the parameter estimation using the real measurements from the generator had large errors. For this reason, it was decided to use measurements created by a Synchronous Machine block from the Simscape library in Simulink which was modelled to be equal to the Voith generator for further simulations. To explore how the algorithm reacts to changes in the machine parameters, a case study is presented where the RLS algorithm was given a deliberately faulty initial estimate for the parameter estimation. The algorithm first showed poor ability to track changes in the machine parameters and would converge towards an erroneous estimate. However, after tuning of the initial parameter covariance matrix, the parameter estimation showed significant improvements. It was able to converge towards the correct value of the parameter even with an incorrect initial estimate. The conjecture from the thesis is that the parameter estimation algorithm, if tuned correctly, could give more accurate estimations for the parameters of the machine, than the manufacturer's parameters obtained from stand-still tests possibly from many years ago. However, before the algorithm could be used in the industry a more effective way for noise filtering and rejection of bad measurements has to be implemented.

Design Considerations and Modeling of a VSC Assisted Resonant Current DC Circuit Breaker for MVDC Applications

Student: **Mathilde Bergerskogen**
Supervisor: **Dimosthenis Peftitsis**
Co-supervisor: **Andreas Giannakis**

Problem description

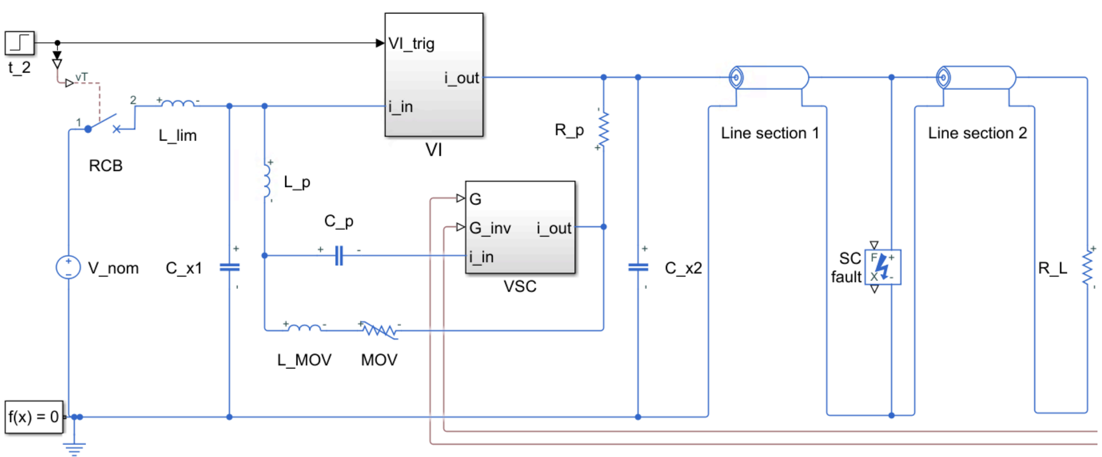
Medium-voltage DC (MVDC) power grids offer many beneficial features compared to the medium-voltage AC counterpart, and are considered well-suited for a wide range of application areas. However, one of the main hindrances towards a widespread of MVDC power grids is associated with the handling of short-circuit faults. In particular, the lack of high-performance MVDC circuit breakers is a key challenge. The main purpose of this master's thesis is to investigate a particularly interesting and promising DC circuit breaker (DCCB) concept: the voltage source converter (VSC) assisted resonant current circuit breaker (VARC-CB). The VARC-CB is originally proposed for high-voltage DC, however the thesis investigates the VARC-CB concept for MVDC applications.

The task

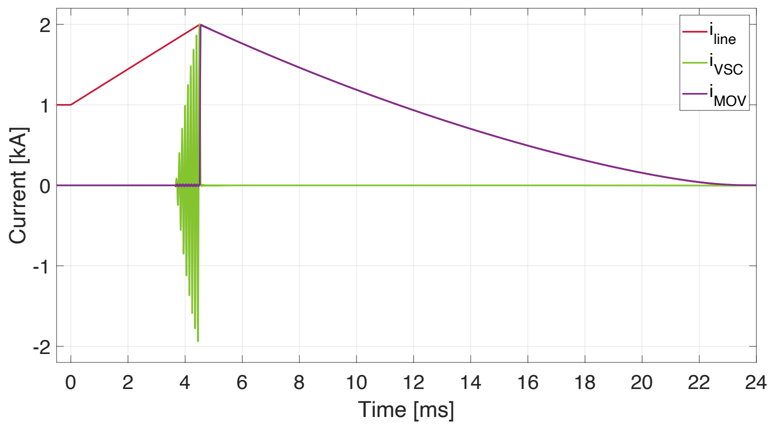
The thesis studies and analyzes the MVDC VARC-CB in detail. An analytical investigation is presented, where several design principles and component limitations are taken into account. Based on this analysis, a complete set of design strategies to be used when designing the parameters of the breaker is derived. Furthermore, a Simulink simulation model of the VARC-CB concept employed in an MVDC power grid is developed, where the component-level model of the MVDC VARC-CB is parameterized using the derived design equations. Through simulations, the analytical investigations, the proposed design strategies, and the developed simulation model are validated. Weaknesses and shortcomings of the analysis and modeling processes are pointed out and discussed, and possible revisions are proposed. In addition, suggestions of improvements in the MVDC VARC-CB design are made.

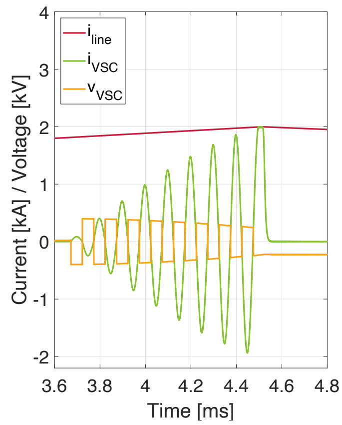
Simulation model

The figure below displays the developed Simulink model, where a VARC-CB module is employed in a simplified MVDC grid topology. To parameterize the model, the developed VARC-CB design strategies were applied, together with data found in literature and in datasheets of relevant physical devices. In the parameterization process, it was found necessary to assume a vacuum interrupter (VI) with high dv/dt capability, in order to obtain an adequate breaker design not violating any component or system limitations.

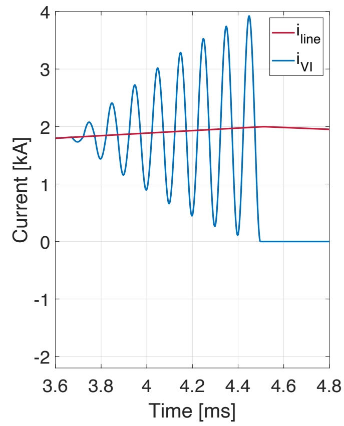


Results





Three main validation simulation cases have been performed. In case 1 a terminal short-circuit fault was simulated. Some of the waveforms obtained are shown in the three figures included. The results proved that the VARC-CB module was able to interrupt the maximum fault current it was designed for (2 kA). The fault current was neutralized within 2.51 ms, which is in accordance with requirements found for MVDC DCCBs in literature. Case 2 verified the breaker performance during nominal load current interruption (1 kA). In case 3 a terminal short-circuit fault with reverse current was simulated. The results verified the bidirectional nature of the VARC-CB.



Two possible improvements in the design and modeling of the VARC-CB module have been suggested. The first is to implement two separate LC circuits, each specifically designed for certain interruption current values. Simulation results show that using this approach can make sure that the interruption conditions for the VI are favorable in all interruption cases. The second improvement is to adjust the VSC triggering instant according to the interruption case, rather than keeping it fixed. Simulation results show that this can minimize the total operation time of the breaker, and it can ensure that favorable VI interruption conditions are obtained.

Conclusion

Except for the maximum allowable fault current being slightly exceeded in the third simulation case, none of the values measured in the three cases violated any system or component limitations. Overall, the results from the cases validated that the developed simulation model behaves as expected, with a satisfactory breaker performance in accordance with the derived design constraints and equations.

At the same time, a shortcoming in the derived equations estimating the dynamics of the VSC current was observed. The developed equations overestimate the maximum oscillating current amplitude achievable by a certain breaker design. This should be paid attention to when using the equations in a design process, to make sure that the breaker module is able to generate a sufficient oscillating current amplitude.

Furthermore, is important to emphasize that more work is required for examining factors influencing the interruption conditions of the VI, in particular the ones related to dv/dt. A more comprehensive analysis and modeling of the system is needed, in order to obtain more accurate design constraints and simulation results related to the dv/dt conditions at VI interruption.

Microgrid Control:
The impact of different control strategies on the system adequacy

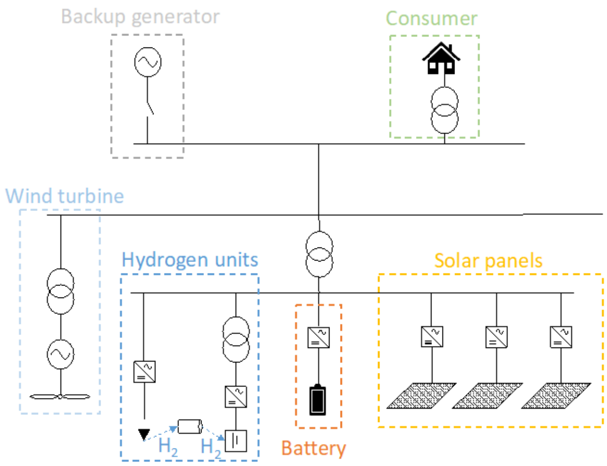
Student: **Ulrikke Bing**
Supervisor: **Kjetil Uhlen**
Collaboration with: **TrønderEnergi**

Problem description

The power supply to remote islands is today usually secured through expensive sub-marine cables or by the use of diesel generators. However, autonomous microgrid configurations with renewables sources and energy storage units pose as an alternative. The renewable sources are highly weather dependent and an advanced control logic must be present to ensure stable operation of the fluctuating sources and the storage units. Several control strategies are possible, and the thesis aims to investigate how different control strategies impact the reliability of an autonomous microgrid.

Approach

As a part of an EU-funded project, TrønderEnergi is currently researching the possibility of implementing microgrid configurations containing renewable power sources at remote islands. At a test site at Rye outside Trondheim, a microgrid consisting of a wind turbine, a PV-system, a battery energy storage system and a hydrogen energy storage system has been installed. The grid will by the summer of 2020 be set in autonomous operation and provide power to the farm Langørgen Øvre. The microgrid will work as a technical pilot and is also equipped with a diesel generator as a backup solution.



A study of the impact of different control strategies will be conducted on the existing microgrid at Rye and production and consumption measurements from the grid will be used as input in the simulations.

Model

Four cases, each with a different control strategy, was developed and investigated by means of reliability theory. The cases were as follows:

- Case 1 - The control strategy already implemented at Rye. A master-slave control strategy with the battery as master-unit.
- Case 2 - A master-slave control strategy with the battery as master-unit and demand-side management.

- Case 3 - A master-slave control strategy with both the battery and the hydrogen system as master-units.
- Case 4 - A peer-to-peer control strategy.

A model of the microgrid was obtained for each of the cases, and the operation of the microgrid was simulated. Three adequacy indices, LOLP, LOLE and EENS, were calculated using both an analytical method and Monte Carlo Simulations. The results made out the foundation of the comparison of the performance of the four control strategies.

Calculation
Based on the adequacy assessments performed, it was found that all four control strategies ensured an availability above 99%. Nevertheless, only minor distinctions of adequacy performance were detected. Case 4 stood out as the case with the most unsatisfactory results. The peer-to-peer strategy does, however, benefit from the fact that no inter-unit-communication system or master controller is needed. These advantages were not accounted for in the calculated indices, and a discussion of how this impacted the results was conducted. Further, slightly better performance of case 3 could be detected. The results did, however, vary in the different simulations performed, and no clear conclusion could be drawn.

Conclusion
The results presented in this thesis were not definite enough to conclude on which of the control strategies that ensure the best adequacy performance at Rye.

Kabling i høyspent distribusjonsnett – Dagens praksis og casestudie av eksempelnett for illustrasjon av nytteverdi

Student: **Julie Marie Heggdal Bjerkeseth**
Veileder: **Eilif Hansen**
Utføres i samarbeid med: **Norges vassdrags- og energidirektorat**

Innen 2100 har klimascenarier gitt indikasjoner på en rekke klimaendringer som kan få konsekvenser for forsyningssikkerheten i distribusjonsnettet. Utstrakt bruk av kabel kan være løsningen for å opprettholde god forsyningssikkerhet, selv med sterkere klimapåkjenninger i fremtiden. Spørsmålet er om kabling av eksisterende luftledninger er samfunnsøkonomisk lønnsomt.

I denne masteroppgaven er det benyttet en kombinasjon av flere metoder. Intervjuer er utført for å undersøke fem nettselskapers strategier og kriterier for valg av overføringsteknologi, samt forskjeller i beredskap, drift og vedlikehold ved valgt teknologi. En teknisk-økonomisk analyse som kombinerer pålitelighetsanalyser (RELRAD-metoden) og nåverdiberegninger, undersøker endringer i pålitelighetsindikatorer og lønnsomhet ved å erstatte eksisterende luftledninger med kabel. Analysen er gjennomført som en casestudie av en fiktiv nettmodell, for kabelandeler 0 til 100 %, for tre prognoser for økning i gjennomsnittlig feilfrekvens.

Funnene fra intervjuene viser at ingen av nettselskapene kabler for enhver pris, eller har et mål om å kable en gitt andel av nettet. Enkelte av nettselskapene har økonomiske retnings- linjer for når kabel skal benyttes. Nettselskapene forsøker å optimalisere gravekostnadene gjennom samordning av kabelgrøft eller justering av trase. Erfaringene til nettselskapene antyder mer organisering og høyere kostnader for beredskap, drift og vedlikehold for luftledning enn for kabel. ROS-analyser som inkluderer klimaendringer er ikke godt implementert hos alle nettselskapene, det gjelder også tilpasning til fremtidige klimaendringer. Resultatene fra casestudiet viser at Case 4, kabling av alle seksjoner, gir best pålitelighet i form av redusert årlig mengde ikke-levert energi, avbrutt effekt, SAIFI, SAIDI og avbruddsvarighet. Besparelsene er størst for prognose 2 for økning i feilfrekvens. Lønnsomhetsanalysen viser derimot at Case 0, videreføring av eksisterende luftledninger, gir lavest totalkostnad over analyseperioden. Alle casene som innebærer kabling gir negativ nåverdi, og anses ikke samfunnsøkonomisk lønnsomme. Det skyldes at investeringskostnadene er store, og at besparelser i kostnader for tap, vedlikehold og avbrudd ikke veier opp for dette.

Fra følsomhetsanalysen ble det funnet at skalering av feilfrekvens for kabel, grøftekostnader og lengder samt endring i kundesammensetning ikke påvirker rangering av casenes lønnsom het i kr. Skalering av disse parameterne, bortsett fra gravekostnadene, vil derimot påvirke pålitelighetsindikatorene. For at kabling av alle seksjoner i nettmodellen skal bli lønnsomt, må gjennomsnittlig feilfrekvens for luftledningene øke til 0,231 feil pr. km og år, gitt at gjennomsnittlig feilfrekvens for kabel holdes konstant. Endring i kundesammensetning viser at kabling blir mer fordelaktig dersom sluttbrukerne har høy spesifikk avbruddskostnad.

Resultatene viser at kabling gir bedre pålitelighet, men ikke nødvendigvis lavere totalkostnader. Det kreves imidlertid bedre undersøkelser av klimaendringers

påvirkning på feilfrekvensen i kraftsystemet, samt mer tilpassede strategier hos nettselskapene

Toward the New Grid Code: Implications of the Fault Ride-Through

Student: **Fredrik Bjørken**

Supervisor: **Jonas Kristiansen Nøland**

Problem description

The fault ride-through requirement has been implemented to many synchronous generators worldwide, where the requirement is described as a voltage profile the synchronous generator should stay within without losing synchronism. In Norway, the fault ride-through requirement was first described in FIKS 2012. Later in 2019, a draft was published by Statnett suggesting a new, improved voltage-time profile, with easier fault clearing time. Both FIKS 2012 and the draft NVF 2020 is described in the thesis, NVF 2020 will be used in the simulations.

Usually a consultant is hired to test the generators fault ride-though capability by putting a voltage profile on the generator. This thesis will show how the actual voltage profile is during a three-phase fault, by changing its distance from the high voltage side of the transformer. The thesis is intended as a detailed support document to aid the fault ride-through analysis.

The task

The model is created in MATLAB Simulink where the critical clearing time and the voltage profile at each distance is presented and describe. A total of six cases is chosen. A short-circuit power of 20 [p.u], 10 [p.u], and 6,67 [p.u] is used, where each of them is simulated with a reactive power at zero and maximum. The reactive power is measured on the HV-side of the step-up transformer connected to the synchronous generator. A single line diagram of the system simulated can be observed in Figure 1. The six cases simulated in the thesis is described in Table 1.

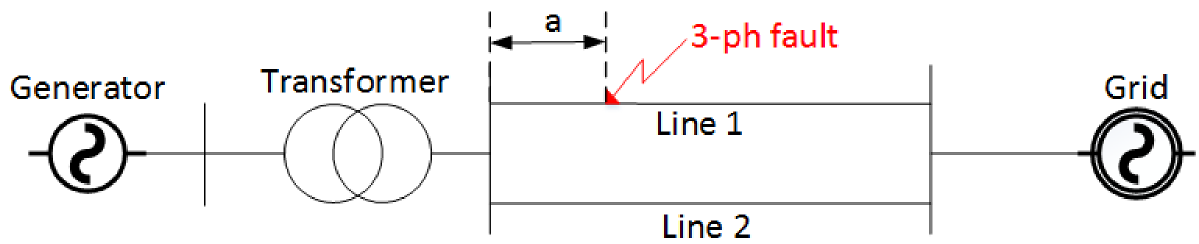


Figure 1. Single line diagram of the system simulated in MATLAB Simulink.

Case	S_{cc} [p.u]	Q [p.u]	a [%]
Case 1A	20	0	0, 20, 40, 60, 80, 100
Case 1B	20	0.396	0, 20, 40, 60, 80, 100
Case 2A	10	0	0, 20, 40, 60, 80, 100
Case 2B	10	0.396	0, 20, 40, 60, 80, 100
Case 3A	6,67	0	0, 20, 40, 60, 80, 100
Case 3B	6,67	0.396	0, 20, 40, 60, 80, 100

Table 1. The six cases simulated in the thesis.

Conclusion

What is observed in the result is that the synchronous machines pre-fault operation conditions have a significant effect on the fault ride-through capability. A change in reactive power from zero to maximum improved the critical fault clearing time of the synchronous generator, and the critical fault distance was closer to the terminals. In Table 2 critical clearing time at each distance "a" can be observed.

a [%]	**0**	**20**	**40**	**60**	**80**	**100**
Critical clearing time [ms] Case 1A	160	180	207	240	287	387
Critical clearing time [ms] Case 1B	204	237	284	357	510	5337
Critical clearing time [ms] Case 2A	134	154	180	203	237	310
Critical clearing time [ms] Case 2B	180	210	253	310	400	3530
Critical clearing time [ms] Case 3A	110	126	146	166	190	243
Critical clearing time [ms] Case 3B	163	193	230	279	339	689

Table 2. Table over the critical clearing times found by changing the distance parameter "a" for different short-circuit power and reactive power.

Battery Storage as Alternative to Grid Reinforcement in the Low-Voltage Network

- A Case Study for a Cabin Field in the south of Norway

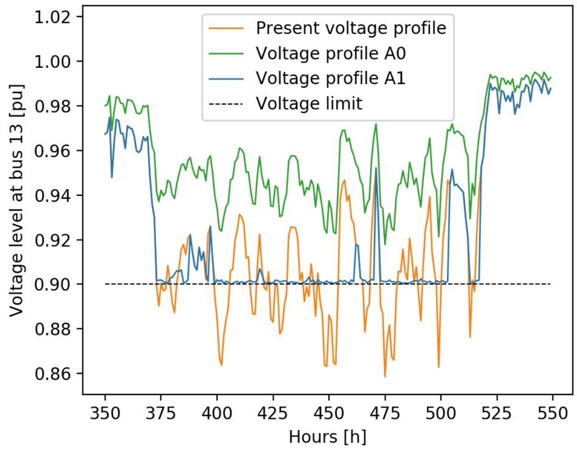
Student: **Maren Refsnes Brubæk**
Supervisor: **Magnus Korpås**
Contact: **Kristin Rekdal**
Collaboration with: **Lyse Elnett**

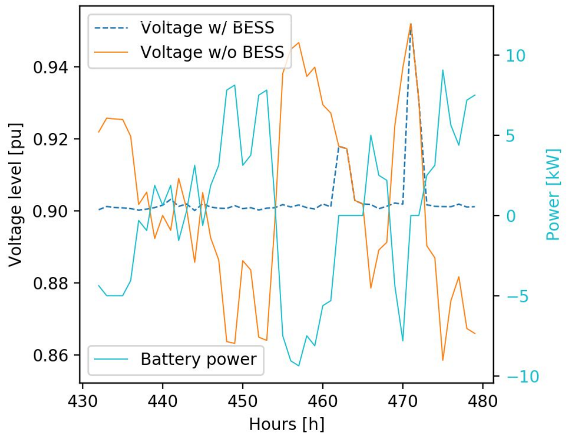
Most of the Norwegian electrical grid was built in a period were the load patterns were less power demanding, and the requirements for the security of supply were lower than today. Since then, society has become more dependent upon electric power, and the implementation of power-demanding devices has increased, causing more stress on the grid. The low-voltage distribution grid is especially volatile for the increased power demand as this can cause significant voltage drops that can damage the system. One particular load type representing an area where such problems can occur is a cabin field. The low utilisation time of power and the high, unpredictable power peaks will stress the grid. An issue for the grid company in these areas is that upgrading the grid to satisfy the quality of supply often leads to an over-dimensioning of the network. As a result the investment becomes very costly relative to the number of customers. An alternative to grid reinforcement is to install a battery in the grid. The battery can provide power to the system during the most demanding hours and therefore avoid the most excessive voltage drops. At the same time, the installation can be a more cost-efficient solution, as well as a smaller intervention.

This thesis will investigate the utilisation of battery storage in a low-voltage distribution grid as an alternative to grid reinforcement. The objective is to perform a techno-economic analysis, to conclude upon the battery's ability to deliver the required services, as well as investigating the economic feasibility. Python has been used to develop a model that takes in hourly AMS data from a cabin field in the south of Norway. The model contains three main parts: a power flow model that uses the backward/forward sweep algorithm as solution method, a rule-based battery algorithm to control the battery operation, and at last an optimal charge/discharge algorithm to supply and withdraw the optimal power from the grid in each time-step. The basic operating principle of the model is that if the voltage in the system deviates more than 10 % of the nominal value, the battery will start providing power to keep the voltage level within the required limits. By using the results from the model to find the optimal size of the battery and the optimal cross-section for the line upgrade, the two alternatives can be compared economically during investment planning.

The results from the analysis show that if a battery with sufficient power and energy capacity is installed, the battery proves as an as good technical solution as the grid reinforcement. The annual costs of installing battery storage are, however, 77 % higher than the annual costs of the grid upgrade. For the alternatives to break even, the cost of battery capacity has to decrease with 43 % relative to the price level today, to a cost of energy capacity equal to 1164 NOK/kWh and a cost of power capacity equal to 3900 NOK/kW. Extensive sensitivity analyses investigate the impact of an increasing number of customers, several lengths of the main supply line, variations in the load profile and the economic impact from the C-rate of the battery. These studies reveal how dependant the required energy capacity of the battery is on the load profile, and hence the importance of an adequate data basis when investigating the use of grid-installed batteries. The results also confirm the costliness of using batteries for storing large amounts of energy. The study concludes upon batteries being a better solution than the grid reinforcement when the power peaks are not too high and only appear periodically.

The figures below show how the voltage level in the system is improved after the installation of a battery or a new line. The orange lines show the current voltage level in the system, the blue lines show the voltage level after the battery is installed, the green line shows the voltage level after a line upgrade, and at last, the cyan-coloured line shows the battery operation, defined as positive during discharging.





Renewable Energy in Longyearbyen

Student: **Emil Risvik Buseth**
Supervisor: **Karen Byskov Lindberg**

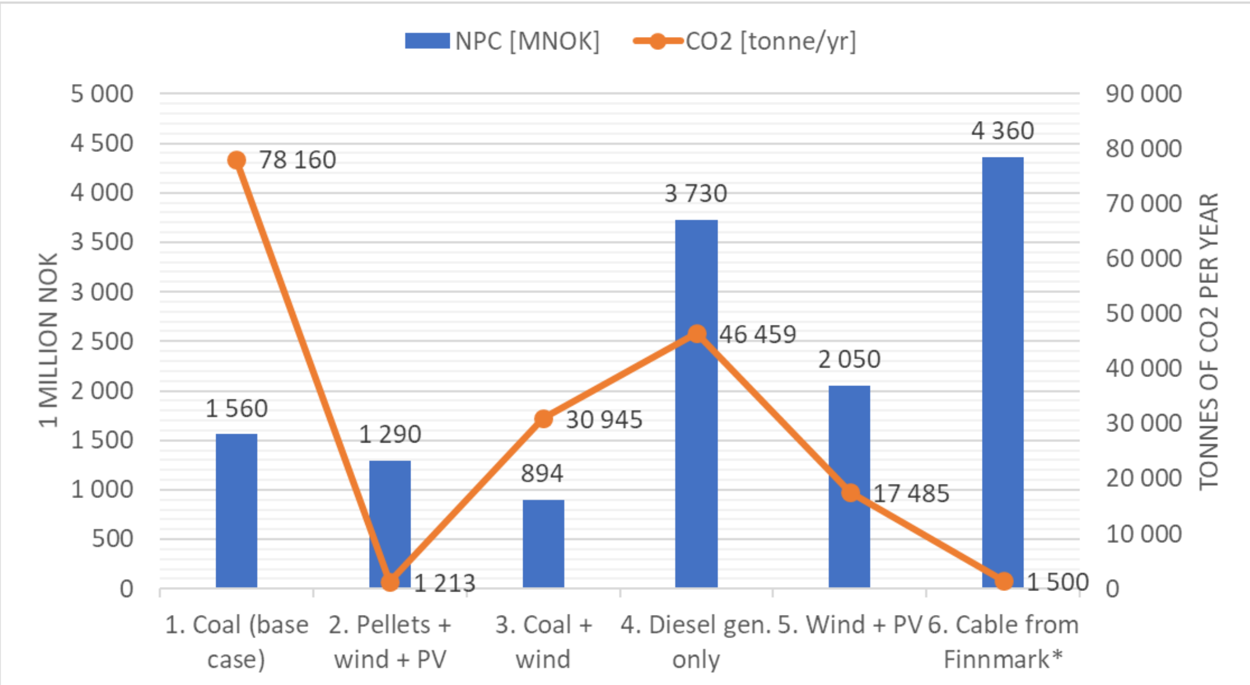
Problem description

Climate change is becoming an increasingly pressing issue, and the effects of it is most experienced in the Arctic. The energy system in Longyearbyen on Svalbard is currently based on coal, but the coal plant is nearing the end of its lifetime. The main research question of this thesis has been to examine: *How can the energy system in Longyearbyen be transitioned towards renewables, in a way that is both cost-efficient and ensures security of energy supply?* To answer this, a case analysis has been done to find potential solutions. There has also been an analysis to see how the proposed systems could handle a transition from fossil fuel vehicles to battery electric vehicles in Longyearbyen.

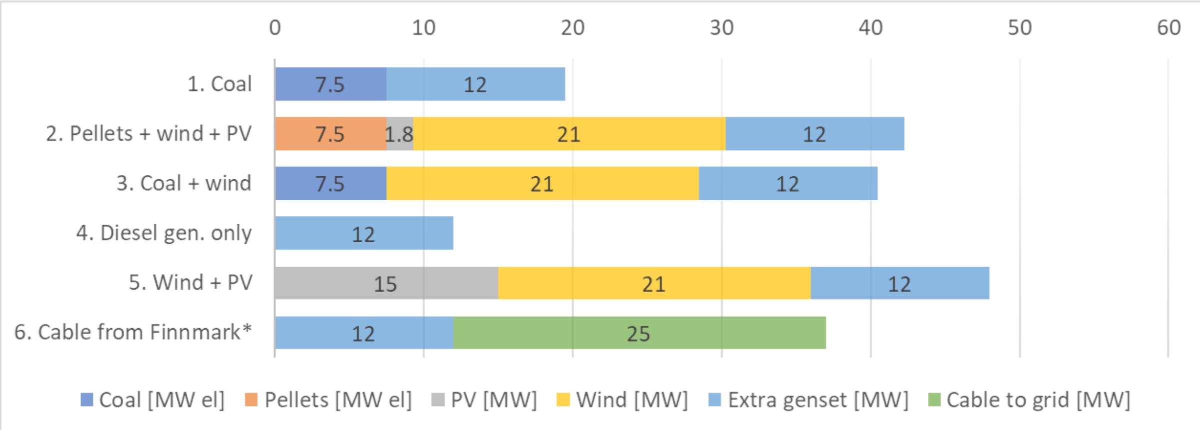
Method

The energy system modelling tools HOMER Pro and eTransport were used to perform a case analysis of technologically feasible solutions to find feasible systems and to create an investment plan. The analysis period was set to 30 years, from 2021-2050. HOMER was used to design five cases, that were judged by how they performed with regards to net present cost (NPC), emissions and improvements in security of energy supply. eTransport, which cannot size components on its own, was used to create an investment plan for a new energy system in Longyearbyen was designed.

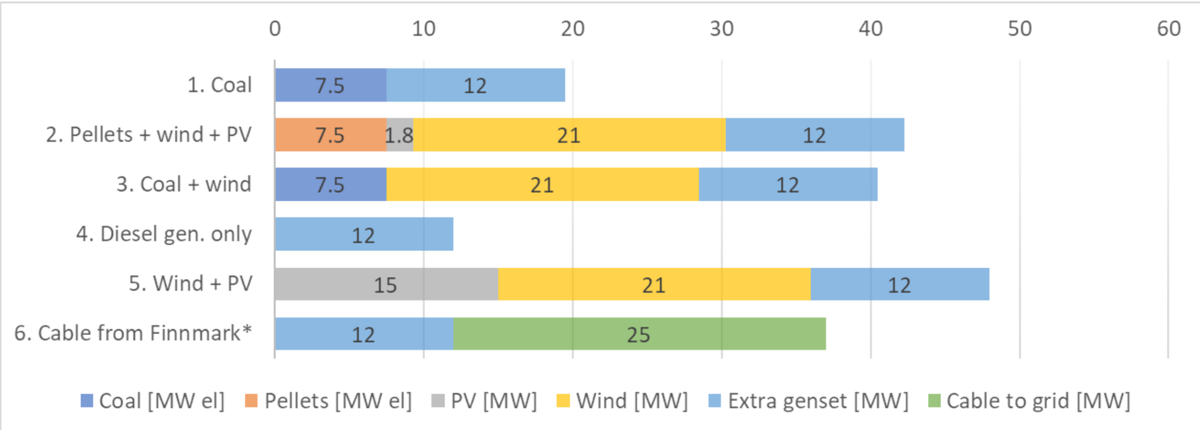
Results



NPC and CO_2 emissions



Installed power capacity



Installed heat capacity

The results from the HOMER analysis shows that compared to the base case (1), there is substantial potential to reduce global greenhouse gas emissions. Case 2 and 3 also offered cost reductions of 20 and 303 MNOK respectively. The alternative of installing a power cable to mainland Norway was examined in a report by ABB, and was included in this analysis to compare it with the other alternatives. Transitioning the fossil fuel vehicles to electric vehicles is possible, and would increase the NPC by 85, 80, 459 and 217 MNOK for case 2, 3, 4 and 5 respectively.

The eTransport analysis indicated that the optimal investment to begin with in 2021 is the 21 MW wind park, along with a 5 MWh battery and a 4 MW electric boiler. The next investments should be postponed for as long as the coal power plant is operable.

Conclusion

A possible transition towards renewables in Longyearbyen could come in two steps: First, a 21 MW wind park, 5 MWh battery storage and 4 MW electric boiler capacity should be installed. These components provide the best benefits with regards to cost and emission reductions from the system. The second step would be to replace the existing coal power plant. A 7.5 MW pellets plant would be the best solution with regards to costs and emissions, but a 15 MW rooftop PV installation and an additional 10 MWh of battery storage is also a feasible solution but would make the system more dependent on backup diesel capacity. It is possible to replace the vehicle park with electric vehicles, and case 2 is best suited for this.

Investigating the impact of Flow-based market coupling on the Nordic area prices

Students: **Vegard Viken Kallset and Andreas Hovde Bø**
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Collaboration with: **TrønderEnergi Kraft AS**

Problem description
The Nordic capacity calculation methodology is currently based on a Coordinated Net Transmission Capacity (CNTC) approach for calculating transmission capacities. This approach assumes that electricity can be directly transferred from one zone to another, limited by a given transfer capacity and reliability margin. Flow-Based Market Coupling (FBMC) has been proposed as the new capacity calculation methodology, and takes, in contrast to the CNTC approach, physical power flows into account. Furthermore, a large amount of new wind power is expected to come online in NO3 and NO4. How this structural change of the power supply in conjunction with the introduction of FBMC will impact the future electricity prices is examined in this paper.

The task
The scope for this preliminary project is to build two models, one based on the Coordinated Net Transfer Capacity, and the other one based on the Flow-Based Market Coupling approach, to simulate the future prices in the Nordic area and Europe.

Model/ measurements
To develop the optimization models the python package Pyomo has been used and Gurobi has been used to solve them. The models are deterministic and are run for one year at a time. In short, they simulate the Nordic system by giving each price area demand and production ability, and by allowing the different areas to send power to each other.

The objective function of the optimization model is maximized welfare economic surplus(Table 1), thus minimizing the variable costs of producing from all the power plants. This includes the fuel costs, costs for carbon emissions and other variable costs for producing at each power plant. In addition, the model contains constraints that accounts for power plant capacity, demand, and the grid. Whereas CNTC uses NTC values, FBMC uses Power Transfer Distribution Factors (PTDF) and Remaining Available Margin (RAM) regarding the grid constraints.

Table 1: CNTC and FBMC has the same objective function, however, the constraints are different.

	Objective function:	Subject to:
NTC	Maximize welfare economic surplus	∑NP=0, CNTC constraints
FBMC	Maximize welfare economic surplus	∑NP=0, FBMC constraints

Three scenarios are implemented to compare the two models; *2020 base case, 2022 base case*, and *2022 with increased wind power plant capacity*. 2020 simulates the power system equal of today, while a reasonable amount of wind power plants are built by 2022. The scenario with increased wind power capacity in 2022 increases wind capacity by 20% for NO3, NO4, SE1, and SE2.

Calculation

For the prices, the results give smaller differences between zones when using FBMC, instead of CNTC(Table 2). This contrast is particularly clear in the scenario with 20% increased wind power. In that scenario, the prices drop to about 12 EUR/MWh in NO3 and NO4 for the CNTC model, while the other price zones have average prices between 22-29 EUR/MWh. In the FBMC model, the prices in NO3 and NO4 is in the same price range of 21-28 EUR/MWh as the other zones, though they are still the zones with the lowest prices.

Table 2: Yearly average prives in EUR/MWh for CNTC and FBMC across all scenarios.

	2020 Base case			2022 Base case			2022 Increased Wind		
	CNTC	FBMC	Diff	CNTC	FBMC	Diff	CNTC	FBMC	Diff
DK1	36,54	36,43	-0,11	33,74	33,77	0,03	26,38	25,38	-1,00
DK2	38,15	38,26	0,11	35,61	35,62	0,01	28,83	27,64	-1,19
FIN	37,27	37,12	-0,15	33,95	33,96	0,01	25,78	24,55	-1,23
NO1	37,13	36,94	-0,19	33,61	33,51	-0,10	24,51	22,67	-1,84
NO2	36,80	36,89	0,09	33,14	33,45	0,31	23,77	22,56	-1,21
NO3	36,49	36,58	0,09	32,23	32,96	0,73	12,36	21,66	9,30
NO4	36,49	36,58	0,09	32,67	32,96	0,29	12,52	21,57	9,05
NO5	36,53	36,80	0,27	32,82	33,29	0,47	23,18	22,22	-0,96
SE1	36,38	36,47	0,09	32,42	32,84	0,42	22,27	21,74	-0,53
SE2	36,41	36,49	0,08	32,45	32,86	0,41	22,30	21,77	-0,53
SE3	37,06	36,85	-0,21	33,66	33,52	-0,14	24,89	23,34	-1,55
SE4	38,38	38,06	-0,32	35,12	35,05	-0,07	27,52	26,39	-1,13

Overall, the net flow between any two neighboring areas is similar for the two approaches, while the gross flow is higher for the FBMC model in both directions. Another difference is that export from the Nordic areas to other European areas is increased in FBMC relative to CNTC in all scenarios.

Total social surplus increases when using FMBC compared to CNTC, even though not all stakeholders benefit (Figure 1). The direction of change in producer surplus and consumer surplus in each zone is mostly determined by whether the price goes up or down in that zone. Share of congestion rent mostly decreases in all zones, except for when reduced-price differences between zones are weighed up for by increased power flow.

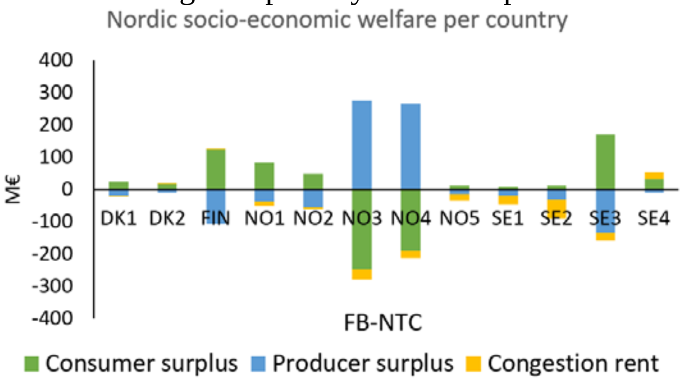

Figure 1: Yearly Nordic FB-CNTC consumer surplus, producer surplus, and congestion rent for the scenario with increased wind capacity 2022.

Conclusion

Overall, welfare increases, price differences are smaller, and congestion is dealt with more efficiently by using FBMC compared with CNTC, especially on a power system with increased wind power capacity.

Investment analysis for Residential Storage and PV Systems under Spanish Grid Tariffs

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Contact: **adrcruz.96@gmail.com**
Collaboration with:

Problem description
This thesis is based on an investment analysis to assess the optimal sizing of solar panels and batteries that minimizes the domestic electricity bill under a Spanish grid tariff. The abolition of the solar tax in 2018 could have opened a new horizon in electricity self-consumption. This research aims to give an objective review about the electricity self-consumption in Spanish households with a range of power installed between 1kW and 10kW, where the big majority of households are.

In order to carry out the analysis, three households with different electrical consumption and power installed were selected from a municipality at the outskirts of Madrid, named Boadilla del Monte. Each of them able to include batteries and solar production. The optimization program finds the optimal size of PV and batteries, as well as the optimal way to control them, to minimize the total annual electricity bill and the annual investment costs for each of the households. The analysis is based on a 25 years investment period considering a discount rate of 5%.

The task

The study will try to answer the following questions:

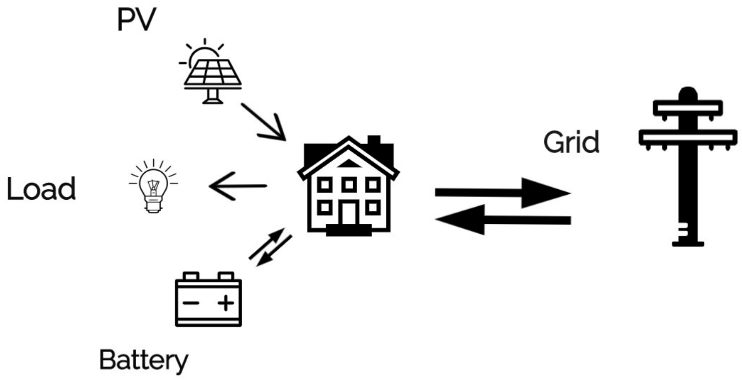
- Is it cost-effective to invest in PV and energy storage technologies in order to reduce the domestic electricity bill for households of the low voltage Spanish grid under a TOU tariff after the abolition of the so-called "Impuesto al sol" law? What optimal size minimizes the domestic electricity bill? How big is this bill reduction in comparison with no making any investment? And how much savings will house owners make?

- Usually, an investment analysis is carried out based on predictions about the future. How far would sizing predictions differ from the actual real ones that minimizes costs the most?

- How energy storage prices influence the investment decisions? What impacts does it have over the domestic electricity bill?

Model/ measurements
The problem is faced with two models, one stochastic and one deterministic. On the one hand, since future electricity consumption, electricity costs and solar radiation is uncertain, a stochastic model is developed to make estimation of future variables using historical data. On the other hand, a deterministic model is later used to test the accuracy of predictions from the stochastic model.

Each household is designed as an entity connected to the power grid and it is based on an energy balance, where the household is able not only to import, but also to export energy to the grid. These energy imports and exports depend on the activity of the appliances, the PV system and the battery, and on the energy consumption.



Calculation

Table 4.1: Optimal size for household 1

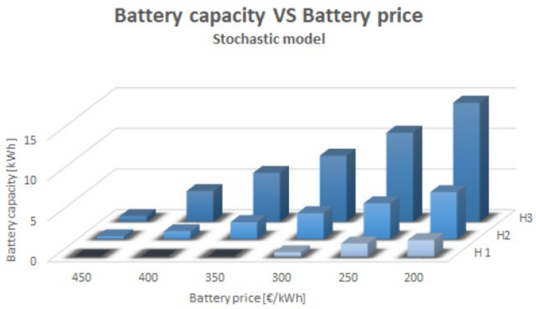
Scenario	Case scenario 2	Case scenario 3
Battery size (kWh)	0	0
Solar system size (kW)	3,65	1,33

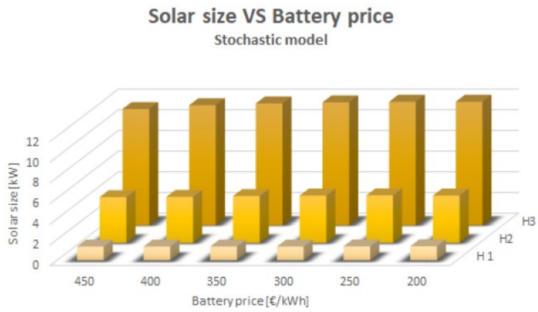
Table 4.2: Optimal size for household 2

Scenario	Case scenario 2	Case scenario 3
Battery size (kWh)	0	0
Solar system size (kW)	4,43	6,16

Table 4.3: Optimal size for household 3

Scenario	Case scenario 2	Case scenario 3
Battery size (kWh)	0	0
Solar system size (kW)	11,2	11,16





Conclusion

At the moment, It is only cost-effective to invest in PV systems rather than in an energy storage. However, results have shown that for households with large energy consumption a battery investment might be reasonable to invest in when battery prices go down.

When predictions are performed under a stochastic linear programming approach, around 10% more expensive annual costs and less savings are experienced.

When battery prices go down some investment in energy storage shows up, while PV systems remains barely affected by this change in terms of size. However, this investment in energy storage do not make a considerable reduction in the electricity bill at the end, only in households with a high energy consumption a noticeable reduction is achieved.

Impact of Local Electricity Markets and Peer-to-Peer Trading on Grid Operations in a Norwegian Low-Voltage Distribution Grid

Student: **Marthe Fogstad Dynge**
Supervisor: **Magnus Korpås**
Co-supervisors: **Dimitri Pinel (IE)**
Pedro Crespo del Granado (IØT)

Abstract

Distributed Energy Resources (DERs) are rapidly entering the power system, introducing both new opportunities and challenges for the system operators. Formerly passive consumers are transitioning into the prosumer role, calling for a restructuring of the conventional top-down system. With the simultaneous advancements in Information and Communication Technology (ICT), new frameworks to facilitate a more consumer-centric market and the deployment of DERs, are emerging. Peer-to-Peer (P2P) markets have thus gained attention in academic research and as pilot projects over the recent years, with promising results in terms of economic benefits. The impacts such market structures will have on the grid operations of low-voltage distribution networks are, however, little explored. As the peers are connected to a complex power system with hard technical constraints, such analyses are essential in order to determine the actual feasibility of local electricity trading.

In this thesis, a novel approach is conducted by combining a multi-period market optimisation model with a power flow analysis tool in MATLAB. With this method, all market decisions can be validated, but not necessarily constrained, by the distribution grid's technical specifications. Two system configurations of DER and storage deployment are analysed, with comparative cases of the impacts of establishing a local market or not. Additionally, an innovative pricing mechanism for reducing total system losses is introduced in a final case study.

The main findings indicate that there are no significant impacts on the grid operation of a P2P market when only Photovoltaics (PVs) are installed in the system. With decentralised batteries available, the P2P trade induced more voltage fluctuations and 13.79 % more losses within the neighbourhood than the case with no local market. The proposed pricing strategy in the final case managed to reduce these losses with 4.67 %. Moreover, establishing a local market showed a higher degree of community resilience and effective use of local resources for both system configurations.

Security-Constrained Optimal Power Flow in Meshed Distribution Grids

Student: **Matias Lunde Ellingsen**
Supervisor: **Olav Bjarte Fosso**

Problem description

With the modernization of the power grid, smart solutions for effective and secure system planning and operation are essential. Traditional power system optimization techniques are being revisited and becoming relevant for new applications. Security-Constrained Optimal Power Flow (SCOPF) is an extension of the Optimal Power Flow (OPF) problem. The objective of SCOPF is usually to find the lowest cost dispatch of power that satisfy all system constraints, now, and during a defined set of likely contingencies, such as line- or generator outages. The majority existing SCOPF software either rely on a DC approximation, which is unsuitable especially for distribution grids, is not freely available, or don't consider post-contingency rescheduling.

The task

The objective of this thesis is to identify a solution method for the nonlinear SCOPF problem and make a prototype implementation in the open-source programming language Python.

Model/ measurements

The OPF is solved by Sequential Linear Programming, utilizing a Trust Region Method. With this approach, the original nonlinear problem is iteratively linearized around the current solution and solved by Linear Programming. The Trust Region method adjusts the "window" for which the linearizations are assumed to be valid based on the accuracy of the previous iteration. To solve the SCOPF problem, where contingency constraints are included, Benders Decomposition is employed. That involves dividing the problem into a base-case master problem and a set of slave subproblems for each considered contingency. These are also solved iteratively, with infeasible subproblems generating a linear constraint for the master problem, known as a Bender's Cut (BC). The algorithm is designed to consider both *preventive security* and *corrective security*.

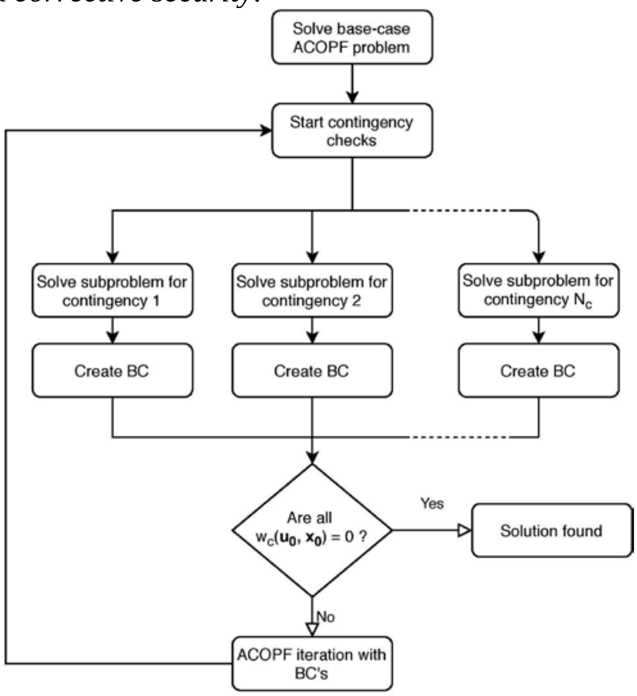


Figure 1: Flowchart of SCOPF algorithm

Calculation

The program is tested and demonstrated on two illustrative systems with some numerical examples. The proposed OPF algorithm performs well on the 6-bus example system, where convergence is achieved in 9 iterations with a cost reduction of 5.45 % compared to the initial "guess". The SCOPF algorithm is demonstrated on an example 12-bus system. "Preventive security" and "corrective security" result in a cost increase of 1.25 % and 0.41 %, respectively, compared to the basic OPF solution. Tests of the considered contingencies reveal that the solutions are valid, but that the corrective solution can be inaccurate for larger allowed corrective rescheduling.

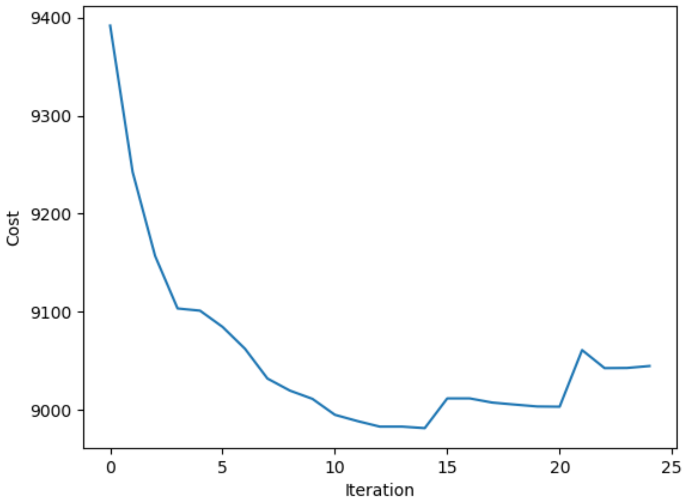


Figure 2: Plot showing the total operation cost at every iteration when testing for *corrective security* on the 12-bus system.

Conclusion

It is concluded that the methods employed for solving SCOPF problems show great promise, and with further work, this can become a useful tool in the planning and operation of future distribution grids.

Techno-economical optimization of energy storage for increased wind farm integration

Student: **Linnea Espevik**
Supervisor: **Jayaprakash Rajasekharan**
Contact: **Sindre Solberg**
Collaboration with: **Siemens Norge AS and Midtfjellet Vindkraft AS**

Problem description

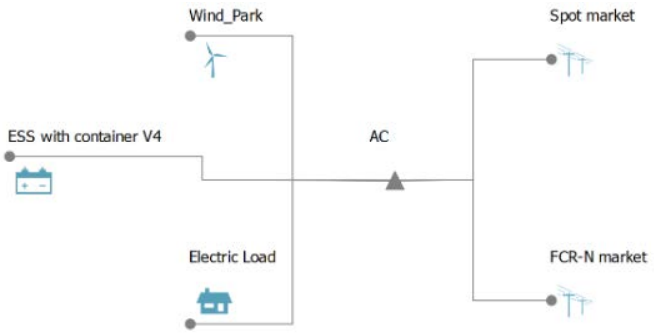
The problem with an increasing share of renewable energy sources (RES) is that the fluctuating nature of some of the most prominent RES, wind turbines and solar photovoltaic panels, can cause stability issues in the gird. A solution to mitigate this can be to install Energy Storage Systems (ESS). ESS can be used both to provide ancillary services and improve RES integration. However, as Distribution System Operators(DSOs) in the current EU legislation cannot own ESS, ESS investments must be profitable. The main objective of this thesis has, therefore, been to assess the profitability and benefits that can be obtained with an ESS investment.

The task

This thesis is done in collaboration with Siemens AS and presented different benefits of installing an Energy Storage System (ESS) with a wind farm (or other volatile production) through a literature review, extensive theory chapter, and a real case study of a proposed Li-Ion BESS for Midtfjellet windfarm. Previous literature was found to have had a primary focus on economic benefits, while the theory chapter concludes that there are several technical features that ESSm can also provide. The case study conducted used the data from Midtfjellet wind farm, and future scenarios for 2030 with both different electricity prices, and the development of the Li-Ion price was conducted. The scenarios included using a multi-market model, where participation in the Norwegian Day-ahead, FCR-N, and FFR market was possible. Optimization of 44 scenarios was carried out in PSS®DE, an optimization program developed by Siemens AS.

Model/ measurements

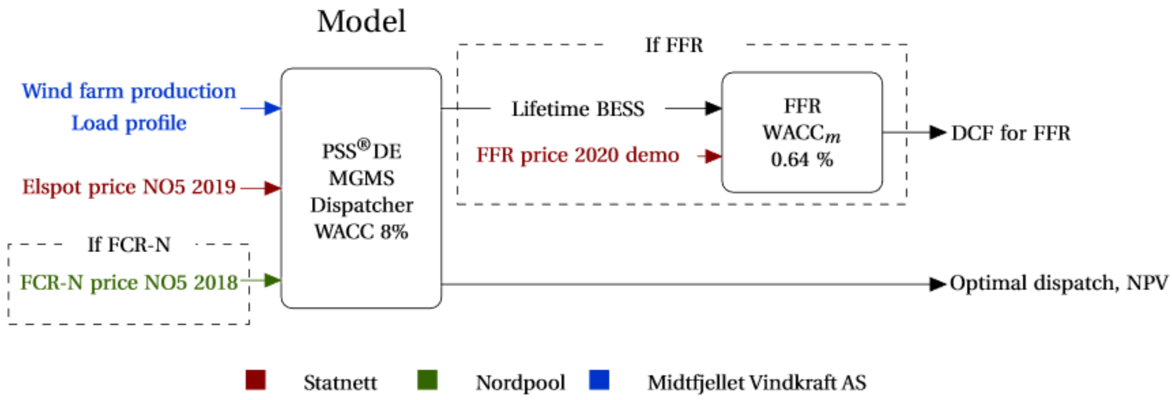
The model contains a Li-Ion BESS, electrical load and wind farm connected to external grids, one with the market structure of the Nordic Day-Ahead market, Elspot, and one for Norwegian primary reserves for normal operation, FCR-N, as shown in Figure 1.



Figur 1: Model in PSS®DE with electric load, wind farm, Li-Ion BESS and two external grids

Restricted

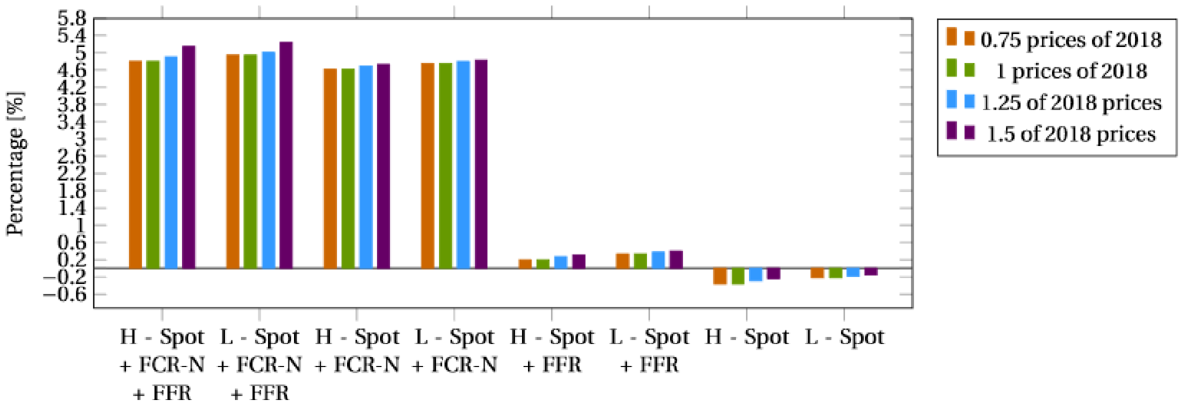
The FFR market, which is to be tested in a demo version by Statnett in 2020, is simulated by raising the SoC level of the battery to ensure sufficient reserves. The revenue from this is calculated using the expected lifetime of the BESS, as shown in Figure 2.



Figur 2: Simulation process

Calculation

The results, as displayed for the 10-year scenarios in figure 1, shows an increase in NPV when FCR-N and Day-ahead market interaction is allowed.



Figur 3: Percentage change in aggregated NPV from PSS®DE and FFR compared to the reference case for 2030 scenarios

Conclusion

The main results from the case study show that a small ESS unit can provide additional revenue for a wind farm, if it can participate in several markets, i.e., through revenue stacking. However, there were some limitations to the multi-market model, as the model used allowed for transactions directly between the markets, without utilization of the battery.

Optimization algorithms for the currents in the Field Weakening region of an Interior Permanent Magnet Synchronous Motor of an Electric Racing Car

Student: **Francesco Fanin**
Supervisor: **Roy Nilsen**
Collaboration with: **Revolve NTNU**

Problem description

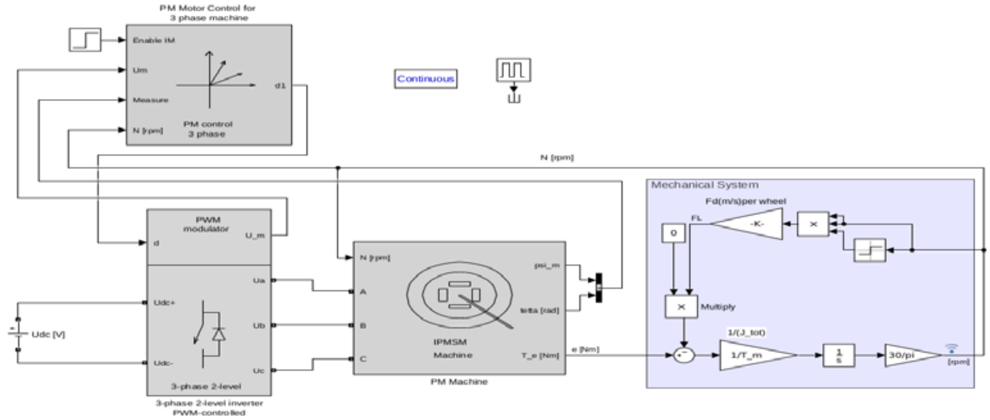
During the 2019 racing season, Revolve NTNU developed its own drive system, therefore a custom inverter and a motor controller were designed and produced in order to control its motors. The inverter features SiC Mosfets with a switching frequency of 20'000 Hz. A field oriented control (FOC) was utilized as a control technique in the motor controller.
The current references were generated using a maximum torque per ampere (MTPA) strategy, while on the Field Weakening region the optimal stator flux angle was calculated using a recursive Newton Rapshon algorithm in order to obtain a maximum torque per flux (MTPF). However, while testing the algorithm on the electric racing car, noises in the stator current were noticed especially at high speeds, the Interior Permanent Magnet Synchronous Motor (IPMSM) being in the Field Weakening area.

The task

In this work, different approaches for reducing current noises in the electric drive at high speeds are explored.These methods calculate the current references offline and the results are stored in a Look Up Table (LUT). A custom LUT, specifically designed for Revolve NTNU's motor, is implemented in order to obtain the optimal current references. Furthermore, a linear algorithm for calculating the current references of a Finite Speed Drive is introduced. An improvement of the Newton Raphson approach used in the previous racing reason is presented. The functionality of the controlling techniques is then tested by performing simulations using Simulink. Finally, the different methods are compared from the results of these simulations, and the most efficient method to reduce the current noises in the Field Weakening region is finally chosen.

Model/ measurements

The simulations are created using Simulink. This work is focused on the current references generation in the Field Weakening area. Thus the Current References Generation inside the Motor Controller block was modified .



Calculation

In the following figure, an example of the simulation results is shown.

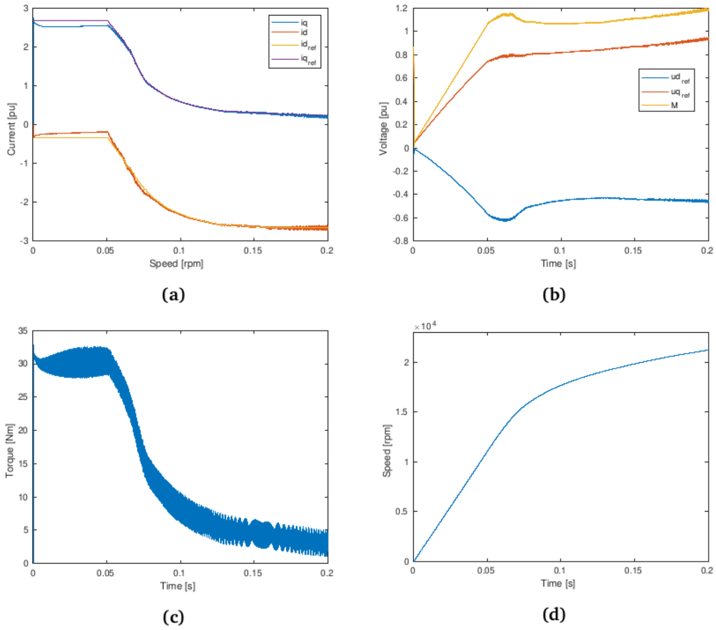


Figure 4.6: Simulation using the linear Look Up Table

Conclusion

Four different algorithms for generating current references in the Field Weakening Region were presented in this work, and their functionality was tested using Simulink. The custom Look Up Table and the Linear Field Weakening Control are easy and effective methods to control the motor at high speeds without having current noises. However, both of these algorithms present numerous approximations, making them unsuitable for an electric racing car.

Generating the Field Weakening current references using the modified Newton Rapshon algorithm appears to be the best choice in terms of performance of the motor, since the current references follow the optimal current trajectory. Finally, the backup algorithm for generating the angle beta generates satisfactory current references, however this method was discarded when applied to the real motor, because it was not able to generate the expected torque.

Power Electronic Converters for Efficient Operation of the Modular HVDC Generator for Offshore Wind Power

Comparison of DC-bus voltage balancing, IGBT module losses and performance gains with the 3L-NPC converter

Student: **Hans Anders Faraasen**
Supervisor: **Gilbert Bergna-Diaz**
Co-supervisor: **Pål Keim Olsen**

Problem description

Offshore wind power is projected an exponential growth in the coming decades as the world need affordable low-carbon and renewable energy resources. The Modular High Voltage Direct Current (ModHVDC) generator proposes using a stator-segmented Permanent Magnet Synchronous Generator (PMSG), where each segment is connected to a dedicated power converter. The converters are series-connected on their DC-side to achieve 100 kV HVDC in turbine terminal. By having HVDC at this point, reduction of conversion steps and AC infrastructure can be reduced. This may decrease risk and cost of energy transmission from offshore windfarms to onshore converter stations and eventually the onshore power grid.

This master thesis emphasizes the power electronic converters related to the ModHVDC machine, concerning both its topology and control. Special technical challenges arise due to the stator segmentation and multiple power converters. Adequate control methods are required for high performance and reliable operation. Additionally, the 100 kV DC-potential necessitates dedicated converters for safe and efficient operation. Research for energy-efficient and high performing power electronic converters was the focus for this thesis. The intention is to use the results for future lab-scale realization of the ModHVDC generator to increase the technical readiness level of the technology.

The task

1. A performance comparison between the three-level neutral point clamped (3L-NPC) converter and two-level voltage source converter (2L-VSC) was conducted. Performance was measured by studying the state variables behaviour, voltage and current waveform, power quality, losses and efficiency for both converters when the turbine was subjected to various wind speeds.

2. To limit the feasible region of design choices for maximum energy-efficient operation, the two converters was studied with three different industrially available 3.3, 4.5 and 6.5 kV IGBT modules. The purpose was to compare benefits of using multiple lower voltage rated modules or fewer higher voltage rated modules with both converters.

3. Special focus was dedicated to DC-bus voltage control due to the series-connection of converter associated with the ModHVDC technology. Both the challenge and potential solutions for control strategies was presented. Eighth generator/converter modules were assigned with normal distributed parameters for simulating a natural voltage variation between modules in a full-scale application. This was used to study the effect of the various proposed strategies in terms of voltage/current stress and system power output.

Model/ measurements

Figure 1 show the simulation model which is related to task 1. The second task was conducted with analytical calculation models and task 3 was a pure mathematical analysis of an eight-segment configuration in steady state.

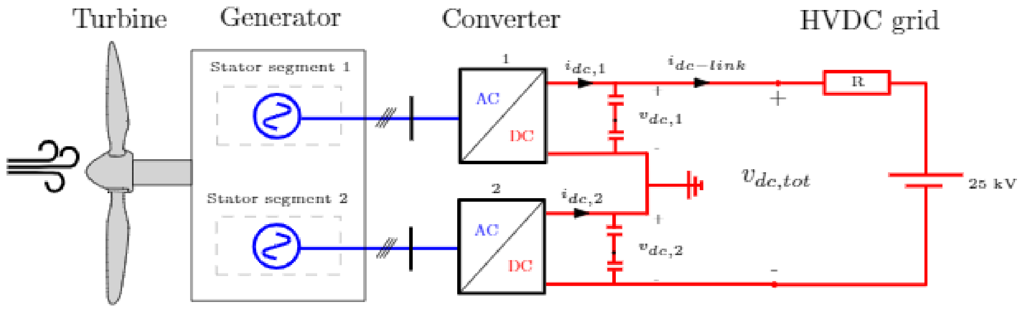


Figure 1 Simulation set-up was limited to only two generator/converter modules

Results

1. The results showed that the both converters provided stable and safe operation. The 3L-NPC converter showed better power quality, reduced DC-link current ripple, lower losses and higher weighted average efficiency than a 2L-VSC. Difference in annual weighted efficiency given in Table 1 can lead to savings of 210 MWh/year in a 10 MW offshore wind turbine.

Table 1 Converter annual efficiency

Converter	η
2L-VSC	0.987
3L-NPC	0.992

2. Figure 2 show converter system efficiency with 10 MW input power for the two converters with three the IGBT modules, as a function of switching frequency.

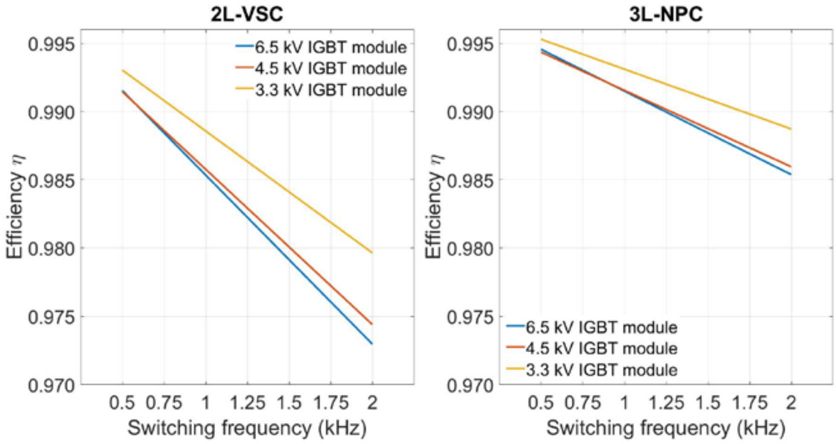


Figure 2 Comparison of converter system efficiency with three different IGBT modules

3. The alternatives for having identical DC-bus voltages at rated wind speed and above are either accepting overloading of some modules or lower the total power output to the module with lowest output power. With the eight modules given normal distributed parameters, the former led to a current overloading of 0.048 pu (8 A) in one module, while the latter resulted in a power reduction of 4.5 \%, which could accumulate to 1.3 GWh/year for a 10 MW offshore wind turbine.

Conclusion

The results show that the 3L-NPC converter out-performs the 2L-VSC in this application and are recommended for future lab-scale realization. Using 3.3 kV IGBT modules are more energy-efficient than less extensive series-connections of 4.5 and 6.5 kV IGBT modules. Finally, controlling the DC-bus voltages in the series-connection of converters are a trade-off between power reduction or increased voltage and/or current stress to some modules. The technology might not claim high efficiency if considerable power reduction is required. Further research is recommended to investigate how to minimize differences between modules and the effect of voltage/current stress to the system in terms of reliability and availability for safe and high-performance operation.

TSO – DSO Coordination for Voltage Control: Simulation Study and Use Case Development

Student: **Mohamed Farooq**
Supervisor: **Irina Oleinikova**
Co-Supervisor: **Merkebu Zenebe Degefa, SINTEF Energi AS**
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Collaboration with: **CINELDI, SINTEF Energi AS**

Abstract

With the increasing share of DG and RES, the changing framework in the energy market, the number of traditional synchronous generators decreases, hence primary sources for voltage control are missing. Furthermore, the voltage in the power system is changing much more rapidly, following system load variations and intermittent RES infeed. In unanticipated low-RES infeed/ high load cases, voltage drops appear dramatically, mainly when there are no devices for voltage control. Considering this, TSOs are increasingly looking for additional resources within the distribution system to be deployed in greater coordination. Hence, it is crucial to develop tools/ approaches for the management and planning of voltage/ control of reactive power in future control centers.

The goal of this Master Thesis is to demonstrate the benefits of a coordination mechanism through high-level Use Case development between DSO and TSO. The coordination scheme depends on an OPF tool attributing Multi-Objective (MO) optimization, which is envisaged as an effective means to resolve the future operational challenges. This contains cooperation between two real-time OPFs running at DSO and TSO control centers. An interoperation chain depending on sequential optimizations and exchange of relevant information and setpoints is defined.

The use case is implemented in simulation in order to manage long term voltage variations. The simulation includes models of DGs and their reactive power controllers and models of network components such as OLTCs. The OPF is implemented using the GAMS, and MATLAB is used to orchestrate the data exchange and managing input and output data for simulation. The results demonstrate the benefits of TSO-DSO coordination at the operational level with the fewer variable voltage profiles and closer to the required references. Simultaneously, the results also illustrate the impact of rerouting reactive power on the total loss in the network.

Model

A six-bus system for transmission grid and a thirty-bus system for distribution grid are developed to coordinate between them as shown in Figures 1 and 2. In Use Cases, TSO and DSO can be kept separately operating their respective OPF for coordinated voltage control. AC Optimal Power Flow (OPF) for TSO and DSO networks are modeled in GAMS with the objective function for loss minimization.

An OLTC transformer is connected only on the TSO network between buses 2 and 6. The primary side of the transformer is connected to bus 2 and the secondary side to bus 6. It is assumed the OLTC tap changer is on the first winding. Afterward, bus 2 of the TSO network is connected to bus 1 of the DSO network. Once the optimal tap for the OLTC in the TSO network is identified, then when DSO OPF is run in order to fix the voltage level of DSO network bus 1 that is identical with the bus 6 of the TSO network. Similarly, the transfer of reactive power identified in the TSO network at bus 6 will be assigned to bus 1 of the DSO network.

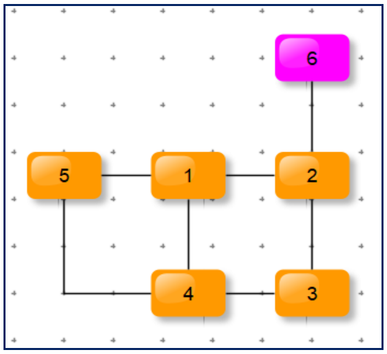


Figure 1: TSO Network

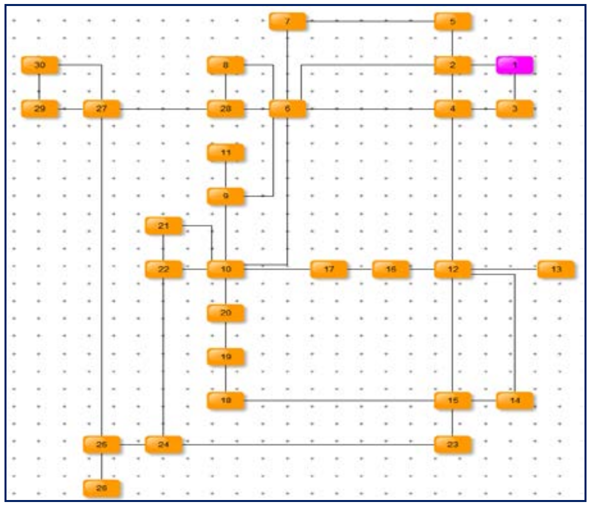


Figure 2: DSO Network

Results

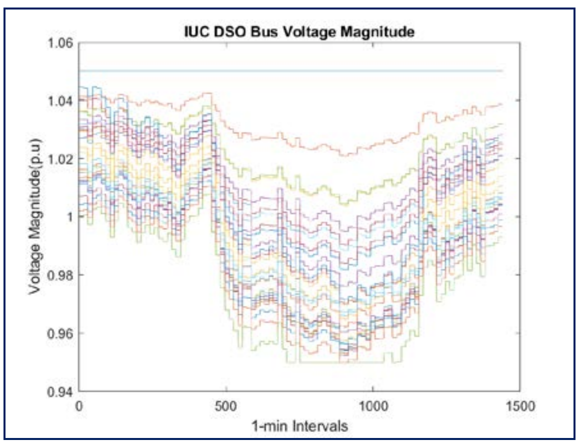


Figure 3: IUC Bus Voltage

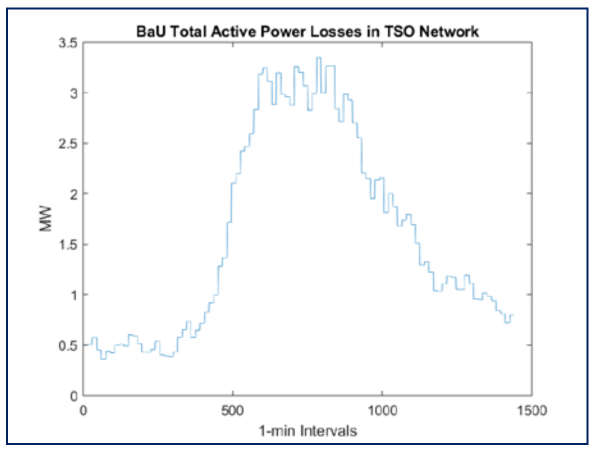


Figure 4: Active Power loss in TSO for IUC Case

In Figure 3, the voltage limit violation does not occur in the implemented use case (IUC), but it is observed that some bus voltages are at their lower limits at some points during the simulation. The total active power losses in the IUC case is lower than in the Business-as-Usual case.

Conclusion

The goal of the thesis is to analyze and demonstrate the DSO and TSO coordination mechanism through high-level Use Case development. Here, an Optimal Power Flow (OPF) tool attributing Multi-Objective (MO) optimization is envisaged as an effective means to resolve the future system operational challenges. This cooperation between two real-time OPFs running at DSO and TSO control sides has shown that TSO-DSO coordination and the availability of distributed generation can improve the long-term voltage variation of both TSO and DSO networks.

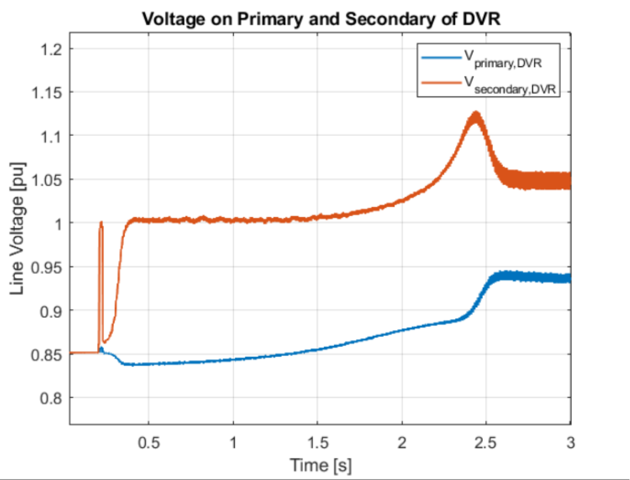
The case study has shown that TSO-DSO coordination can be effective in volt-var control in both TSO and DSO networks. In this study, a sequential loss minimization OPF has been adopted by both TSO and DSO in order to optimize reactive power flow in both systems and control the long-term voltage variation.

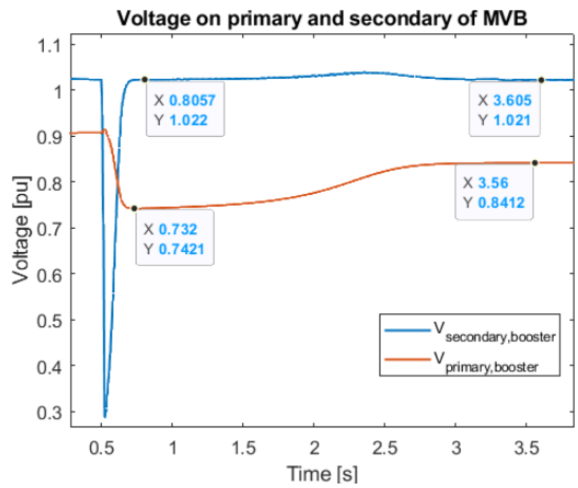
Voltage Regulation in Low Voltage Distribution Grids – Study of Different Technologies and implementation of a VSC based series regulator

Student: **Arjan Festøy**
Supervisor: **Kjetil Uhlen**

These days, more power demanding equipment such as EV charging, induction cooktops and power electronics based devices are installed in low voltage distribution grids in every part of the country. This introduces potential problems regarding voltage quality due to the state of the overhead lines and cables supplying consumers, especially in rural areas where the trend of old infrastructure with low short circuit capacity is high.\\

In this thesis, a real IT-based low voltage distribution grid is modelled in the Simulink environment where two series-connected voltage regulators, the Magtech Voltage Booster (MVB) and the Dynamic Voltage Restorer (DVR), are installed and simulated during the start of an induction motor. By analyzing the response and impact of the voltage regulators, the goal is to establish a set of guidelines for choosing the correct voltage regulation method in accordance with the grid's topology based on the R/X factor and short circuit capacity.\\





Through the simulations done, it is clear that both the modelled voltage regulators manage to control the voltage at the secondary side to 1 pu, supporting the induction machine in a way that the startup sequence finishes without problems. However, the MVB is consuming significant amounts of reactive power which leads to voltage drops upstream in the grid. This is further empowered if the network has a R/X factor lower than 1. The DVR on the other hand is producing the necessary amounts of active and reactive power needed to inject the correct voltage, without consuming from the grid due to the VSC and energy storage. This is an important point as the DVRs impact of the grid compared to the MVB is minimal and enables the DVR to theoretically fully protect loads for the safety of supply during short circuit contingencies and other great voltage sag events.

Installing the DVR in grids with a resistive R/X factor, however, is not ideal since the DVR cannot supply unlimited amounts of active power, and is significantly more expensive than other installations such as the MVB - and the ultimate goal for these devices is to be a cheaper and more convenient alternative to a total reinvestment in the grid.

Modelling and control of a fault-tolerant bidirectional hybrid microgrid for marine applications

Student: **Ole Martin Flatjord**
Supervisor: **Elisabetta Tedeschi**
Contact: **Atle Rygg**
Collaboration with: **SIEMENS Offshore Marine Centre**

Problem description

This master thesis investigates the possibility of forming a robust bidirectional hybrid AC/DC marine power system with a voltage source converter(VSC) as the critical interfacing unit. Figure 1 shows the system studied in this thesis. The DC grid contains a switch-connected battery and a controllable current source representing the grid. The AC grid is constituted by a three-phase voltage source, a Thevenin series inductance and an LCL-filter used for switching frequency attenuation. The work is particularly aimed towards the development of a flexible VSC control strategy able to maintain the DC voltage in case the main unit responsible for DC voltage control, i.e the battery, is disconnected. The DC grid forming responsibility is then put on the interfacing converter powered by the AC grid. Instantaneous fault detection and proper change in converter control mode from power management to DC voltage control is proposed. Finally, actions to minimize voltage deviation and recovery time should be implemented in a robust way to ensure seamless operation.

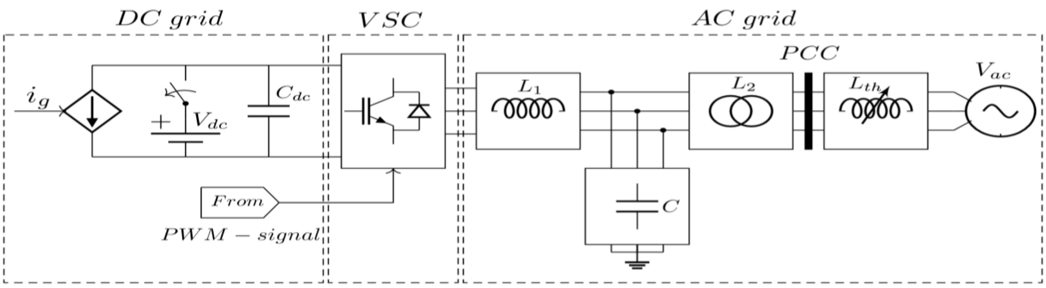


Figure 1: The system studied in this thesis.

One concern regarding the AC distribution power quality is connected to overmodulation of the VSC. Overmodulation contributes significantly to total harmonic distortion(THD) and must be discussed and limited. The upper allowable limit of THD in the marine power system is 8% with a maximum contribution per harmonic order of 5%

Model

The simulation model is illustrated in Figure 2. From left to right, the power system and the control system are shown respectively. The control system is built in a triggered sub-system block in order to introduce an accurate sampling delay. The control system includes: current control, DC voltage control, Q-control, P-control, active damping, harmonic compensation, fault detection, and transient current reference impulse blocks.

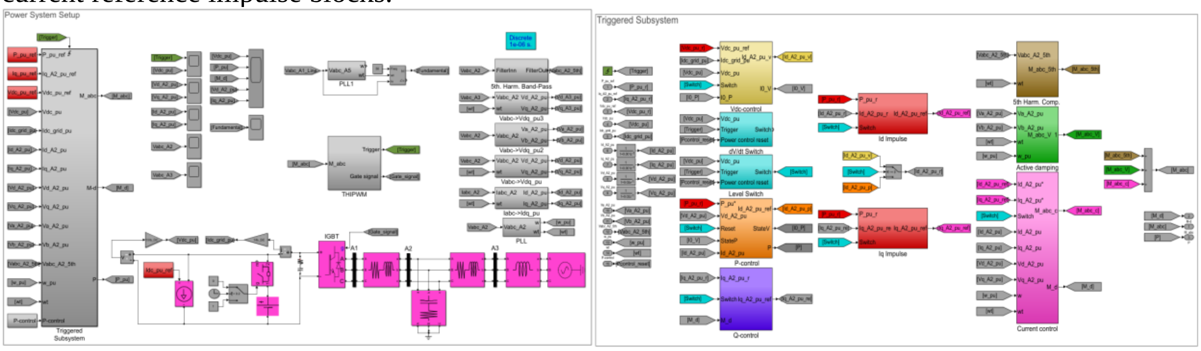
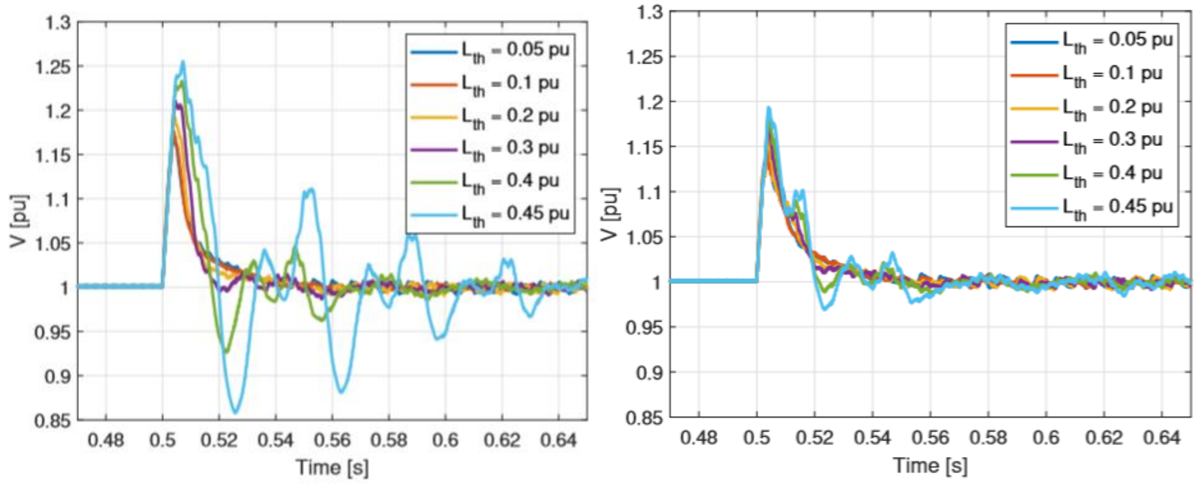


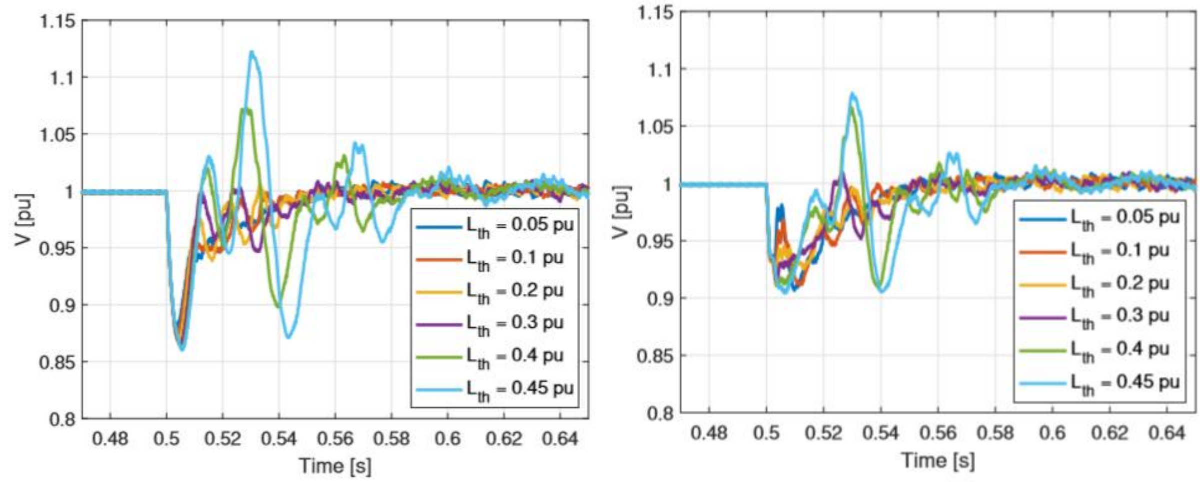
Figure 2: MATLAB/Simulink Model

Results

The thesis especially focuses on limiting the transient in the DC voltage when the battery is suddenly disconnected. The converter then changes control mode from active power control to DC voltage control in order to maintain the voltage. Figure 3 shows the voltage transient when active power is transferred from the AC to the DC grid prior to the fault. The rightmost graf shows the improvement in the voltage transient when an impulse is added in the current controller reference, when a fault is detected, to fast reverse the power flow. Lth is the AC grid series Thevenin impedance. Figure 4 shows a similar scenario, when power is transferred from the AC to the DC grid prior to the fault. Fault detection is made at a voltage level of 1.1pu and 0.95pu



Figur 3: Voltage transient during battery disconnection with power from AC to DC grid prior to fault.



Figur 4: Voltage transient during battery disconnection with power from DC to AC grid prior to fault

Conclusion

Reactive compensation limits voltage total harmonic distortion(THD) to levels below 11% at the point of common coupling(PCC). By further introducing a selective harmonic compensation strategy, the 5th order voltage harmonic is compensated, and the resulting voltage THD holds levels below 6% for all grid conditions. This is within the permitted limits of 8% voltage THD given by the marine power system standard. When the battery is disconnected, the implemented change of control mode ensures retained DC voltage. The transient peaks are increased with increasing grid inductance and power transfer prior to the fault. Introducing transient current reference impulses in the control system has shown to fast reverse the power flow and reduce the peak of the transient. When rated active power is transferred to the DC grid or to the AC grid prior to the fault, the peak of the voltage transient is reduced by 43% and 50%, respectively, compared to the voltage level at fault detection.

Assessing impacts on energy flows and CO_2 emissions due to an alteration of interconnection topology between Norway and the UK

Student: **Ole Marius Forbord**
Supervisor: **Professor Magnus Korpås**
Co-supervisor: **Associate Steve Völler**

Problem description

Promoting sustainable development and reducing carbon emissions have become integrated aspects of energy planning, analysis and policy making in many countries. An increasing number of parties from all levels of the society are involved in the carbon mitigation initiative. Hence, it becomes crucial to clarify and identify to which extent different parties are accountable for CO_2 emissions. Doing so requires the establishment of effective methods for calculation and analysis of carbon emissions in the power system. A useful tool in this context is power flow tracing, which can be used to support qualitative ideas with quantitative analyses of power flows in the grid.

The task

Indeed, to ensure meeting climate targets without sacrificing security of supply and grid stability, the European grid is getting more and more meshed and interconnected. Several large-scale transmission projects are under construction or planned in Europe. Amongst them is a projected sea cable that is intended to interconnect the Norwegian grid with the Scottish. The construction of this interconnecting resource has, the last year, been a controversial topic in the Norwegian political landscape. An economic assessment provided by The Norwegian Water Resources and Energy Directorate (NVE) concluded that the increased exchange capacity due to this cable would be socioeconomic profitable. However, the environmental effects regarding carbon emissions following the cable were not accounted for. Consequently, this thesis sets out to investigate, through both qualitative discussions and quantitative simulations, the environmental footprint of a similar, generic, cable - hereafter denoted as the UK-N cable. Doing so involves indeed examining the impact such a cable has on power production, power flows and power prices.

Model/ measurements

The assessment performed in this thesis is conducted by means of two scenarios; one reflecting the European energy outlook presented in EU's "Reference Scenario 2016" and the other extending this scenario by increasing the share of VRES and power surplus in Norway, Sweden and the UK. These two scenarios are simulated with and without the generic UK-N cable using a power market simulator called the EMPS. An in-house developed power flow tracing (PFT) module then utilizes the results from the simulations, correlating power flowing in a line to specific nodes of production and consumption. The workflow using PFT and some of its applications is demonstrated in Figure 1.

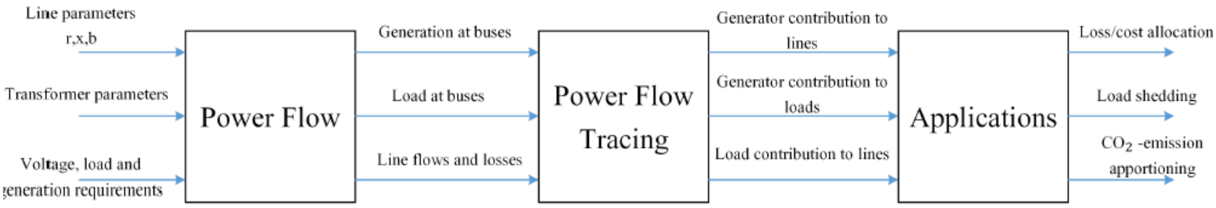


Figure 1

Calculation

Firstly, the UK-N cable is found to bring environmental benefits in terms of reduced CO_2 emissions in both scenarios. For the simulated system as a whole the CO_2 emissions reduce with 0,05 Mton and 1,3 Mton in 2040 - Current Policy and 2040 - Wind\&Solar, respectively.

Secondly, the changes in CO_2 emissions are unevenly distributed among the different countries. Figure 2 shows how UK is the only country interconnected to Norway that reduces its CO_2 emissions following the implementation of the UK-N cable.

Thirdly, distributional effects from the alteration in interconnection topology causes the net export on existing interconnections from Norway to drop. The total net power export, however, is seen to increase with the UK-N cable.

Ultimately, the power prices in Norway are found to raise due to the UK-N cable. The increase for 2040 - Current Policy and 2040 - Wind\&Solar, is on average 2,2 €/MWh (3,5\%) and 0,6 €/MWh (1\%), respectively.

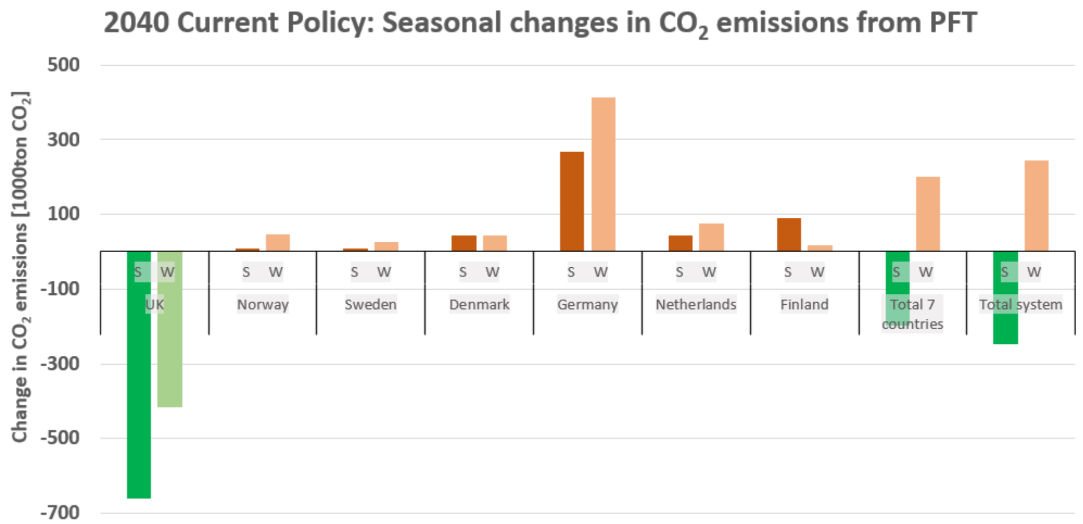


Figure 2

Conclusion

What implications do the results in this thesis so have for policymaking and the common goal of carbon mitigation?

First of all, this thesis demonstrates the importance of expanding system borders when studying effects of a topological alteration of the power grid. The modern power system is severely complex and intricate, and an alteration in topology in one part of the grid can have major, potentially unexpected, impacts other places in the system. Indeed do the scenario analyses show that the UK reduces domestic CO_2 emissions following the UK-N cable. However, depending on how the power system develops, this carbon mitigation can to large degree be offset by increasing carbon emissions elsewhere!

Environmental policymaking seen nowadays is getting more and more ambitious. National action plans for sustainable development typically assign goals for future domestic CO_2 emissions as a way of measuring progress. This thesis shows, however, that the assessment of CO_2 emissions heavily depends on the system boundaries. Accordingly, domestic carbon emissions are to large degree also affected by the policymaking elsewhere in the power system. Consequently, close cross-border cooperation is indeed crucial for reaching carbon obligations and creating the sustainable society of tomorrow.

Continuation Power Flow as a tool for multi-step simulation in meshed and radial power systems

Student: **Markus Formo**
Supervisor: **Olav Bjarte Fosso**
Collaboration with: **SINTEF**

Problem description

The modern power grid experience an increase in demand due to expansions in the networks and the discovery of new technologies. There has been a rapid increase in green and renewable energy, combined with a development towards today's interconnected grid with more distributed generation. This distributed generation gives a new load distribution, along with the fact that many of these are intermittent and therefore having a less stable load profile. This results in more unforeseen situations and challenges for the grids in meeting these new demands. To keep up with this rapid development, the security, flexibility and delivery of power transmission is essential. Stability in the power distribution is crucial in the modern society, and therefore occurrences of either grid collapse and/or voltage collapse must be prevented. Voltage collapses usually occur on power systems that are faulted, heavily loaded or have a shortage of reactive power. Power flow analysis is one of the necessary tools used worldwide to study the voltage profile of a transmission network.

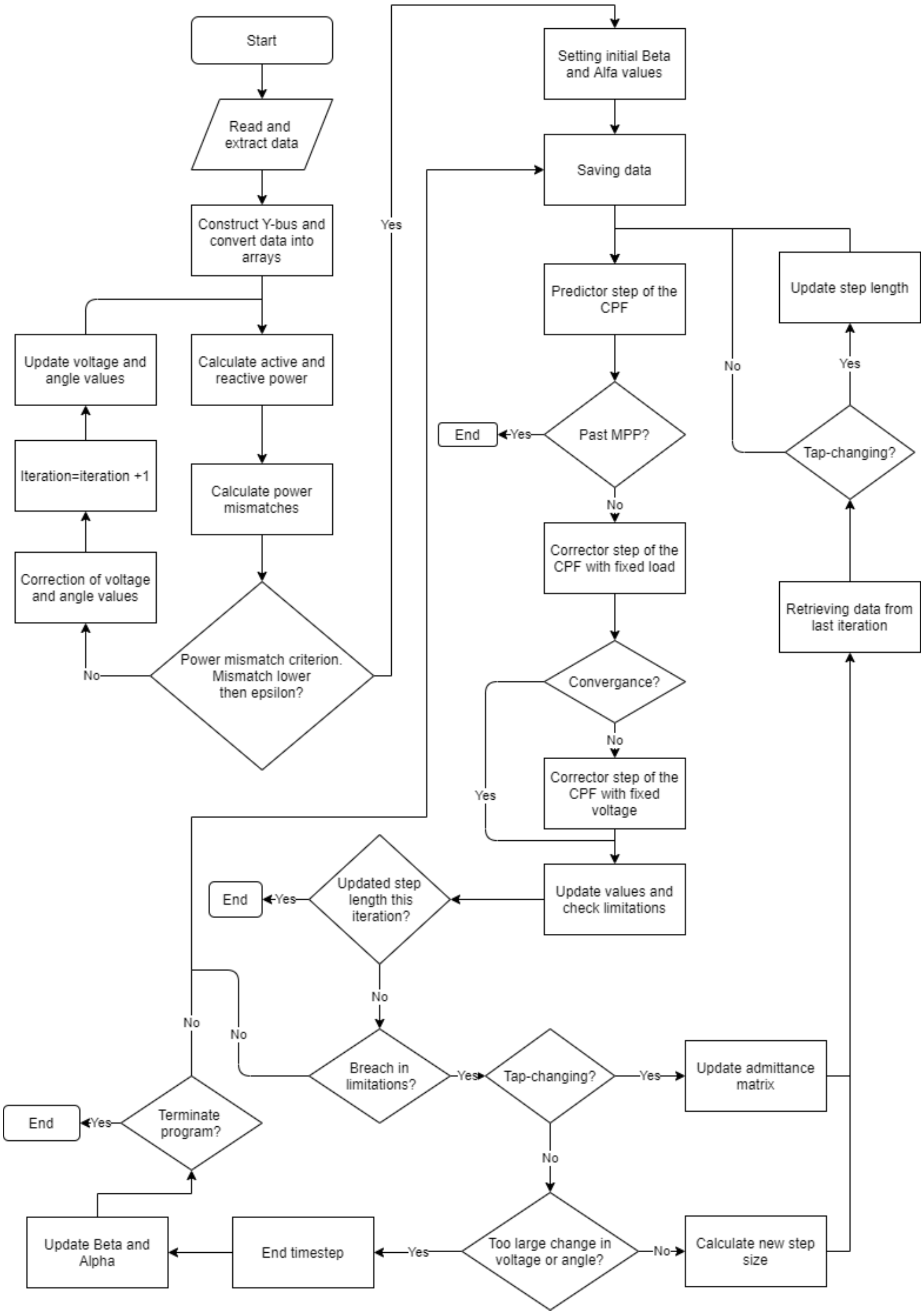
The task

Load flow analysis is used to plan for optimal operation, control of existing systems and to plan future expansion in accordance to the growing load demand. Such analysis contribute in identifying the effects of new loads, new generating stations, new lines, and new interconnections prior to being installed. This can result in minimizing system losses, and to verify the system stability.

The objective of this thesis is to construct a program, simulate a quasi-static method and to investigate the system's performance. Python was used to implement the program, which is based on external forecasts of generation, load, and energy storage profiles. The Python model will be able to simulate time-series of generation and load with a flexible time resolution. The concept is based on using the previous load distribution to predict both angles and voltages for the next time interval. The observation of both line flow and voltage magnitudes are essential, and therefore the addition of some monitoring tools were included in the form of line stability indices.

Model/ measurements

The constructed model was tested throughout different simulations run on a 9-bus IEEE grid setup. There are many aspects of such a computation to test. Therefore the focus of these simulations were on the use of initial values, addition of a special load flow case, and the testing of the monitoring devices used.



Conclusion

To conclude that this tool is fully operational, more simulations are needed to validate the proposed concept and to further improve the program. The different results obtained in this thesis shows how an operator could influence the system's ability to balance the desired load and generation. The flow conditions were closely monitored, with some additional tools, and effective measures were taken whenever limitations were breached. These results show that the proposed concept and constructed program can provide a fundamental analysis on a lightly meshed grid with no sudden inclusions on new load demand.

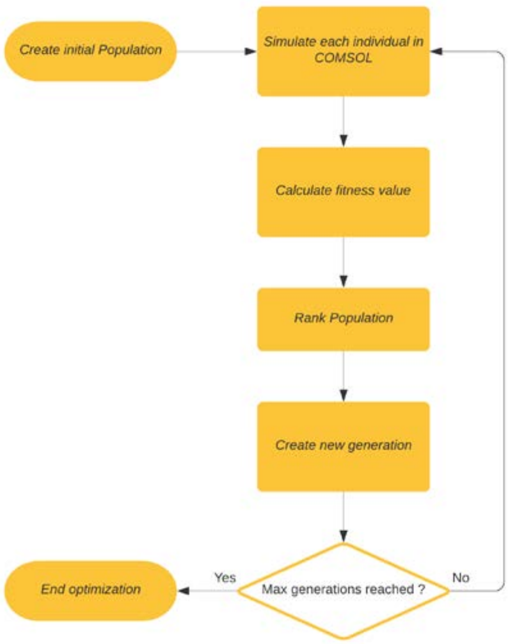
Design and Optimization of a Super-Compact PM-Motor for Aviation Using Genetic Algorithm

Student: **Sigurd Bøyum Fossum**
Supervisor: **Robert Nilssen**
Contact: **sigurdbf@stud.ntnu.no**
Collaboration with: **Rolls Royce Electrical Norway**

Problem description
This thesis investigates electromagnetic design possibilities for a prototype of a super-compact PM-motor meant for aviation. To make electric aviation commercially attractive, a high-performance motor that combines low weight with high efficiency is needed. An optimization study based on a genetic algorithm technique was implemented in MATLAB to meet these requirements

The task
The genetic algorithm evaluated design options by running FEM-simulations in COMSOL. For all cases, the objective of the optimization was to maximize the power density while limiting the torque ripple and electromagnetic losses of the PM-motor.

Model/ measurements
Two different study cases were optimized; one with a short pitch winding layout, another with a full pitch layout applied to the machine. Furthermore, an optimization study where the airgap was lengthened to reduce the torque ripple was performed. The optimization procedure is shown in the following figure.



Calculation

Due to confidentiality reasons, the exact results cannot be shown here. What can be said is that a relatively high power density was achieved for all three cases.

Conclusion

The combination of a genetic algorithm and FEM-simulations proved to be a useful method for design and optimization of a PM-motor, yet a time-consuming process with approximately 30 hours to complete each optimization.

Understanding the Subsynchronous Oscillation Occurring in Offshore Wind Farm Converters Connected via HVDC

Student: **Dan Godhei**
Supervisor: **Mohammad Amin**

Problem description
Subsynchronous oscillations occur in Wind Farm (WF) Inverters when connected to High Voltage Direct Current (HVDC) systems. Locate and evaluate what how these harmonic distortions (HD) influence control and power flow.

The task
To valuate how HD influence WF Inverter-HVDC when coupled together, this thesis presents a model of a 2-level Voltage Source Converter (VSC) and a HVDC rectifier Multi Modular Converter (MMC). The converters are evaluated in a frequency and a time domain.

Model/ measurements
The model is built in Matlab Simulink. The WF Inverter, shown in 1 is controlled with a current controller and PLL controller.

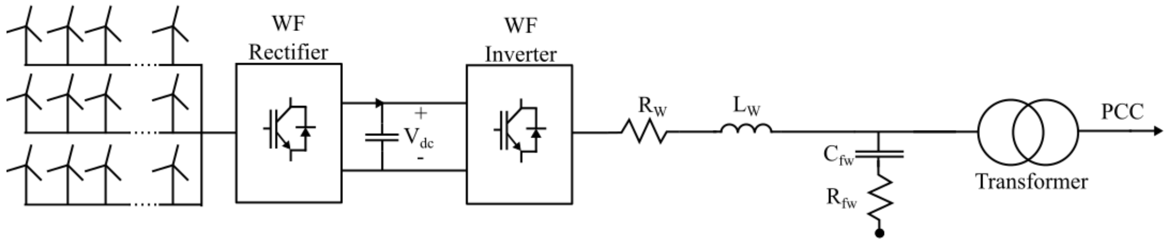


Figure 1: Wind Energy Conversion system.

The MMC Rectifier shown in 2 is controlled by an ac voltage controller and circulating current control.
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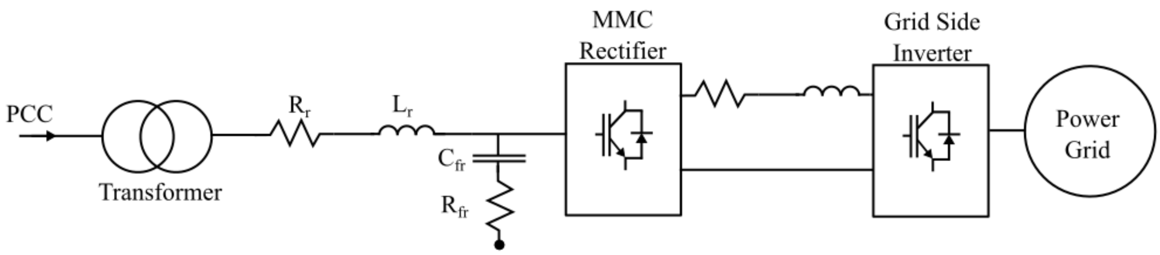


Figure 2: High Voltage DC conversion and transmission system.

Result
By running the model through four different cases for 50MW and 10MW, it becomes clear that the system has stable power flow from the WF side to the grid. The power flow for 50MW can be seen in 3. There it can be observed that the control system spends some time to produce a stable output. It can also be observed that even though the power flow reaches a stable state are there a lot of noise in the signal. This noise is can, to some extent, traced back to the control system for the converters. But, the source of these oscillations is not completely understood.

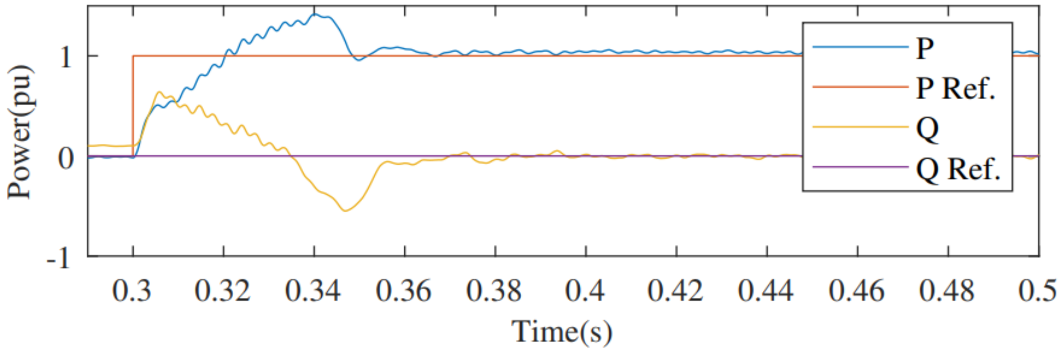


Figure 3: Power flow from the WF side to the HVDC side for 50MW.

Conclusion

Tests performed in frequency and time domain show that an interconnected WF Inverter-HVDC system can be controlled to produce the desired power output. The test in the time domain shows that triangular phase shifted PWM technique will divide the on-off time equally among MMC SMs. The tests in the time domain show that with high MMC submodule capacitance can the voltage across each capacitor be considered constant. The test also uncovers that subsynchronous oscillation is of great concern in this high power system. Literature referenced in this paper indicates that sources of these oscillations are interaction between WF Inverter and HVDC controllers. Time domain test indicates that some of the HD originates from the control technique and interaction between the controllers can both increase and decrease subsynchronous oscillations. It is shown that the total harmonic distortion can be reduced for an interconnected system due to passive component impedance. Test results in the frequency domain acknowledge that HD could occur due to low stability margins.

Adaptive Neural Network-based PSS Designs for Modern Power Systems

Student: **Thomas Grong**
Supervisor: **Jonas Kristiansen Nøland**

Problem description

As global power systems transition into a larger share of renewable energy, changes in their operating characteristics become increasingly prominent, and instability events more frequent. Therefore, existing controllers, like the power system stabiliser (PSS) in synchronous machine excitation systems, must be able to provide a more active and accurate regulation than ever before. However, little effort has historically been put into the tuning of the PSS or improving its design. This means there is much room for optimising its performance.

The task

This thesis presents two approaches for implementing neural networks (NN) into the PSS design. Firstly, an auto-tuning system for the conventional PSS (CPSS) is proposed, where optimal parameters are obtained from the particle swarm optimisation technique, using a linear model of the machine. Secondly, a novel NN-based PSS controller is proposed, where its phase response is a controlled input. This controller, named the sine shifting neural network (SSNN), is unique in that its creation requires no electrical machine theory. Finally, the proposed approaches are compared to a static CPSS and a no PSS approach by time-domain simulations.

Model/Measurements

The approaches were implemented into the MATLAB/Simulink environment. Figure 1 shows the implementation of the CPSS auto-tuner, and Figure 2 shows the SSNN scheme.

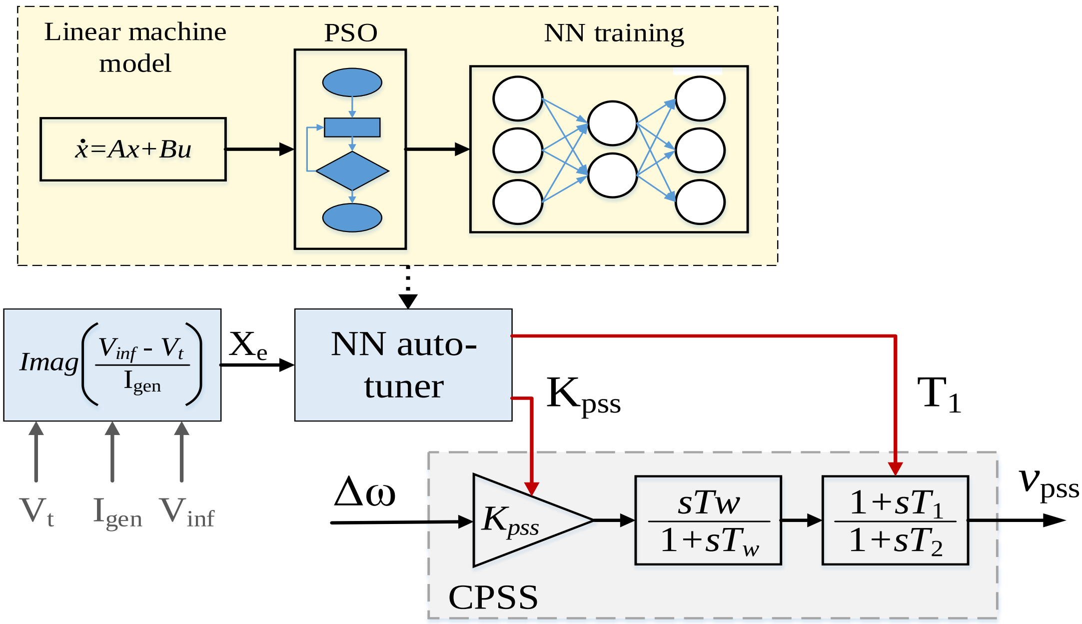


Figure 1 The CPSS auto-tuning system

Results

From the simulations, the settling time of the rotor speed deviation after a disturbance was used as the performance metric. As Table 1 implies, the SSNN provides superior damping. It is able to reduce the settling time to under 1 s for all performed tests, where the other approaches resulted in the 2-4 s range. Figure 3 gives one of those tests, showing the damping performances. The CPSS auto-tuning system worked as intended. However, the optimisation did not give a consistent improvement in damping for all tests compared to the static CPSS.

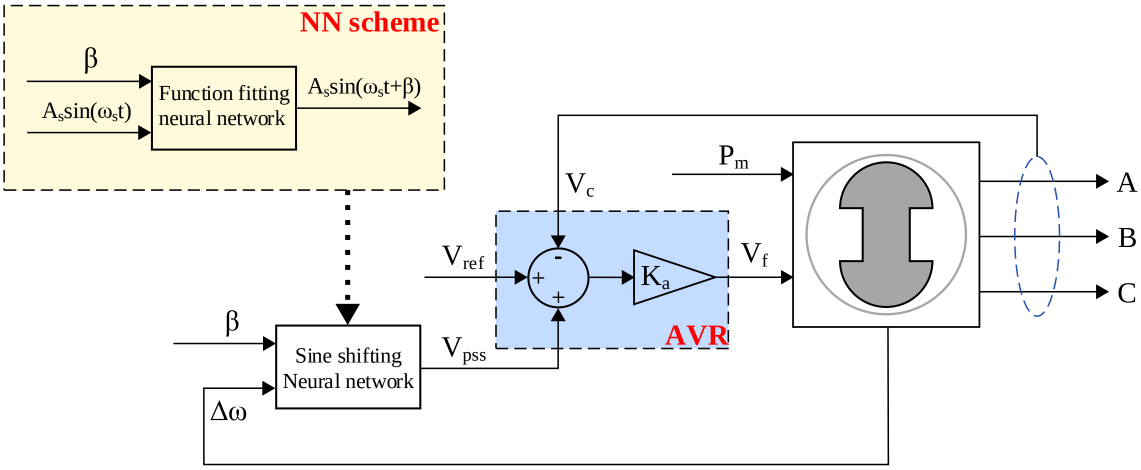


Figure 2 The SSNN scheme

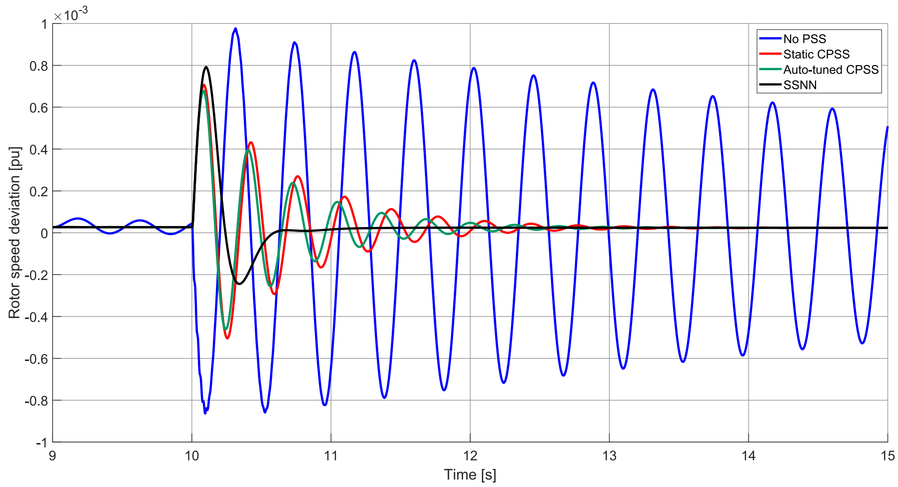


Figure 3 Damping performance for a reactance step from 0.03 to 0.05 pu

Conclusion

The work shows that neural networks have great potential in improving PSS designs. The SSNN approach is particularly promising, due to its versatility and simplicity. It shows that an NN can be trained as a well-performing PSS without needing advanced machine modelling. The implication of this work is a potential for better-performing synchronous machines to aid in the robustness expected of the power system as the global energy transition progresses.

Table 1 Settling time (to ±2 % of the steady-state value) of the performed tests

Reactance step [pu]	Settling time [s]			
	No PSS	Static CPSS	Auto-tuned CPSS	SSNN
$0.03 \rightarrow 0.05$	>5	2.482	2.339	0.621
$0.005 \rightarrow 0.1$	>5	2.909	2.085	0.878
$0.05 \rightarrow 0.03$	>5	2.732	3.161	0.537
$0.1 \rightarrow 0.005$	>5	3.474	4.331	0.710

Konsekvenser og lønnsomhet av effektkontrollalgoritme som sluttbrukertiltak ved innføring av effektbasert nettleiestruktur

Student: **Camilla Scharp Gulbrandsen**
Veileder: **Eilif Hugo Hansen**

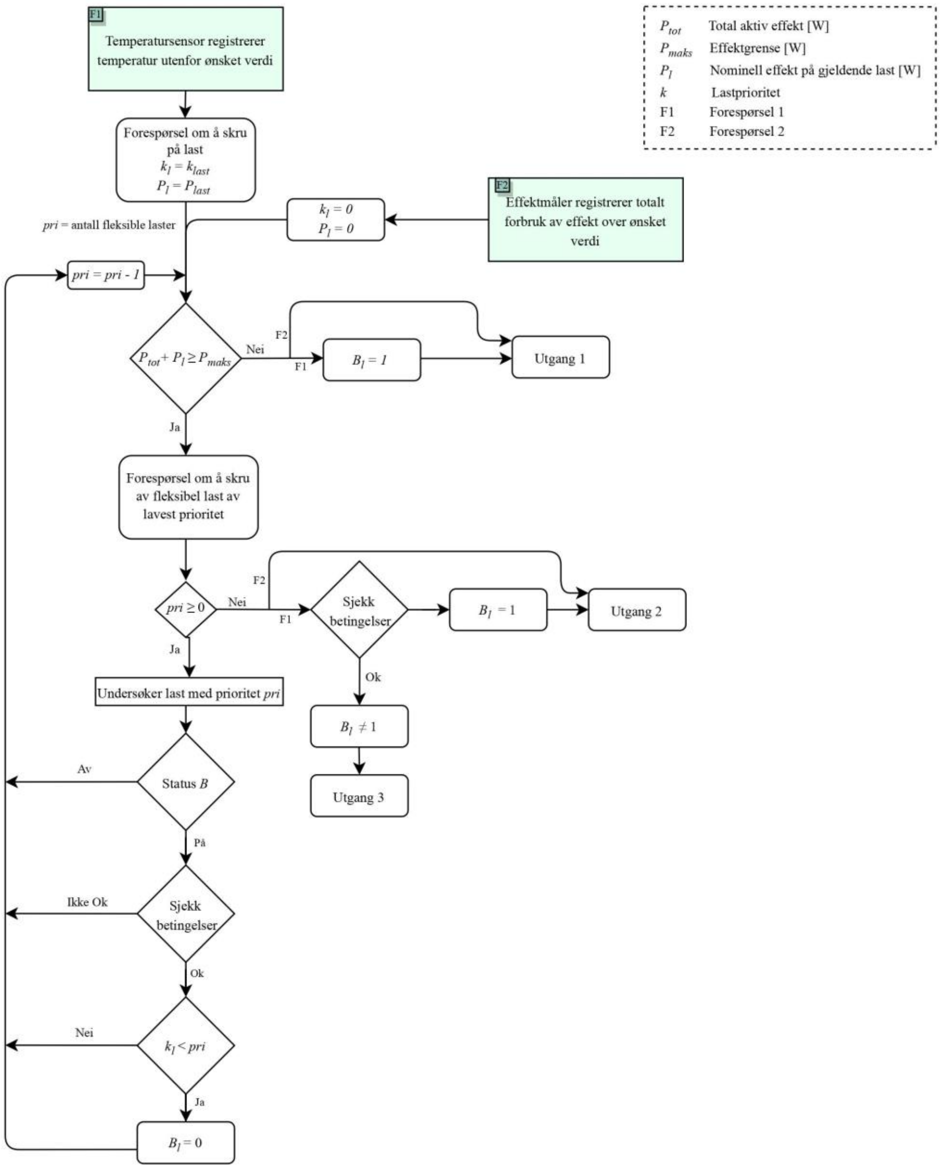
Problemstilling og oppgavebeskrivelse
Norges kraftnett er under press. Elektrifisering av samfunnet og økt forbruk av effektkrevende laster, som elbillader, induksjonstopper og hurtigvarmere, fører til økt behov for utbygging av kraftnettet. De forventede investeringskostnadene som følge av dette vil påvirke kundens nettleie, da kraftnettet er 100% brukerfinansiert.

Gjennom endringer i nettleiestrukturen ønsker RME å incentivere kunder til å endre forbruksmønster. Gjennom omlegging fra energibasert til effektbasert nettleie vil kunden ønske å redusere sitt maksimale effektuttak, og på denne måten bidra til å redusere kapasitetsproblemet, og til en effektiv drift og utnyttelse av det eksisterende strømnettet. At sluttbruker kan og stiller seg villig til endre forbruksmønster kaller vi forbrukerfleksibilitet. På bakgrunn av laster i norske husholdninger, og energi- og effektforbruk, har Statnett estimert et potensiale for forbrukerfleksibilitet for denne sektoren på hele 6,3 GW i 2030.

For å styre husholdningens effektforbruk, og raskt respondere til de hyppige variasjonene i strømnettet, kan det med fordel integreres et automatisk laststyringssystem i boligen. Med ønske i å redusere effektforbruket, og følgelig kundens nettleie, er det i denne besvarelsen testet en effektkontrollalgoritme for automatisk laststyring i Smarthus-laboratoriet, utformet som en leilighet. Leiligheten er utstyrt med laster tilsvarende en konvensjonell norsk leilighet, og flere av disse er egnet som det vi kaller fleksible. Dette er laster som ved utkobling i korte tidsrom ikke skal gå på bekostning av opplevd komfort, eller som ved tidsforskyvning ikke skal føre til misnøye hos forbruker. Eksempler på slike laster er gulvvarme og elbillader. Den implementerte algoritmen skal med laststyring sørge for at husholdningens effektforbruk ikke overskrider en forhåndsbestemt effektgrense. Dette skal den gjøre ved å hele tiden overvåke forbruket, og koble ut nettopp disse fleksible lastene dersom nødvendig. De fleksible lastene er rangert i en prioriteringsliste, slik at det er forbruker selv som velger hvilke av lastene som er viktigst, og skal kobles ut sist. Effektgrensen bestemmes også av forbruker selv.

Effektforbruk etter implementering av automatisk laststyringssystem er i denne masterbesvarelsen studert, og resulterende effektbaserte nettleier er kalkulert og sammenlignet med nåværende energibaserte nettleiestruktur. Økonomiske betraktninger ved bruk at effektbasert tariff med tidsdifferensiert energiledd er også sammenlignet med tidligere utregnede nettleier, for å undersøke virkningen av varierende energiledd.

Modell/målinger
Under er flytskjemaet som illustrerer effektkontrollalgoritmens funksjonalitet. Algoritmen testes for 8 scenarier, inkludert et basisscenario. Scenariene er kombinasjoner av tiltak, med reduserte effektgrenser, smart lading av elbil og streng styring av varmtvannsbereder.



Konklusjon
Resultatet av målingene var en reduksjon av maksimal effekt og total energi, både i og utenfor topplasttimer, for alle scenariene. På det meste ble maksimal effekt redusert med 55%. Dette var tilfellet med en effektgrense på 4 kW, smart lading og streng styring av varmtvannsberederen, begrenset til timene utenfor nettets topplast.

Nettleiene for de målte scenariene er beregnet med dagens og RME sine foreslåtte modeller; abonnert effekt, målt effekt og sikringsdifferensiert nettleie. Både med og uten tidsdifferensiert energiledd ble nettleien lavest ved sikringsdifferensiert nettleiemodell. Implementering av effektkontrollalgoritmen ga økonomiske besparelser for alle scenarier og forslåtte nettleiemodeller, med basisscenariet som referanse. De største besparelser var ved abonnert effekt, etterfulgt av målt effekt. Følgelig ble også tilbakebetalingstiden ved innkjøp av smarthusteknologi kortest for disse modellene. De økonomiske besparelsene med både dagens nettleie og basisscenariet som referanse er studert for å se den samlede konsekvensen av ny nettleie, i kombinasjon med automatisk laststyringssystem. Resultatene belyser at kunde *kan* spare ved riktige valg av tiltak.

Stability limits for optimal power flow related to congestion management

Student: **Margrete Haaland**
Supervisor: **Kjetil Uhlen**
Co-supervisor: **Sigurd Hofsmo Jakobsen**
Collaboration with: **SINTEF Energy Research**

Problem description
A great amount of the vital services in today's society is dependant of electricity, making the power system an essential infrastructure. Congestion, and other challenges, becomes more common when the power system is upgraded with renewable energy and digital solutions. In addition, the power demand increases faster than the power system is upgraded, making it crucial to utilize the power system optimally. The security rating of the transmission lines is not common to used when the transmission constraints are decided. The security rating is decided by the stability of the system. In this thesis, the stability is investigated through dynamic simulation, with focus on voltage stability and rotor angle stability, to determine the security rating of selected lines.

The task
The aim of this thesis is to perform dynamic simulations of a 4-bus model and an aggregated model of the Nordic power system (N44) to decide the transmission constraints of selected lines. The transmission constraints will be used when the optimal power flow is simulated to investigate how the constraints affects the operating costs. For the N44 model the optimal power flow was simulated after a contingency to investigate the redispatch and change in operating costs for different transmission constraints.

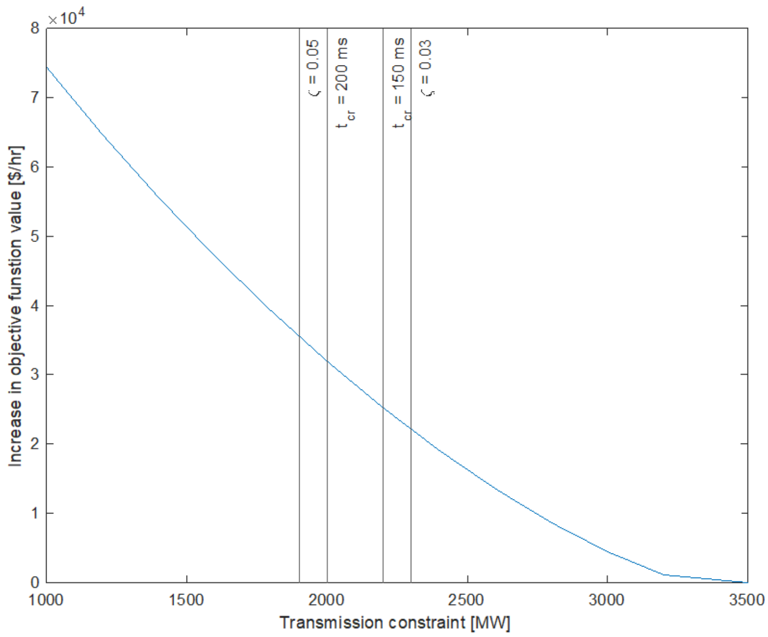
Model/ measurements
The models that were analyzed in this thesis was a 4-bus model with two generators and two loads, and the N44 model of the Nordic power system. The dynamic simulations were performed in PSS/E and focused on a contingency of a specific line in both models. For the 4-bus model, the focus was on one of the lines connecting a generator and a load. For the N44 model, the focus was on one of the lines connecting Eastern Norway and Sweden. The dynamic analysis included voltage stability analysis and rotor angle stability analysis and was performed for different operating states for both models.

The optimal power flow simulation was performed in MATPOWER in MATLAB. The simulations were performed on equivalent models to analyze how the objective function value, and the redispatch after a contingency, was affected by the transmission constraint.

Calculation
The transmission constraint for the 4-bus model were decided by the voltage stability. For the line connecting the generators, it was set to 1000 MW, and for the line connecting the loads it was set to 600 MW. The solution of the OPF simulations showed that the operating cost was not affected by the transmission constraint. This was because the lines without constraints carried most of the flow.

For the N44 model, it was found that the rotor angle stability, with the damping ratio ζ and the critical cleating time t_{cr}, was the limiting factor. The proposed transmission constraints were 1900 MW for $\zeta = 0.05$, 2300 MW for $\zeta = 0.03$, 2000 MW for $t_{cr} = 200$ ms, and 2200

MW for t_{cr} = 150 ms. The OPF was simulated after the contingency with different values of the transmission constraint. The increase in operating cost as a function of the transmission constraint is shown in the figure. The proposed limits for the different values of damping ratio and critical clearing time is marked.



To obtain a power flow solution with a requirement of a damping ratio above 0.03 and a critical clearing time above 150 ms, the transmission constraint should not be set higher than 2200 MW. This transmission constraints corresponds to an increased operating cost of 25 000 $/hr.

Conclusion

When the dynamic simulations were performed on the 4-bus model, it was discovered that the voltage was the limiting factor. The optimal power flow simulations showed that the transmission constraints did not affect the cost at optimum under normal operations, as the power flow of the constrained lines did not exceed the limits.

Similar simulations were performed on the Nordic 44 test system when a contingency on one of the lines connecting Easter Norway and Sweden occurred. It was discovered that the limiting factors related to stability was the damping and the critical clearing time. By simulating the OPF for different transmission constraint, it was found that the operating cost increased when the transmission constraint was decreased.

Sensorless control of synchronous machines

Student: **Johan Palmstrøm Hald**
Supervisor: **Roy Nilsen**
Contact: **johanphald@gmail.com**
Collaboration with: **Hydrocen**

As the European continent is seeing a rapid dismantling of dispatchable power generation, for intermittent renewable energy sources such as wind and solar power, the need for flexibility in the continent's electrical grid is ever increasing. With this increased demand comes increased pressure on the Norwegian grid, as Norway's well-developed suite of hydropower installations is a highly sought after commodity. However, the continent's demand for flexibility far outstretches the available Norwegian resources. One way to cover this demand is the synergy of adjustable speed hydro (ASH) synchronous machines and pumped hydro.\\

For the combination of pumped hydro and ASH synchronous machines to work efficiently there is a need for a robust control system. The cutting-edge in control of electrical machines over the last decades has been sensorless control, wherein the position and speed of the rotor are estimated rather than measured. Offering higher reliability and robustness, in addition to lower costs and reduced system complexity, the future of electrical motordrives is sensorless control.

In this Master thesis, which is a continuation of the specialization project done in the fall semester of 2019, a novel approach of sensorless control of a separately excited synchronous machine with damper windings is presented. The methodology utilizes additional excitation signals in the field current to detect the rotor position, in what is called the self-sensing method. The method has been combined with the already established estimation methods based on the generation of back-EMF, called the current and voltage model. Due to a lack of back-EMF information at standstill and low-speed operation, both the current and voltage model has insufficient available data to estimate the rotor position at standstill and low-speed operation accurately.
Through an extensive investigation and analysis of the self-sensing method and various phase-locked loops combinations (PLL), it was shown that the model, being solely reliant on the additional field excitation signals and its response on the stator currents, drastically reduced the error at zero-crossing and low-speed for torque-controlled operation. While the gains achieved for torque-controlled operation is dependent on the acceleration of the rotor through zero-crossing, due to inherent limits in the PLL structure, the self-sensing model has been unequivocally shown to improve the sensorless control for standstill and low-speed operation.

The same improvements have been proven under speed-controlled operation where the introduction of the self-sensing model has shown a drastic increase in the sensorless control structure's ability to hold torques through zero-hold and -crossings, where comparative testing running only the current and voltage model showed complete system collapse.

Utilization of energy storage systems in ports

Student: **Tobias Grande Hansen**
Supervisor: **Kjetil Uhlen**

Problem description
Ports are undeniably affected by technological development in the maritime industry and new technological and environmental demands arise from both governmental and private actors. Within a decade, Norwegian ports are expected to supply AMP to almost all vessels, and the government is working hard to facilitate hybrid and total-electric solutions. This development introduces new challenges for ports. Some of these challenges are related to the costs of the required AMP and charging equipment, while others are related to constraints in grid capacities. A third challenge that has been highlighted lately is the high energy costs that are caused by AMP-and charging loads. The high costs weaken the competitiveness of AMP, hybridization, and total-electrification, as the ports are forced to charge more for AMP and charging-power.

The task
The report studies the potential of utilizing energy storage systems (ESSs) in Norwegian ports by giving a description of relevant system theory prioritizing analysis of energy storage technology, studying the economic feasibility of utilizing energy storage systems in ports to cut costs of supplying vessels with electrical energy, studying what energy storage technologies and ESS dimensions are most favorable for a selection of port loads and by conducting a sensitivity analysis to determine how variations in model parameters impact the feasibility of energy storage in ports

Model/ measurements
A comprehensive optimization model is created in Python to study the potential economical feasibility of including an energy storage system to a given port based on relevant system parameters and current regulations.

Conclusion

In this report, the potential of utilizing ESSs in ports are analyzed. The objective is to study whether electrical energy storage can be leveraged to cut costs of supplying the future electrified marine traffic by cutting energy costs or by acting as an alternative to grid investments.

Ten chemical energy storage technologies are studied, as these are considered most relevant for port use. The performance of all the technologies is expected to be improved towards2030. Thisincludestechnicalcharacteristicsaswellasthedevelopmentofcosts. Of the ten technologies that are found to be potential candidates for port use, the molten-salt batteries, NaS and NaNiCl, the Vanadium redox flow battery(VRFB), and the Lithium-ion NCA-battery technologies stand out as most promising. The safety, maturity, and supply of the technologies are however not taken into consideration. The Levelized cost of storage (LCOS) is introduced, but as this cost model has weaknesses related to its maturity and lack of possibilities to combine several applications, a new cost model that excludes energy costs is derived.

With the current Norwegian regulations, the participation in the day-ahead, intraday, and reserve markets for the trading of power is achievable for ESSs, but this is still uncommon. ESSs can perform several grid applications, but many of these applications are difficult to quantify. This also makes analysis of a combination of grid applications and behind-the-meter applications unsuitable. It's unclear what grid tariffs will be used for ESSs in the future, but the grid tariff of commercial customers can currently be used. The main driver of costs using this grid tariff is the monthly peak power charge, which greatly facilitates the implementation of ESSs.

The Norwegian government has ambitious plans regarding maritime electrification, first of all through a goal of emission-free ports where feasible by 2030, and further by facilitating hybridization and total-electrification [38]. With the planned development, the ports are challenged in terms of high energy costs and high power demands. This, combined with the current Norwegian regulations, establishes a promising foundation for theutilizationofESSsthatcombineloadlevelingandenergyarbitrageinports. Following the regulations, the ESS should be owned by the port or a third party.

Three types of ports are analyzed: a City port dominated by passenger traffic, a Cargo port, and an Offshore/subsea base. Further, a scenario that represents an aggressive implementation of AMP and a scenario that represents an aggressive implementation of AMP combined with plug-in hybridization of part of the fleet, are modeled. The loads are modeled for one year in timesteps of one minute and are based on the vessel traffic schedules of each port. With a lack of proper methodologies to estimate AMP- and charging-needs, each ship's load is estimated based on modest coefficients from Enova and assumptions of battery size. To be applied to the optimization model, the minutely loads are averaged over one hour, hence involuntarily leveling some of the peaks slightly.

With energy storage characteristics and costs that represent the 2016-level, utilization of ESS is only feasible in the Cargo port for the most aggressive Scenario, indicating that an investment in port ESS is in general not profitable. With energy storage characteristics and costs predicted for 2030, the utilization of ESS in the City and Cargo ports are profitable for both scenarios. The energy storage technology that provides the largest cost savings is NaS, followed by NaNiCl, Lithium-ion NCA, and VRFB. The offshore/subsea port is unsuitable for the implementation of ESS, as the monthly peaks are costly to shave and the yearly load is in general quite leveled. The majority of cost savings come from the reduction of monthly power peak related grid tariffs. The reduction in energy costs is close to negligible, and the system's ability to sell energy to the grid is in most cases trivial. An interesting discovery is that the optimal ESS capacities and power ratings are determined only by the system's ability to reduce the monthly peak powers. This indicates that profit from energy arbitrage in the Norwegian electricity grid is minor. The ESSs do however sell power to the grid on some occasions, but the frequency and volumes are heavily dependent on the size of the ESS.

With power capacity constraints of 70%, 80%, and 90% of the annual peak consumption, the annual costs of supplying the caseloads are in general increased. To supply the loads, the optimization model chooses power ratings and energy capacities that exactly reduce the annual peak to the given threshold. In some of the cases, the grid constraint does not interfere with the optimal operation of the system, hence not increasing the costs. Also here, the most aggressive scenario in the Cargo port gives the most promising results. The Offshore/subsea port has the highest cost increases by introducing grid capacities by far, hence strengthening the already mentioned deficit in terms of ESS feasibility. As the upgrading of port grid capacity will vary on a case-to-case basis, no comparisons between these solutions are conducted.

A sensitivity analysis is conducted for three key parameters; the grid tariff, the electricity price, and the end-of-life return value. As expected, the grid tariff is proven to be significant in the sizing of the ESSs and the direct correlation between grid tariff and annual cost reduction is clear. Further, conducting case studies with electricity spot prices that represent a selection of European system prices shows that energy arbitrage is much less profitable in Norway than in other countries. The optimal capacities and power ratings are larger using these spot prices than using the Norwegian spot price, indicating that the dimensionsarenotsolelybasedonthemonthlypeakdemandswhenusingotherelectricity spot prices. Thedevelopmentintheend-of-lifereturnvaluealsohasthepotentialofbeing decisive for the utilization of ESS in many ports. An increase in end-of-life return value reduces the lifetime cost, increases the size, and hence reduces the annual costs of the port systems.

Optimization of battery energy storage system: A case study for an electric vehicle fast-charging station

Student: Eirik Haugen
Supervisor: Magnus Korpås
Contact: Kjersti Berg
Collaboration with: SINTEF Energy Research

Problem description

Electrification leads to increased demand for electricity in several sectors, including the transportation sector. The traditional approach of reinforcing the existing grid is an alternative to install a stationary BESS to shave power peaks. By installing a battery storage system, the operator can store energy for the busiest time periods and thus keep the grid power below a desired limit.

The thesis investigates a case study of a fast-charging station where the load increases to a level above the current transformer limit. The goal is to determine which investment alternative makes the most economic sense by comparing battery installation to reinforcing the grid. By creating an optimization model, which minimizes the overall costs for the fast charging station operator, the best economic outcome is secure. The optimization model includes battery capacity degradation. Sensitivity analysis shows how the impact of different parameters, such as degradation, spot price, grid tariff, and the time step, have on the system.

Model

The load increase, which initiates the need to reinforce the grid or installing a battery, is an electric vehicle (EV) charging demand at a fast-charging station (FCS). The modeled EV charging demand, which is the case study, is based on detailed information handed in from Tensio for a specific and anonymous FCS in Trøndelag. The method is mainly developed in previous work but are modified a little. The EV charging demand is modeled on a minute basis.

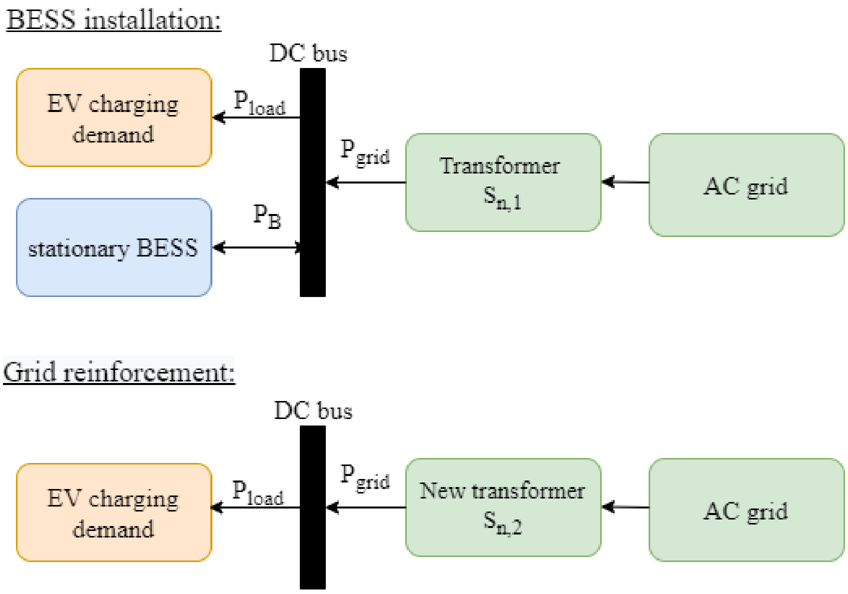


Figure 1: Visualization of the two options to meet the increased load demand.

The modeled EV FCS is input to the optimization model. The optimization model is built up with necessary operational constraints, which include battery degradation (cyclic and calender mechanisms), power and energy balances, and necessary limits on different variables. The optimization is implemented in Julia with the JuMP package, and the optimization solver is Ipopt, which was required because the problem is non-linear.

Calculation
The NPV for grid reinforcement is 10 362 kNOK and for BESS installation 11 268 kNOK. Installing a BESS gave about 800 kNOK in operational cost savings but is still 900 kNOK short to be more profitable than reinforcing the grid. The transformer loss costs for grid reinforcement is 45 kNOK and for BESS installation 42 kNOK. However, the energy losses are slightly higher for the BESS case than for the grid reinforcement, with a difference of 2 195 kWh annually.

The degradation analysis shows the impact of degradation in the first and last year. The calender aging is determined in this case because the temperature is assumed to be constant. The cyclic aging depends on operational behavior. The calender aging is much higher than the cyclic aging the first year. After a few years, the calender contribution to aging is less.

Two simulations without degradation, one with a minute resolution, and one with an hourly resolution are compared. The difference in costs for one year is 265 kNOK. This corresponds to an additional cost of 14.5 % when the simulations are done with minute resolution compared to hourly resolution. The power tariff costs are 194 kNOK less with an hourly time step. The level of peak shave with the hourly resolution is lower than minute resolution.

A change in the grid tariff regime impacts the economic result. If the grid tariffs are changed to the price regime which exists in the Oslo region, the accumulated cost difference, which is equivalent to the NPV difference, is 639 kNOK in the advantage of reinforcing the grid.

Conclusion
The results obtained from the optimization shows higher discounted costs for installing a BESS than reinforcing the grid. The optimal BESS configuration of 225 kWh and 300 kW in the case study cuts the peak power from the grid with 19 % and generate operational cost savings of 800 kNOK. When installing a BESS, energy arbitrage gives small cost savings compared to the savings from reduced power tariff. From a grid perspective, there is no significant difference in energy losses or costs of energy losses.

Degradation is important when dimensioning a BESS to ensure the ability to peak shave all the years of operation. If so is done, the degradation has low impact on the operational costs.

The time step analysis shows that the total operational costs are 14.5 % higher when the time resolution is in minutes compared to hours. A sensitivity analysis on grid tariffs shows that a more expensive grid tariff regime increases the cost savings for the BESS compared to grid reinforcement. The alternative grid tariffs made the NPV 6.7 % higher, while the NPV difference between BESS and grid reinforcement decreased by 29 %.

In the end, the future battery investment costs projections will give a 54 % decrease in the NPV difference between BESS and grid reinforcement. With alternative grid tariffs, the reduction in NPV difference between BESS and grid reinforcement is 75 %.

Comparison of iron loss calculation models including rotational loss

Student: **Siri Faremo Haukvik**
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Collaboration with: **Rolls Royce**

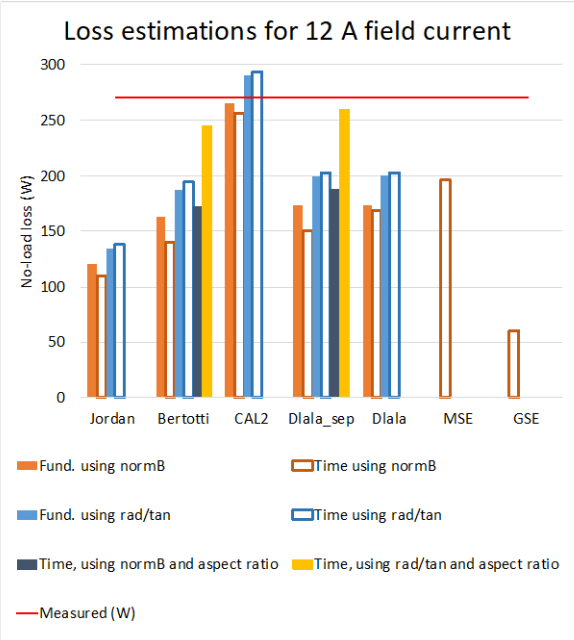
Problem description
Calculation of core losses in electric machines has been a topic of research for over hundred years. Still, there is no standard method that is fit for all purposes. Optimal choice of method can be geometry-, material- and application dependent. However, the method selection is often limited by available material data provided by the material manufacturer. Thus, there is a need for sufficiently simple, nevertheless acceptably accurate, methods for use in machine design.

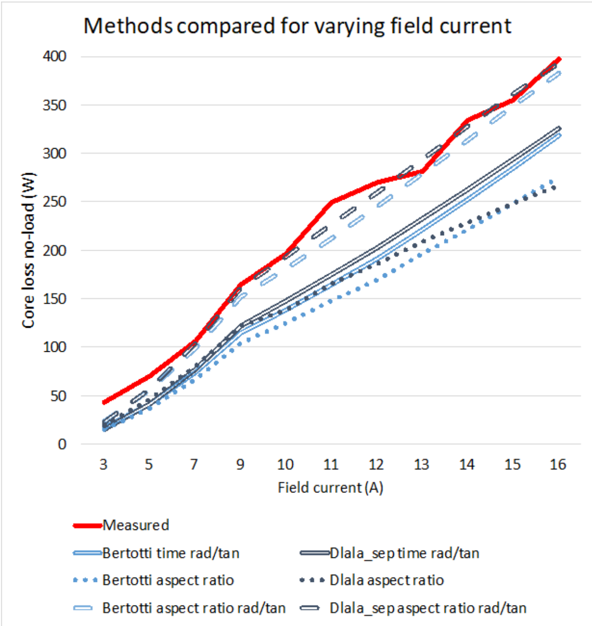
The task
This thesis aimed to investigate iron loss calculation models for use in electrical machines, with focus on including low-frequency harmonics and rotational losses through time-domain analysis. An extensive literature review has been conducted to obtain overview of existing methods, with focus on post-processing methods mainly within the concept of loss separation. A broad variation of practice has been discovered, where decisions regarding method are often based on application-specific requirements. This results in difficulty finding common ground for comparison of methods.

Model/ measurements
Therefore, a benchmark FEM model of a hydro generator prototype was developed in COMSOL Multiphysics, where five variations of loss separation methods were implemented, focusing on method for coefficient determination and the use of the anomalous loss term. The methods were further expanded to include rotational flux by calculation in radial and tangential direction. Moreover, by evaluating the degree of rotational flux per FEM element, the models using three loss terms were expanded to include rotational loss density by coupling generalized functions expressing the ratio of rotational loss relative to alternating loss per polarisation. The Modified Steinmetz Equation (MSE) and the Generalized Steinmetz Equation (GSE) were also implemented, but were not expanded to include rotation.

The loss evaluation methods were also implemented for a model of a high speed PM motor to evaluate behaviour for a different machine. This is to evaluate the general applicability of the models.

Results
The variable coefficient method including anomalous loss seems most accurate when calculated using radial and tangential components and rotational loss density. This method resulted in an average 7% deviation from measured results is found for the hydro generator over a wide range of excitation level, for a method using variable coefficients. For nominal operation, 1- 2% deviation for both the hydro generator and the high speed machine is obtained, without the use of correction factors.





Conclusion

The main findings were:

1. Variable coefficients seem to be more accurate than using constant coefficients if fitted carefully, however might have more impact for machines operating at higher frequency, due to the separation of loss components having larger impact on the total sum of losses.
1. The point-wise methods for determining variable coefficients (Dlala, Dlala_sep) are more stable in accuracy than the direct surface fit (CAL2)
2. For machines with a high degree of rotational flux, the COMSOL built-in normB should not be used. This is particularly inaccurate in combination with time-domain analysis.
3. Including rotational losses through aspect ratio (degree of rotation) combined with rotational loss density curves seems to drastically increase accuracy, with 20- 21% reduction in relative error for the hydro generator.

Providing good overall accuracy for both hydro generator and high speed machine, this seems to be a flexible tool. It should be remarked that the investigated methods are dependent on accurate material data, particularly the specific losses and the magnetization curve.

Additive Manufactured Amorphous Metal in High-speed Interior Permanent Magnet Motor

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Supervisor: **Robert Nilssen**
Contact: **Astrid Røkke**
Collaboration with: **Rolls-Royce Electrical Norway**

Problem description

Amorphous metals are interesting metals which main purpose are yet to be discovered. The metals are brittle, which means that the metals break when the mechanical stress reach beyond the ultimate tensile/compressive yield strength. The main feature of the metal is the mechanical strength, which is three times higher than what a typical high-tensile steel has. In this master thesis an additive manufactured (AM) amorphous metal is used in the rotor of a high-speed interior permanent magnet (IPM) motor. This to see if the material can compete against permanent magnet motors that use traditional materials.

The task

An additive manufactured amorphous metal ring was tested in a Brockhaus MPG 100 electric steel tester after heat treatment at different temperatures close to the crystallization temperature of the metal. The best result was used as rotor material in an IPM COMSOL model and simulated in a time-dependent study together with a surface mounted PM (SPM) motor for comparison. Different output values were then looked upon for both machines.

Model/ measurements

High-speed PM motors were investigated. The machines had a speed of 15 000 rpm, where the frequency was 1 500 Hz as a result of 12 poles.

Two COMSOL models were created representing the machines. The models were parameterized to easily adjust necessary parameters. The same stator design was used for both motors for better comparison. The IPM had embedded magnets inside the rotor forming V-shapes, while the SPM had the magnets mounted on the rotor surface using Halbach array as magnet pattern.

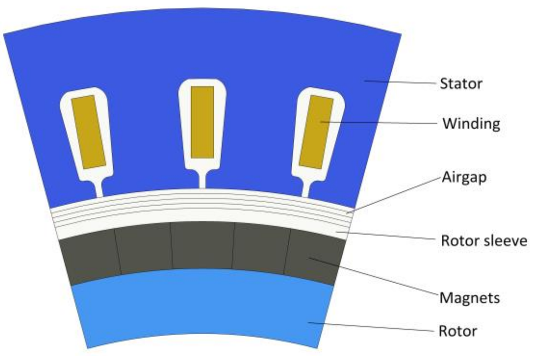


Figure 1: COMSOL model of the SPM motor.

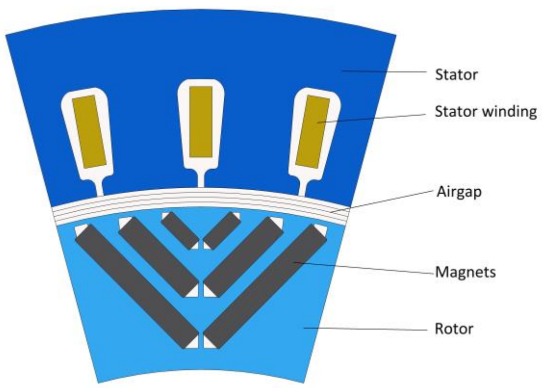


Figure 2: COMSOL model of the IPM motor.

Calculation
Mechanical calculations were carried out to estimate the thicknesses of the iron bridges in the IPM. At the same time the output power was evaluated to see the effect of the magnets' placement in the rotor. The AM amorphous metal ring was tested to obtain the B-H curve, which was then used in the rotor of the IPM. Finite element calculation was executed for both models, where torque, inductances and losses were the main values investigated.

Conclusion
The amorphous metal did not get satisfying values in terms of relative permeability, but the machine performed well despite this. The reason for this is the thin iron bridges used in the model because of the strong rotor material. The results showed that AM amorphous metals can be used in PM machines and perform similar results as normal used materials do.

Demand response in a short-term hydro-thermal multi market model.

Student: **Solveig Bække Hefte**
Supervisor: **Hossein Farahmand**
Co-supervisor: **Mari Haugen**

Collaboration with: **SINTEF Energy Research**

With the increasing penetration of variable renewable energy sources balancing services needed in the grid increases. Intermittent energy causes imbalances in the grid with its lack of flexibility and inertia, affecting the markets of trading power and optimizing the power balance. The importance of flexibility is increasing with the increasing share of power traded closer to the operation time and the fluctuation coming from variable energy resources. The need for flexibility and modeling hydropower scheduling more accurately is seen as important.

In the future, there will be an increasing need for flexibility and controllability both on the demand and production side with a need for price forecasts for all electricity products. SINTEF Energy Research has developed a short-term multi market model, PriMod. It optimizes the power scheduling in a better approach and calculates the marginal cost for all physical products on a finer time scale. The flexibility on the consumer side has not yet been formulated, and model demand response in a more accurate hydropower scheduling model could decrease the price.

This master thesis investigates the impact of price-based demand response in weekly scheduling of hydropower in the Nordic system. The object is to model demand response into PriMod with the focus on the residential side to capture its impact. Methods implemented are gradual adaption of consumption and demand side management with the focus of price-based demand response where the price adjust the consumption. Gradual adaption of consumption is modeled under the assumption that the consumption is adjusted from the price from the last week with an inertia parameter. Demand side management is focused on load shifting and peak clipping, here curtailment.

The results showed that the impact price-based demand response had on the weekly scheduling model, PriMod, was a decrease in the price, peak-demand, and demand when the prices in the system and area were above the compensation cost of demand side management. Further, price-based demand response led to a decrease in investment costs in the grid and a lower electricity bill. From the seasonal variations, the greatest decrease in price was in the winter which was 1.68% while the summer and fall were 0% due to low prices. Results regarding reservoir level showed a marginal effect as the water values were the main variable that affected the price. The water value is though affected indirectly by price-based demand response as it decreases with the increasing potential of demand response. When flexible loads were increasing it had a good effect with an increasing impact. Altogether this shows a marginal difference for an end-user, but for the social welfare this will have a great impact due to a decrease in the network charges.

Moreover, demand response can contribute to the balancing market under reserve mechanism where they have a greater potential to work as a faster frequent reserve in the Nordic balancing market. Demand response has the potential to work closely with all markets as long the assumptions are well formulated and tested as mentioned as one of the greatest barriers towards demand response.

Further work should be to investigate having demand response as a reserve mechanism and modeled it into PriMod. Also, the tariff structure should be discussed on a government level to incentivize price-based demand response in a better approach.

A study on optimal utilization of electric heating for buildings

Student: **Camilla Hengebøl**
Contact: **Karen Byskov Lindberg**

Problem description

From January 2020, heating systems based on oil or gas are not allowed in Norway. In addition, stricter building regulations in order to meet the goals set for reduced CO2-emissions is expected. This enforces new solutions for optimal use of electricity and heating in buildings.

This master thesis is a further development of an existing model developed in a master thesis from 2018 [1], and further developed in a master thesis from 2019 [2]. The model is a Mixed Integer Linear Program (MILP) implemented in the programming language Python, with the modelling extension library Pyomo. The use of the model has been limited to an energy-efficient Single Family House (SFH).

The objective of this thesis is to use the already existing model in order to decide whether a point-source or a waterborne heating system is the favorable option in regard to heating. This is investigated for a SFH, an apartment block and an office building. In addition to the heating system itself, all three buildings have been investigated for two different building standards. The objective was to see if the insulation of the building had an impact on which heating system that was the favorable option. For this purpose, an implementation of new building types with associated heating loads has been done. In addition to this, a review of input values for the model has been done, and new investment costs for larger building has been found.

In order to compare the results, four different cases has been decided. Whereas the base case PS is a point-source system where the building standard implies an old badly insulated building, an upgrade including post-insulation of the building can be done. This upgrade results in the second case for the point-source system, PS_R2.

The two other cases have both updated from point-source system to a waterborne heating system which results in different applicable technologies for the heating. These two cases are also divided in one case where the building standard is the same as in the base case WB, and one case where the building standard is upgraded by post-insulating WB_R2.

Throughout the work of this thesis, the complexity of the choice of heating system has become clear. It can be stated that an upgrade of heating system from point-source to waterborne system will reduce energy system costs. Nevertheless, the results show that the reduction of costs for the energy system is not high enough in order to earn the cost of the renovation. At the same time, changes in electricity price and stricter restrictions of CO2 emissions will favor the waterborne solution when seeing the problem in a long-time perspective.

An analysis of energy storage system with wind power for multi-market operation under uncertainty

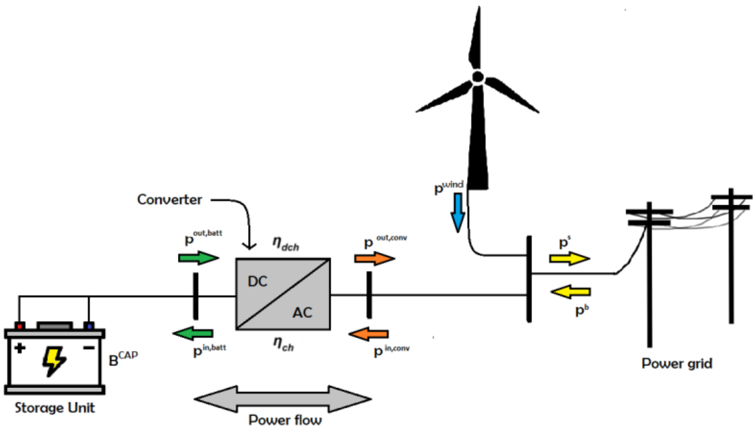
Student: **Jon Hvideberg Holte**
Supervisor: **Jayaprakash Rajasekharan**
Co-supervisor: **Kasper Emil Thorvaldsen**

Problem description
A decentralised energy structure with distributed generation in the form of renewable power production is becoming more common. Renewable energy sources, such as wind power, are unregulated sources dependant on the weather. This implies that the sources cannot be turned on and off by choice and have a highly variable power production which is difficult to predict. Balancing energy demand and supply over time could thus become more challenging. Energy storage systems are recognised as a key technology to overcome this challenge, but then an optimal energy scheduling is crucial to obtain a profitable energy system.

The task
The main tasks in this work are the following:

- Present a short-term optimisation model for energy system scheduling where it seeks to maximise its profit in a multi-market setup while using a stochastic backwards dynamic programming (SDP) framework.
- Investigate the integration of an unregulated power source, such as wind power, in an energy storage system that operates in a multi-market setup.
- Compare and analyse the results and behaviour of the optimisation model in a case study consisting of both a deterministic and stochastic setup involving two seasonal cases.

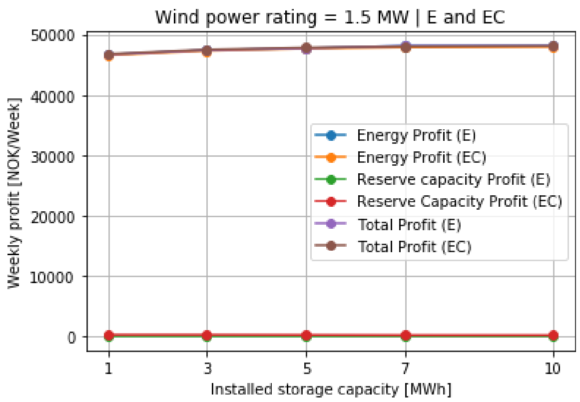
Model/ measurements

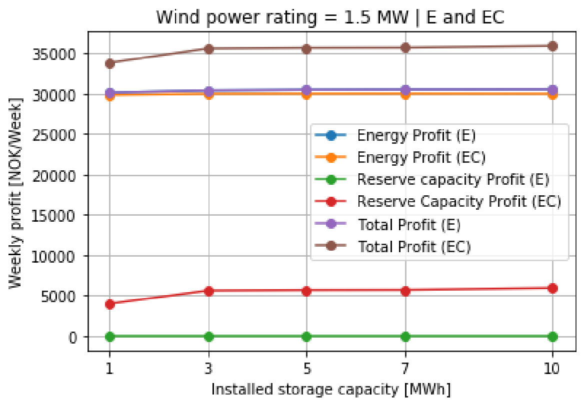


In this thesis, an optimisation model was created for an energy storage system consisting of a wind turbine, a storage unit, and a 1 MW converter. This system is connected to the main grid with a transfer capacity and participates in both the energy market and the reserve capacity market, making it a multi-market operation with the objective to maximise its profit. The model itself is a short-term model operating at a level that is both multi-stage and multi-scenario stochastic and is based on concepts found in hydropower optimisation. It consists of a two-step process with two phases. Firstly, in the strategy phase, the model uses stochastic dynamic programming to obtain the storage values for the energy system, which is the marginal value of stored energy. Secondly, these storage values are used in the simulation phase to simulate the optimal scheduling strategy.

To analyse the results and behaviour of the optimisation model, a deterministic and stochastic case study is included and seasonal data is used to showcase the model in different situations. The deterministic case study focuses on wind power sizing and system behaviour under an extreme scenario. The stochastic case study has a more thorough analysis of two very different seasonal cases, winter and summer. The model has been tested with different storage capacities and various wind power ratings. To analyse the multi-market feature, the energy system has been tested when only allowed to operate in the energy market, compared to operating in both markets.

Calculation
The results below are the operational profit result for the stochastic winter and summer case. This include the profit in each market and the total profit from both markets. The label *E* means operating in only the energy market (singe-market setup) while *EC* means operating in both markets (multi-market setup).





While the winter case with high wind production almost solely operates in the energy market, the summer case benefit from the multi-market opportunity with 12-16 % of total operating profit coming from the reserve capacity market. When participating in both markets, the total operating profit in the winter case with high wind production was 34-38 % higher than for the summer case depending on storage capacity.

Conclusion

- Most, or all, of the total profit is earned by selling wind power in the energy market.
- An increase in wind power production, either by installing a larger turbine or experiencing high wind periods, decreases the multi-market operation.
- High wind production leads to high or solely participation in the energy market and low wind production leads to participation in both markets which is characterised as a contribution from the storage unit.
- The model will only prioritise the reserve capacity market over the energy market when the reserve capacity price is higher than the energy price.
- To minimise power shed and maximise profit a 1.5 MW wind turbine is considered ideal for this system.
- A storage capacity above 1 MWh does not lead to a significant profit increase in the energy market.
- A storage capacity above 3 MWh does not lead to a significant profit increase in the reserve capacity market.

Stability study of an Isolated Grid in a Turbo-electric Aircraft

Student: **Alexander Onarheim Høgh**
Supervisor: **Trond Leiv Toftevaag & Jonas Kristiansen Nøland**
Contact: **Børge Noddeland**
Collaboration with: **Rolls Royce**

The interest in electric propulsion technology in the aviation industry has seen a rapid increase during the past years, promising lower emissions, reduced operating costs and higher efficiency. Most of the electric aircraft system solutions presented in the literature or under development include heavy batteries that limit the aircraft range and power electronics that introduce losses, increases system weight and introduce a single point of failure.

The thesis proposes a turbo-electric aircraft with the aim of analysing the electrical system stability during system initialization and under load perturbations. The estimated power requirement of the proposed turbo-electric aircraft was based on the Dash-8 Q400 regional turboprop aircraft as a point of reference. The system analysed in the thesis focused on the electrical system states, and the aircraft flight dynamics were neglected entirely. The dynamical simulations were performed in MATLAB/SIMULINK, while COMSOL was used for machine parameterization.

Through eigenvalue analysis and dynamical simulations, a system natural frequency depending on machine and electrical parameters was identified. By use of control theory, two different solutions were proposed to counteract the torque oscillations occurring during load perturbations. The results showed that the settling time of the oscillations could be reduced substantially, but it was concluded that more work was needed to evaluate the technical viability of the proposed solutions. During system initialization, several issues related to start-up power, energy and stability were identified, and it was concluded that more work was needed to model the starting dynamics to fully evaluate the feasibility of the proposed turbo-electric aircraft.

Transient Stability Assessment of Virtual Synchronous Machine based Wind Energy Conversion System

Student: **Henrik Høstmark**
Supervisor: **Mohammad Amin**

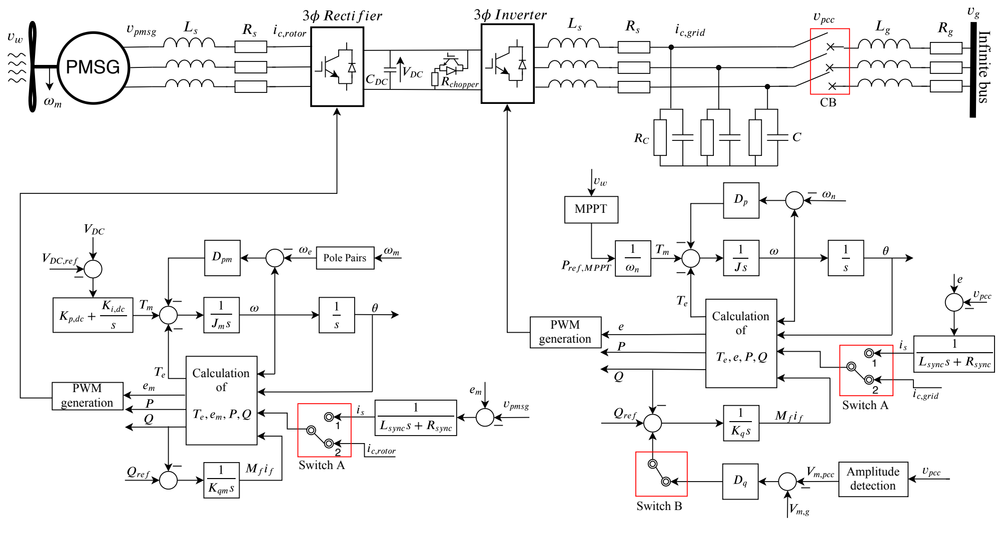
Problem description and objectives:

The virtual synchronous machine (VSM) control method for power electronics seems like a promising method of enabling converter connected power generation with the ability to provide the grid with ancillary services such as frequency control, voltage control and virtual inertia. The Synchronverter VSM has been proven to provide all of the above, but just as the conventional synchronous generator (SG), the Synchronverter is prone to experience transient rotor angle instability if exposed to a severe contingency. The main objectives of this thesis have therefore been to analyse the transient rotor angle stability of the Synchronverter VSM, using both traditional stability analysis methods, known from the conventional SG, and modified analysis methods, and to improve the stability by introducing enhanced control loops to the Synchronverter control system.

The Synchronverter control structures and their mathematical models have been used to derive a dynamical system that can be used to investigate the Synchronverter analytically. Both the equal area criterion (EAC) and transient energy function (TEF) have been adapted to the analytically modelled Synchronverter dynamical equations to obtain the critical clearing angle (CCA) and critical clearing time (CCT) of the system. The TEF has also been used to derive a quasi-steady approximate Lyapunov method for predicting the stability of the VSM.

System Model:

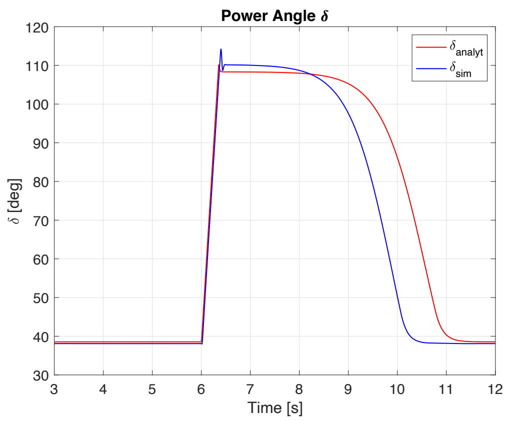
The analytical system and related results were compared to simulation results using a simulation model in the MATLAB/Simulink environment, tested for a balanced three-phase-to-ground fault which decreased the grid voltage to 0.1 p.u.. The model consists of a wind energy conversion system connected to the grid through back-to-back converters. Both the rectifier and inverter are controlled using the Synchronverter control system.

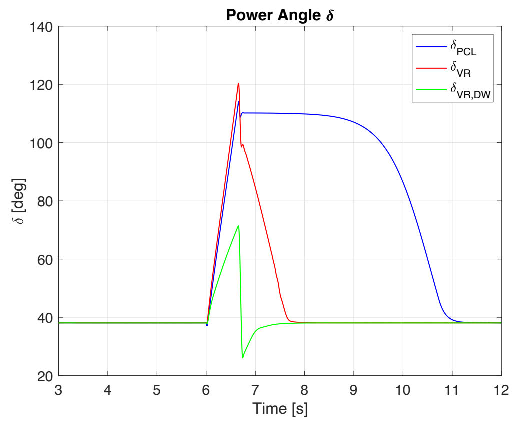


Results:

The results of the stability analysis of the original system showed large variations in the performance of the different analysis methods. While the EAC and TEF utilising the classical model without damping gave a far too conservative result for the stability, deviating with 88.47% from the real CCT, the TEF including the damping term gave a too high prognosis, 57.45% above the real CCT, and thus predicted an unstable system to be stable. The derived quasi-steady approximate Lyapunov method was, however, able to incorporate the deteriorating effect that the reactive power loop of the VSM has on the system stability, while also considering the large impact damping has on system stability for a VSM with a relatively small virtual inertia. As such, the quasi-steady method yielded very precise estimates of both the CCT and CCA, having a deviation of only two cycles from the system CCT of 386.1 ms. When compared to the responses of the simulated system, the dynamic responses of the derived analytical system were shown to be practically identical.

An unfeasible high post-fault current was identified when clearing the fault at the CCT. To mitigate this current and improve the transient stability, three enhanced Synchronverter control topologies were derived; a power correction loop (PCL), a virtual resistor (VR) loop, and a system equipped with both a virtual resistor and artificial damper windings (VR/DW). Simulation results show that all three systems drastically advance the stability limits, with improvements of 66.9% and 97.00% for the PCL and VR systems respectively. The VR/DW system is however found to be stable even for a clearing time of 1.5 s, and no CCT was found within the first 4 seconds after fault initiation. While all three enhanced topologies improved the CCT, only the VR/DW system was demonstrated to satisfyingly mitigate the post-fault current to acceptable levels at all possible clearing times. Furthermore, the VR/DW controller yielded fast and well-dampened tracking of references, demonstrating elegant controller responses that actively mitigated high-frequent oscillations.





The figure to the left depicts the original Simulink system and the analytical model of the original system for a fault-clearing time of 386.1 ms and 352.2 ms respectively, while the figure to the right depicts the three enhanced systems for a clearing time of 644.4 ms.

Conclusion:
Based on the results it is concluded that traditional stability analysis methods using the classical model are no longer viable for the VSM, but that the derived quasi-steady method shows excellent ability in predicting the stability limits also for the virtual synchronous machine. Moreover, the novel enhanced Synchronverter controller, equipped with both a virtual resistor and artificial damper windings, is concluded to be a far superior controller implementation compared to both the original Synchronverter and the two other investigated enhanced control topologies. Its demonstrated capabilities related to both stability improvement and post-fault current mitigation are concluded to be exceptionally good, yielding results far beyond what would typically be demanded in the power system.

Optimal planning of fast charging stations for EVs – A Norwegian case study

Student: **Eirik Ivarsøy**
Supervisor: **Magnus Korpås**
Co-supervisor: **Bendik Nybakk Torsæter**
Collaboration with: **SINTEF Energy Research**

Abstract

The integration of electric vehicles (EVs) plays an integral part in reducing GHG emissions from the transport sector. In recent years, the number of EVs has increased rapidly. Due to government policies and technological advancement, the growth is expected to continue. The EVs have a limited range, but it will often be sufficient for daily routines. However, to enable long-distance travel, a network of fast charging stations (FCSs) is needed. Fast charging of EVs is characterized by its stochastic nature, high power, and short charging time. This can potentially result in bottlenecks in the grid.

To face the challenges that come with the integration of FCSs into the distribution grid, an optimal planning scheme is needed. The main objective of this master thesis was to develop a model to decide the optimal planning of an FCS network. In this thesis, an EV mobility model, FCS load model and distribution grid model are combined in an optimization model to decide the optimal planning of FCSs.

The FCS load model is developed to determine the load profile at different FCSs. The FCS load model includes the EV traffic flow, EV charging curves and temperature-dependent driving consumption. The available traffic data was inadequate. Hence, a mobility model was developed to create a more detailed traffic flow of EVs in the system. The EV mobility model determines the route of each EV. The FCS load model determines the charging need of the different EVs and which FCS they will charge at. Then, by aggregating the charging needs of the EVs, the charging demand at each FCSs is determined.

The data about the Norwegian distribution grid is not open to the public. Thus, a novel distribution grid model was developed, which creates and dimension distribution grids. The proposed distribution grid model is based on power system planning principles, taking into consideration both economic and power system aspects.

The aforementioned models are combined in the optimization model. The optimal planning of FCSs is a nonlinear problem and a particle swarm optimization (PSO) algorithm is implemented to solve the problem. The proposed optimization model is a two-step model, the first step determines the location of the FCSs, and the second step determines the number of charging points.

The performance of the developed optimization model was tested on a 74 km stretch of highway between Gardermoen and Hamar. There are many aspects to consider when planning an FCS network. Thus, different objective functions were used in the optimization model. The first case study minimized the additional energy losses in the distribution grid due to the integration of FCS. For the second case study, the cost of FCSs was added to the objective function. For the final case, the perspective of EV owners was taken into consideration, by

assigning a cost to EV detours. Thus, for the last objective function, the perspective of the DSO, FCS operator and EV owners were included.

The results illuminate how the optimal number of FCSs and their location is highly dependent on the objective function. For the three case studies performed, all got a different optimal number of FCSs. The proposed optimization model was able to find the optimum solution with all the three objective functions. To compare the different objective functions, the social cost was computed for all three cases. The results showed that the social cost was highest for case 2, which only considers the DSO and FCS operator perspective. This resulted in a 25.2% higher social cost for case 2 than case 3, with most of the increase due to a 5400% increase in the detour cost. Thus, emphasizing the importance of considering the perspective of all the interested parties when planning an FCS network. The effects on the serviceability of an FCS when reducing its peak power were investigated. This showed promising results as the peak power of the FCS could be reduced significantly, with little impact on the serviceability of the FCS.

Optimisation of cost and emissions of an EV parking lot within a Zero Emission Neighbourhood by utilising demand response programs, PV and an external battery

Student: **Thomas Kallevik**
Supervisor: **Hossein Farahmand**
Co-supervisor: **Kasper Emil Thorvaldsen**

Problem description
In the near future, the world must rapidly reduce the emissions of greenhouse gases to cope with the human-made climate crisis, and to meet international agreements. As the energy sector is a significant emitter, reduction in this field will be crucial. In this transition, renewable, non-dispatchable energy sources will replace non-renewable and dispatchable energy sources. This means there will be an increased need for flexible sources. At the same time it is a rapid increase in electric vehicles which will result in more energy consumption, however electric vehicles has also the ability to be a flexible source. There is also a decrease in the costs of solar panels, and it is natural to think they will play an essential role in the future energy system. In order to reduce the emission of greenhouse gases, a Zero Emission Neighbourhood can be crucial, since it has an overall goal to have zero emission, but also as it will create awareness of the CO2-footprint in the energy.

The task
The goal for this master thesis is to use bidirectional vehicle-to-grid charging of electric vehicles, solar panels and an external battery to minimize CO2-emissions for a Zero Emission Neighbourhood. It also has a goal to maximize profit for electric vehicle users by exploiting different demand response programs. The thesis is also looking at how flexible the proposed system is.

Model
The proposed model in this master thesis was based on previous work done in the field. Two-step stochastic programming was used to develop the model, where the first step was the decisions made in the day-ahead market, while the second step was during the time of operation. The model made ten different scenarios with an equal probability of happening. To model the uncertainty and the scenarios, a truncated Gaussian distribution was used to get initial soc, arrival time and departure time for the electric vehicles. In this research, the soc departure was modelled with two different minimum limits, one for when it departed and one for when it was present at the parking lot. This was to ensure the desired departure soc for the user. The departure soc was also made flexible, so the activated reserves by the system operator could be met.

Conclusion
The research found that implementing solar panels, an external battery and minimisation of CO_2-emissions to a system with bidirectional charging would increase the daily result by 24.57 €/day compared to a system with only bidirectional charging. The preferred demand response program was time-of-use, and it saved 1.15€/day compared to the fixed-rate tariff. With soc departure at 70%, the system is close to net zero emission. The proposed uncertain parameters on the arrival time, departure time and initial soc were less determining than anticipated. To understand the real profit and the possibilities the proposed system must be included in a complete Zero Emission Neighbourhood as there are other loads in the system as

well as the electric vehicles. Systems like this still have a challenge with getting the end-user to join in. This is why this research has made several adjustments to the operator role with the results of lower profit, but higher end-user consideration. Based on the results, a new balancing market should be developed for smaller, more stochastic customers as today's market is not flexible enough. The research showed that the proposed system is able to provide flexibility, and hence it can be important in the future with more unregulated renewable energy.

PSCAD Simulation of Distance Protection Performance in a Grid with Inverter Interfaced Generation

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Collaboration with: **Statnett SF**

Problem description
In this thesis, the performance of distance protection in a grid with inverter interfaced generation has been studied through simulations in PSCAD. The work has been conducted in cooperation with Statnett, who has requested the need for research on this topic based on a recently published ENTSO-E report. The Fosen Wind project in Norway is the practical example of where protection issues are expected due to the large penetration of wind power. The main problem has been defined as "Are there indicators one can point to for determining when distance protection relays will start experiencing performance issues due to the increasing share of inverter interfaced generation?".

Model description
The PSCAD model has been developed from scratch and consists of a Grid-feeding inverter model (representing a 3.6 MVA type 4 wind turbine), a grid, and distance protection relays. Essentially, the model is a transmission line with inverters connected to the left end (Bus 1 / Inverter side) and a grid equivalent connected to the right end (Bus 2 / Grid side), with distance protections installed on both ends of the line. The model development has been described in detail and most of the system parameters have been provided. A verification of the model has been included as well.

Setup
Four sets of simulations have been executed with a balanced three-phase to ground fault located on the center of the line. The fault resistance has been varied, ranging from 0.1 mOhm to 10 Ohm. The main focus has been to obtain results for the inverter side relay's impedance diagrams and tripping times.

Results
Simulation set 1 showed that a single inverter connected to Bus 1 caused unsatisfactory tripping for the inverter side relay. The performance was generally worse for higher fault resistances, causing no tripping at all.

Simulation set 2 showed that ten inverters connected to Bus 1 also caused unsatisfactory tripping for the inverter side relay. However, the relay performance was slightly improved compared to Simulation set 1. Again, the relay performance was worse for higher fault resistances.

Simulation set 3 showed that the share of inverter interfaced generation (opposed to synchronous generation) connected to Bus 1 influences the inverter side relay performance. The relay was able to trip satisfactorily (within 0.1 s) for inverter shares of 50% or less, for fault resistances of 1 Ohm or less. With few exceptions, there were no satisfactory trippings for inverter shares of 70% or more. The relay performance was reduced for increasing inverter shares of the total generation and increasing fault resistances. The instances which caused no tripping at all, were linked to a combination of higher inverter shares and higher fault resistances, yet the fault resistance had the greatest impact.

Simulation set 4 showed that the ratio of the short circuit current contributions from each side of the line influenced the relay performance. The relay located on the side with the lowest short circuit current contribution suffered more the greater the short circuit current contribution from the other side. For similar short circuit current contributions from the two sides, both relays were able to trip correctly and fast. For higher short circuit current contributions from Bus 2, the relay located at Bus 1 suffered from reduced performance, especially for higher fault resistances. Still, the relay was able to trip satisfactorily for fault resistances of 0.1 Ohm or less, when the short circuit current contribution from the other side was up to roughly 70 times greater.

The distance protection relay located on the grid side of the line did not experience any problems during any of the simulations.

Conclusion

However, due to the model assumptions and weaknesses, the obtained results cannot be used to give any general statement regarding the performance of distance protection in a grid with inverter interfaced generation. Thus, the main problem cannot be answered. More research is needed to be able to give accurate statements related to which problems should be expected and under which circumstances they will occur. The model should be developed further, with an improved inverter model and distance protection algorithm, such that unbalanced faults can be studied as well.

A Study of How Integration of Solar Photovoltaic Impact a Housing Cooperative in Norway

Student: **Emilie Kjenstadbakk**
Supervisor: **Magnus Korpås**

Photovoltaic solar panels are the fastest-growing energy source in the world at the moment. Solar power in Norway has traditionally been used to cover electricity need for locations without a connection to the electricity grid, such as cabins. Over the last couples of years, an increase in the grid-connected solar PV systems have been seen. As the sun provides free and environmentally-friendly energy, it is an attractive energy source to utilize. Even in Norway, the solar resources are sufficient enough for solar PV to become expedient. As the Norwegian power generation consists of mainly hydropower, a flexible energy source, the power flow can withstand the implementation of more unregulated power sources, such as wind and solar PV.

In this thesis, an evaluation of how the integration of solar photovoltaics (PV) impact different accounts of a housing cooperative in Trondheim, Risvollan, is conducted. A simulation of the energy demand system with different energy supply investment options are done in eTransport. Primarily two main scenarios are looked into, a solar PV system which utilizes all the available roof area at Risvollan and one scenario where half of the area is used. Then simulations are conducted for the two scenarios when the electricity price for the power from the grid is varied, and when charging of electric vehicles is added to the demand in various amounts. Calculations of CO2 emissions are also done for the housing cooperatives, with and without solar PV. Furthermore, estimations of self-consumption and self-sufficiency for Risvollan with the two different solar PV systems and when electric vehicles are added.

The main results reveal that with the current system units cost and grid electricity prices, the solar PV systems researched was not able to match the price of grid electricity. When the self-consumption is high, and the predicted worst-case electricity price is used, the solar PV is close to matching the annual costs of the fully electric system. Furthermore, an LCOE calculations show that the system unit price for solar PV is too high to make solar PV profitable, a decrease from 12 NOK/Wp to 8,8 NOK/Wp must be introduced before the solar PV could match the electricity price. The results showed that the waterborne district heating systems is the least economical system analyzed, but it is discussed that if flexibility is emphasized the district heating system may be of more interest, especially from a socio-economic view.

A limitation of this research is that income from selling surplus generated electricity from the solar PV is not taken into account; this could affect the amount of decrease in system unit price before profitability is reached.

Assessing the Microgrid at Campus Evenstad

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Collaboration with: **Statsbygg**

Problem description

The increasing integration of Distributed Energy Resources (DERs) in the electrical distribution system is complemented by the application of microgrids. It offers flexibility to the power system and is a tremendous asset to improve the grid resilience to macrogrid failures. It can disconnect from the utility during grid disturbances, to operate in islanded mode, offering a continuous supply of power to its connected loads. However, the resilience offered is in jeopardy if the microgrid is not properly protected against faults occurring within its boundaries. DERs in the power distribution system causes the magnitude of fault currents to dynamically change, depending on the operational mode of the microgrid (grid-connected or islanded mode). This is in direct conflict with the operating principles of traditional static protection devices, challenging its successful operation. This thesis addresses the protection challenges faced at an actual inverter dominated microgrid implementation, located at Campus Evenstad in Hedmark. As the inverter units supply limited current during faults, significant fault current ratios are experienced in the network. This challenges the successful operation of the implemented over-current protection, especially in islanded mode of operation.

The task

Perform a detailed analysis of the microgrid network located at Campus Evenstad, identifying protection issues faced at the installation, by analyzing the performance of the implemented microgrid protection scheme. This is accomplished by developing a simulation model of the microgrid network.

Model/ measurements

A simplified sketch of the developed simulation model is depicted in Fig. 1, which has been implemented in MATLAB/Simulink. To obtain reliable results from the simulations, a lot of effort has been placed on obtaining accurate operational data from the installation. Moreover, since the fault currents in islanded mode of operation are almost entirely determined by the fault response of the power electronics interfacing the DERs to the microgrid, a lot of emphases have been placed on developing solid models of these units. By subjecting the microgrid to three-phase faults, the simulation model has been utilized to analyze the performance of the implemented system protection, based on over-current protection. This is achieved by comparing the resulting fault currents in the network to breaker settings at Evenstad, analyzing the response regarding

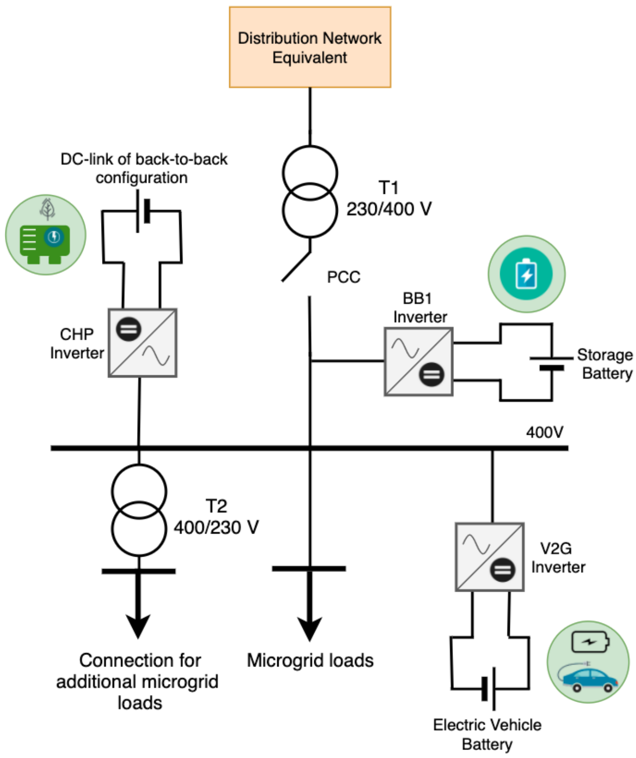


Figure 1: Simplified representation of the implemented Simulink model.

protection principles. Moreover, the tripping of DER units has been examined considering anti-islanding requirements, both during short-circuits, and in the islanding transition.

Calculation

Fig. 2 and Fig. 3 gives the results from one of the simulated scenarios in the thesis, during a fault at the microgrid CHP board. They provide the measured fault currents through the breaker protecting the CHP board and illustrate the difficulties experienced in the microgrid network during faults in islanded mode of operation. During grid-connection, the fault currents are well above the instantaneous trip setting of the breaker, ensuring fast fault isolation. However, due to significant fault current ratios in the microgrid, the fault current in islanded operational mode falls in the overload region of the Protection Device (PD). This leads to a long tripping time, challenging the selective operation of the implemented microgrid protection. Additionally, DER units may trip according to their anti-islanding protection. This conflicts with the offered benefits of microgrids, as the system requires a black-start during faults in islanded mode, disrupting the continuous supply of power to unaffected microgrid loads.

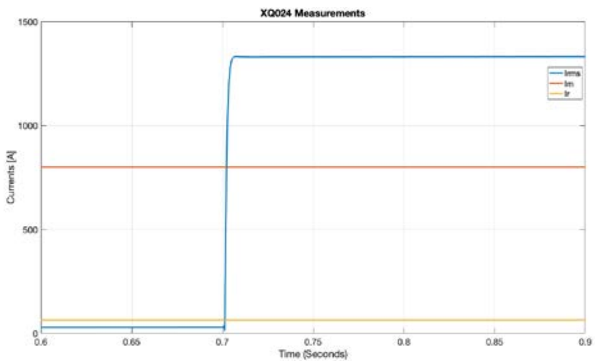


Figure 2: Measured RMS current (blue) through breaker XQ024 during a fault at the CHP board in grid-connected mode of operation. The measured current is above I_m (the instantaneous trip setting, orange), ensuring fast disconnection.

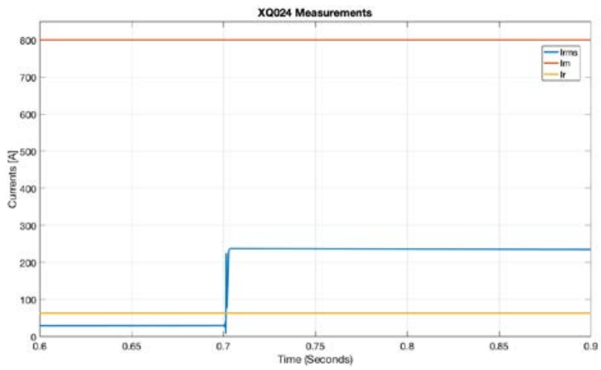


Figure 3: Measured RMS current through breaker XQ024 during a fault at the CHP board in islanded mode of operation. The fault current lies in the overload region of the PD, leading to a high tripping time.

Conclusion

The main findings from the research were:

- In the islanding event, the system experiences voltage transients due to power-mismatch in the microgrid. Consequently, DER units may trip according to their anti-islanding protection. Implementing proper microgrid control, through energy management, may help to mitigate the problem.
- During faults in grid-connected operation, the implemented protection scheme maintains a reliable and selective operation. The exception was during a fault at the longest feeder in the system, were coordination between PDs were disrupted.
- Selective operation of the protection scheme is not maintained during faults in islanded mode. High short-circuit ratios in the microgrid challenge the successful operation, as the fault currents fall in the overload region of the PDs. Reliable operation of the protection system is therefore reliant on DER units tripping according to their anti-islanding requirements.

Voltage Stresses in Converter-Fed Electric Aviation Motors – A Finite Element Analysis

Student: **Kristoffer Fæster Klaussen**
Supervisor: **Hans Kristian Høidalen**
Contact: **Njål Rotevatn**
Collaboration with: **Rolls-Royce Electrical Norway**

Problem description

Electrification in aviation is a new field of application that implies severe restrictions on size and weight and requires optimum designs. Today, extra stress on machine windings comes from fast switching power electronics. This thesis focuses on the uneven voltage distribution occurring in the winding of inverter-fed motors.

The task

- Perform measurements of voltage distributions in stator windings of the developed test object.
- Perform numerical or analytical calculations of the voltage distribution.
- Investigate the effect of reduced air-pressure at high altitudes.
- Propose required insulation thickness to withstand the voltage stresses and thus contribute to motor design optimization.

Model/ measurements

This thesis examines the voltage distribution in windings subjected to short rise times by using analytical and finite element analysis, where two different configurations are considered: a simple 4-turn winding and a more complex 8-turn winding. The analytical method studies the equivalent capacitive circuits of the two configurations, where the initial voltage distribution is calculated, electrostatically. In FEM, 3D models of the two configurations are developed to examine the voltage distribution, which is based on transient electromagnetic waves physics. A voltage step is considered as the input signal, with a rise time of 6 ns. Parameter studies were examined regarding insulation thickness, permittivity and grounding.

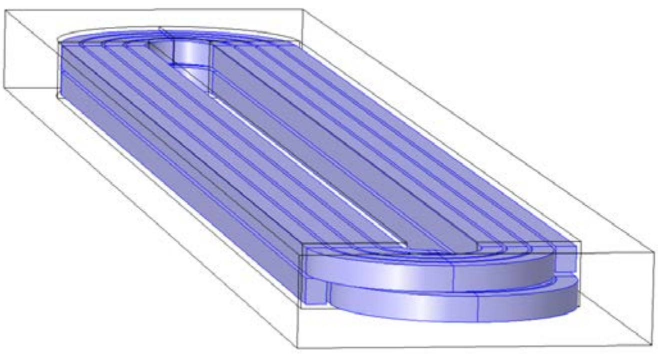


Figure 1: 3D model of the 8-turn winding

Calculation

The capacitances in the equivalent circuit used for the analytical calculations were calculated in FEM by a 2D model of the winding slot section. The FEM simulations of the 3D windings resulted in significant oscillations within the winding. A time instance was selected to compare the voltage distribution of the two different methods.

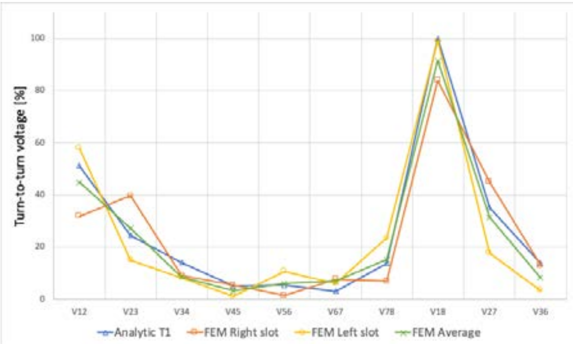


Figure 2: Voltage input at turn 8 and turn 1 grounded

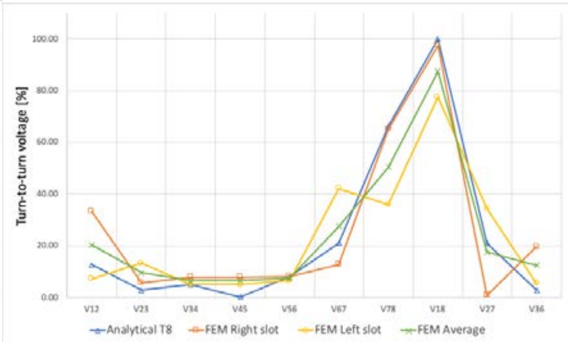


Figure 3: Voltage input at turn 1 and turn 8 grounded

The comparisons of the 8-turn cases showed there was a correlating effect in both study methods. The two FEM voltage distributions were averaged, which showed a more agreeable result regarding the analytical voltage distribution.

Conclusion

The voltage distribution improved by decreasing the turn insulation thickness and mainwall insulation permittivity and increasing the mainwall insulation thickness and turn insulation permittivity. The changes in these cases were confirmed by comparisons of FEM simulations, where the maximum and minimum parameter were simulated. However, to propose the required insulation thickness to withstand the voltage stresses, further investigations are needed. The breakdown strength has to be calculated by considering both the overshoot from the cable and rise time, and the uneven voltage distribution.

Modeling of SiC MOSFETs and Parameter Fitting Using a Genetic Algorithm

Student: **Sindre B. Kongerød**
Supervisor: **Dimosthenis Peftitsis**
Co-supervisor: **Ole Christian Spro**

This master thesis demonstrates the use of a genetic algorithm to optimize parameters of simulation models to accurately represent the measured static characteristics of a SiC MOSFET at room temperature. Various models in the literature for simulating SiC MOSFETs are investigated and classified. Two models from device manufacturers are selected for the optimization process; an improved model based on the Cree model and the model from ROHM. A genetic algorithm is implemented and used to fit the two models to experimental measurement data. The static characteristics – also known as IV-curves – of a commercial SiC MOSFET (C3M0075120D) were measured using a commercial curve tracer.

Two methods for obtaining the characteristics when using the curve tracer are investigated and discussed. Among the test settings of the machine, the pulse width of the applied voltage or current pulse has been found to strongly influence the measurements. The junction temperature of the device-under-test is investigated through simulations while applying the same pulse as it experiences during characterization. Often, the junction temperature is assumed to be approximately equal to the case temperature for short test pulses. By using the manufacturer provided thermal model of the device, it is found that the junction temperature increases significantly for several of the characterization points during a complete curve tracer test. Hence, the junction temperature is greater than the case temperature when the measurements are taken, and this error can carry over to the modelling of that same device. These thermal investigations are verified by thermal calculations using the thermal impedance from device datasheet. The figures below show the measured IV-characteristics at two different pulse widths including the temperature difference between junction and case, ΔT, as a colormap on the lines.

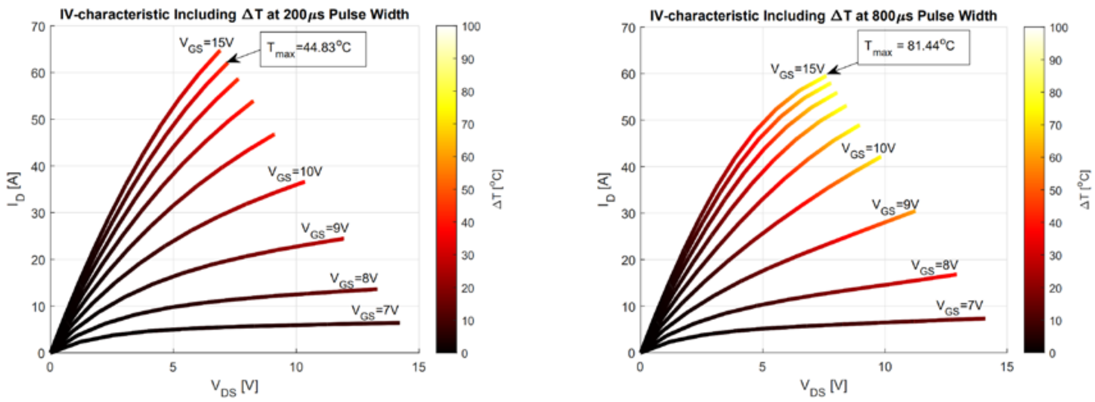


Figure 1: Effect of pulse width on IV-characteristic measurement

In this work, the temperature increase during experimental characterization is taken into account by the optimization algorithm. This is accomplished by setting the junction temperature to the values obtained from thermal calculations at each measurement point in the simulations. The genetic algorithm adjusts the model parameters to fit the measurement data. The figure below shows the flowchart of the implemented genetic algorithm.

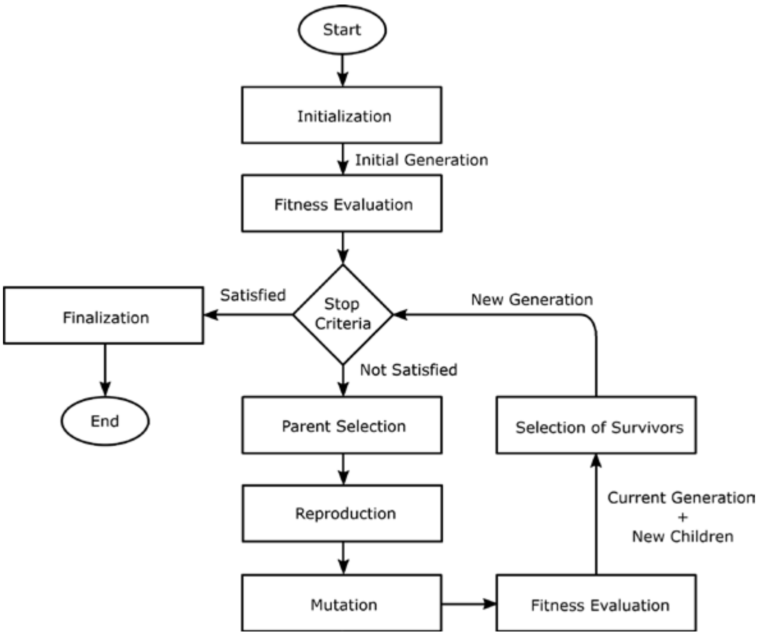


Figure 2: Flowchart of genetic algorithm

Both models obtain parameter values that provide an overall fit of the measurement data. However, the ROHM model is found to have better fit in all runs of the algorithm.

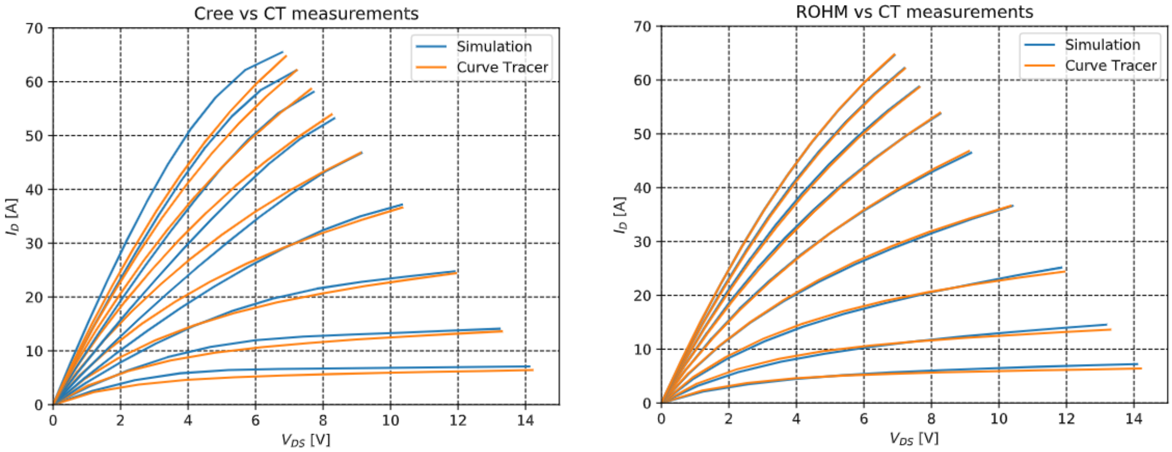


Figure 3: Results from fitting the models

The use of a genetic algorithm works to obtain a match between measurement data and the model. This opens the opportunity to test many different implementations of models without having prior knowledge about how the model work. Models can be optimized and compared to evaluate what models work well. Consequently, these models can be investigated further to understand why they perform well or what they might be missing in order to perform well. The same procedure and principles can be used on different parts of models. I.e. the GA with its implementation is not necessarily limited to only fitting IV-characteristics. It may also be adjusted, along with the simulation configuration, to optimize different characteristics, such as CV-characteristics, dynamic switching behavior, reverse recovery of intrinsic diode and more. Ultimately, by optimizing a model for many different aspects based on measurement data, an accurate and universal model may be found. This can help obtaining more accurate SiC MOSFET models to better explore the advantages of WBG materials in different applications.

Back-to-Back Based Voltage Control of an Isolated Grid Supplied by a Hydro Turbine Driven Induction Generator

Student: **Eivind Krakk**
Supervisor: **Jonas Kristiansen Nøland**
Co-supervisor: **Trond Leiv Toftevaag**

Problem description
The objective of this master's thesis has been to utilize common available products and design a proper control system for an isolated hydro-power system. The squirrel cage induction machines are the most commonly used electric machines for drives applications worldwide and is thus easily available in all power ranges. Their simple construction makes them cheap compared to alternatives such as the synchronous machine at the same power rating. Generator control and operation is emphasized to be within the rated current and power. The load voltage should be reliable and satisfy the Norwegian quality requirements for low voltage grids; 230 ± 3% RMS and 5.0 % THD at 50 Hz. To achieve this, a back-to-back converter topology and a passive LCL-filter are used to achieve high load voltage quality, which in this case is considered more important than finding the most cost-effective solution.

The task
The system contains three independent control systems: A governor for the hydraulic turbine, a control system for the generator side voltage source converter (VSC) and a control system for the load side VSC. Two different generator control approaches are built from scratch and investigated: V/f-control (scalar method) and the indirect vector control (IVC) approach. These control systems are the focus in the thesis and they aim to maintain the DC-link voltage based on measurement of stator currents, in addition to mechanical speed and DC-link voltage. The functionality and mathematics of the hydraulic governor and the load controller are explained and included.

The V/f-control approach tries to keep the ratio between voltage and frequency equal to the nominal V/f-ratio. IVC is based on estimating the rotor flux position to achieve a synchronously rotating dq-frame where the control is performed. The gate signal is generated by the S-PWM and current hysteresis techniques.

An induction machine is by itself robust and cheap, relative to its power rating. A per unit induction machine model has been developed and implemented in MATLAB/Simulink. The per unit model is scaled to five different power ratings in the power range [1.5 kW – 11 kW]. The system behaviours at V/f-control and IVC for the different generator ratings are of interest when selecting the generator rating and is thus emphasised. The benefits of using an additional flywheel to stabilize the mechanical speed by increasing the moment of inertia is also given attention in the thesis.

Model and Measurements
Simulink is used to model the self-standing system: A simple mathematical model of the hydro turbine is achieved by using the classical linear hydraulic turbine transfer function. The water flow through the gate openings are controlled by tuned permanent and transient droop functionalities. The governor input is the speed in addition to a feedback from turbine output.

The induction generator receives the mechanical torque developed by the turbine and generates an electromagnetic torque. Its terminals are connected to the generator side VSC.

The generator behaviours are well controlled by either V/f-control or IVC. The control ensures that enough reactive power is delivered to the induction generator and maintains the DC-link voltage at its reference as the system load vary. The load side VSC inverts the DC-link voltage by using sinusoidal PWM (with 3^{rd}-harmonic injection), based on the load voltage. The passive LCL-filter is used to filter out high order harmonics. Figure 1 shows an overview of the model:

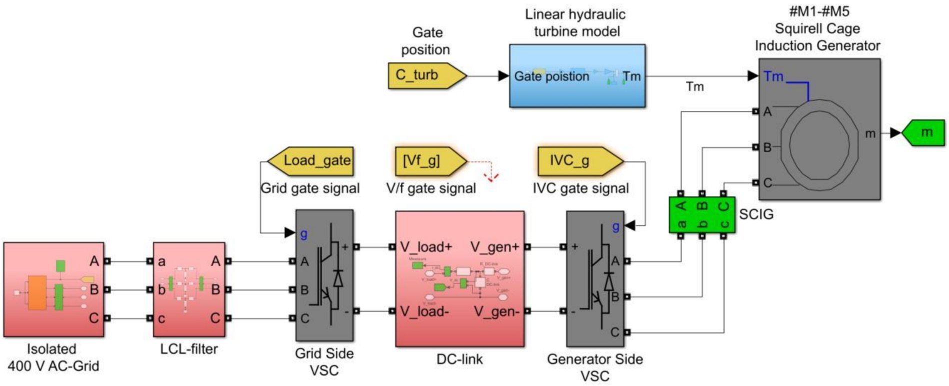


Fig 1: Simulink model containing turbine, induction machine, VSCs, DC-link, LCL-filter and AC-load

Simulations

Five different ratings of the induction machine have been established (#IM1-#IM5) based on the per unit model. These are used in the five test approaches: In Test 1, both the V/f-control scheme and indirect vector control scheme (IVC) are tested with constant mechanical speed. Both generator control systems were found to be quick, and generators rated above 1.5 kW can handle a load step of 1.5 kW. The response increases with the power rating due to more available current. Test 2 evaluates the parameter dependency (rotor time constant, T_r) in IVC with constant speed. Test 3 evaluates the system performance driven by the turbine model when the load is increased step-by-step. The speed needs a couple of seconds to reset between the load steps. Total moment of inertia and power rating determines how fast the load can increase. In Test 4 the load side behaviour and filter performance are tested for a constant DC-link voltage. It functions well and the Norwegian quality requirements for low voltage grids are satisfied with good margins when load demand is increased from 0 to 1.5 kW.

Test 5 interconnects the whole system, such that the performances of load voltage found in Test 4 relies on the generator controller's ability to maintain the DC-link voltage. This again relies on the nominal generator current, in addition to an adequate mechanical speed which is maintained by the hydro turbine and governor. By applying an equivalent step-by-step load profile as done in Test 3, the governor and turbine is capable to respond by increasing the mechanical torque and keeping the speed within the range that can maintain the DC-link voltage and thus also load voltage. The load side behaviour become similar as in Test 4 assuming the turbine, generator and DC-link capacitor can handle such changes.

Conclusion

Based on the analysis it is recommended that the ratings of the generator and turbine in a realized system are higher than the rated load demand: A generator rated with 2.2 kW or 3.0 kW, supplies the load demand of 1.5 kW and additional system losses while staying within its rated conditions. In total, the analysis of the isolated system shows that the solution obtained by using a back-to-back converter arrangement can be used to obtain a load voltage of high quality (of 230 V ± 3% and THD < 5 %) and keep the generator operation within the rated conditions.

Achieving counter-rotation by utilizing harmonic components of the magnetic field in a fractional slot concentrated winding permanent magnet motor

Student: **Ole Erik Holthe Leangen**
Supervisor: **Robert Nilssen**
Contact: **Arne Nysveen**
Collaboration with: **HydroCen (NTNU)**

Problem description

Pumped hydroelectric storage (PHS) is a well-suited storage technology to balance inconsistencies in electricity sources like wind power, due to its high energy capacity and ability to store energy over extended periods. To further expand the PHS capacity, HydroCen, a research center at NTNU, investigates the possibility of modifying existing hydropower plants to operate in pump mode. One large obstacle in using existing plants for this purpose is the position of the turbine with respect to the outlet. If the water pressure becomes too low on the suction side of the turbine operating in pump mode, cavitation occurs. Cavitation must be avoided to reduce unnecessary losses and wearing of the turbine and surrounding structures. Hence, it is investigated if a boosterpump in the suction tube can sufficiently increase the suction side pressure of the main turbine and reduce the cavitation. As the boosterpump is placed prior to the main turbine in pump mode, it is crucial to limit the water spin, as this would affect the pumping performance. For this reason, it is investigated on the possibility of making a counter-rotating boosterpump.

The task

This thesis focuses on the electromagnetic design of this boosterpump. It is investigated if a phenomenon in a fractional slot, concentrated winding can make two rotors rotate different directions withing the same stator. If the boosterpump can be made with this phenomenon, a proposed machine layout should be presented.

Model/ measurements

The models used in the analysis were made in two steps – one initial calculation of core sizes, which was later implemented in Emetor. Emetor then proposed a motor layout which was used in the FEM analysis. Three different winding layouts were examined. The FEM analysis was executed in COMSOL Multiphysics, and both 2D and 3D models were made. Due to limited resources, only the 2D models were fully calculated. Figure 1 illustrates how the motor could end put looking.

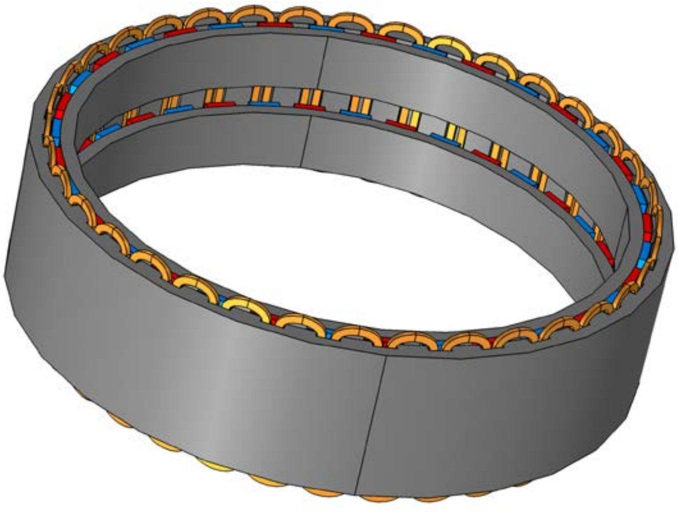


Figure 1: Illustrative geometry.

Calculation

The final design proved fitting to the boosterpump application, as the yielded torque matched the given specifications. Figure 2 shows the torque profile of the machine's two rotors, where it can be observed a clear difference in torque ripple. As this result is only based on 2D analyses, the ripple between the rotors are not included.

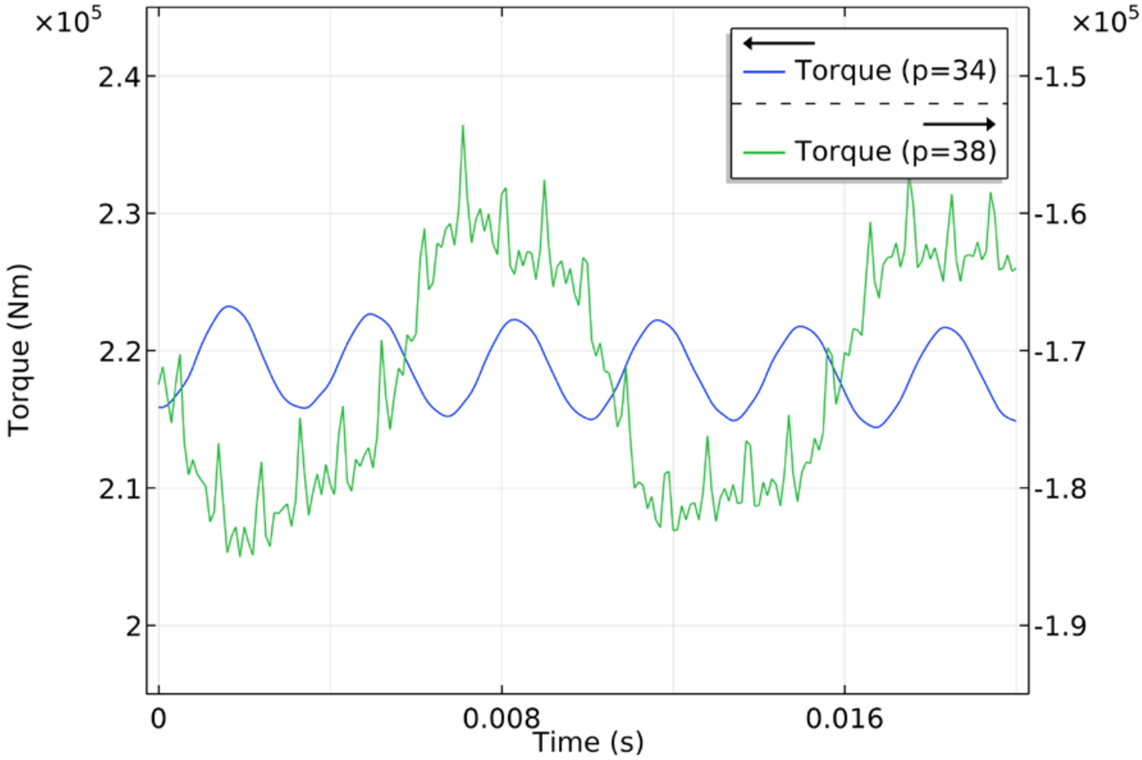


Figure 2: Torque profiles of the rotors

Conclusion

The proposed motor design seems to meet the requirements of the boosterpump while using this phenomenon to create counter-rotation. However, a final conclusion could not be made, as only results from the 2D model were analysed. The 3D model would include the rotors' influence on each other which is a crucial part of the analysis.

Towards DC-microgrids with Stability-Preserving Plug-and-Play Features: Passivity-based Control Design of DC/DC Converters under Compensated Modulation

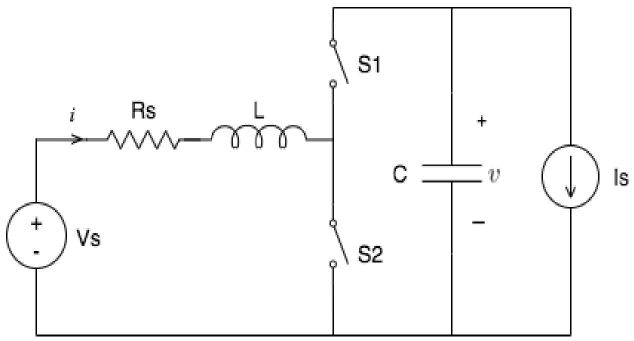
Student: **Eirik Haugen Lillefosse**
Supervisor: **Gilbert Bergna-Diaz**

Problem description
The aim of this thesis is to develop a passivity-based control design of DC/DC converters for stability-preserving microgrids with plug-and-play features, for the purpose of a stable DC-microgrid operation in the case of any future topology change in the microgrid.

The task
The task is to apply nonlinear theory such as Lyapunov and passivity, in addition to more known system theory concepts such as the Gershgorin disk theorem, to design the controller of a DC/DC converter in such a way that it is supportive for plug-and-play features. More precise the tasks are to:

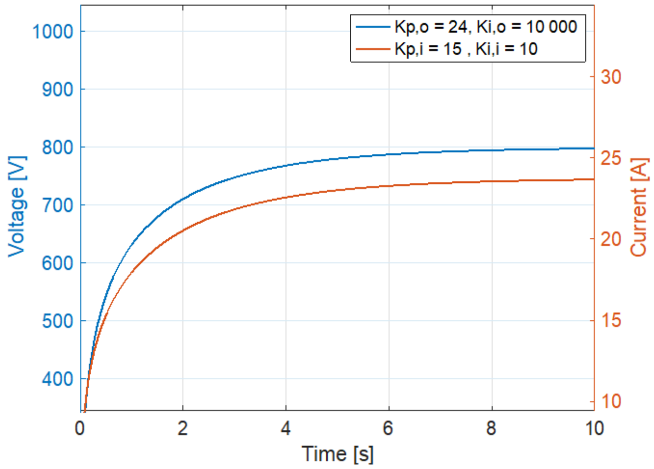
- Develop a design criterion for the inner-loop controller and system parameters to ensure a time-scale separation between the current and the voltage in the inner-loop. If the time-scale separation is ensured, a stability proof created in the specialization project can be used, and the analysis of the nonlinear voltage-dynamics will be simplified.
- Mathematically derive a passivity-based control for the outer-loop in voltage-mode.
- Do analyses and simulations of the converter-model, in order to obtain analytical insight into the dynamics of the current and voltage. Since the new control design might be in conflict with the time-scale separation criterion earlier derived, it must be created a new design criterion of the controller such that the time-scale separation is guaranteed.
- For power transferred in the negative direction of the converter it is expected that some problems might occur. These problems must be investigated and if possible solved.

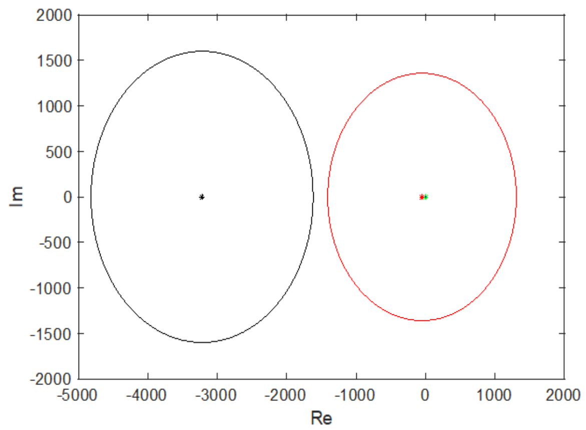
Model
The model consists of a topology similar to a bidirectional state-space averaged Buck-Boost converter, with a PI-controller in current-mode for the inner-loop and a passivity-based PI-controller in voltage-mode for the outer loop. The converter operates exclusively under the so-called compensated modulation strategy; i.e., where the current dynamics have been linearized by means of feedback. The simplified converter model can be seen in the figure to the right.



Calculation
The main results have consisted of mathematical derivations, analytical analysis, and validation of the analyses and derivations through simulations in Simulink and eigenvalue analysis with help from the Gershgorin disk theorem. A stable converter was derived, and the resulting stable voltage and current dynamics can be seen in the figure below to the left, for a

given set of tuning parameters. The figure below to the right shows the corresponding domains of the eigenvalues of the current in black and voltage in red. These domains have been calculated through the Gershgorin disk theorem, and for two separate circles where the current-circle is located to the left, i.e. more negative, than the voltage-circle, stability is guaranteed.





Conclusion

It is proven that TSS can be guaranteed as long as the inner-loop proportional-term is greater than the integral term, by a factor determined by the relationship of the inductance and capacitance. The result is extended by adding a voltage-regulating outer-loop based on passivity-theory. For this converter system, a new PI control design is derived. It was found that the outer-loop integral term is the most critical parameter, and that it must be small compared to the inner-loop tuning parameters to guarantee TSS. At last, the DC/DC converter power transfer bidirectionality is investigated, such that power can be both received and transferred, while preserving the plug-and-play features. Bidirectional power transfer was achieved. Although good results were obtained for the positive power transfer direction, it was found that the negative power transfer direction did not allow a straightforward and precise regulation of current or voltage. Instead it was suggested to settle for a droop-type of behavior for the control in the case of a negative power flow. The mathematical tool of the Gershgorin circle theorem has been applied for deriving the TSS design criteria. The theorem gave an analytical insight into the convergence rate of the voltage and current variables and their dependence on the system and control parameters, which was instrumental for enforcing the desired TSS.

Islanded Microgrids: A Predictive Approach to Control Operation

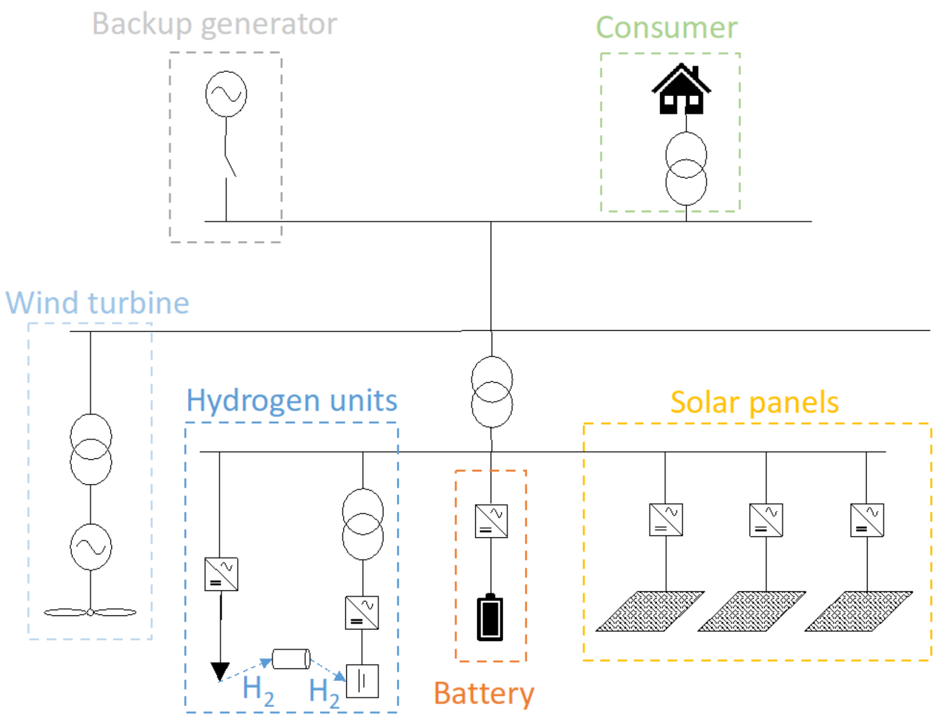
Student: **Nina Lindholm**
Supervisor: **Jayaprakash Rajasekharan**
Collaboration with: **TrønderEnergi**

Problem description

Building an island mode operated microgrid is a solution to supply remote areas with electricity. In order to contribute to the decarbonization, fossil fuel solutions are not an option. Weather dependent energy sources are common, in order to make these microgrids renewable. To compensate for their intermittent behaviour power predictions are useful. This thesis set out to design a new control system for a microgrid, taking power predictions into account. With the aim of reducing the necessity of the backup diesel generator, the hope is to design an operational strategy that makes the microgrid more independent.

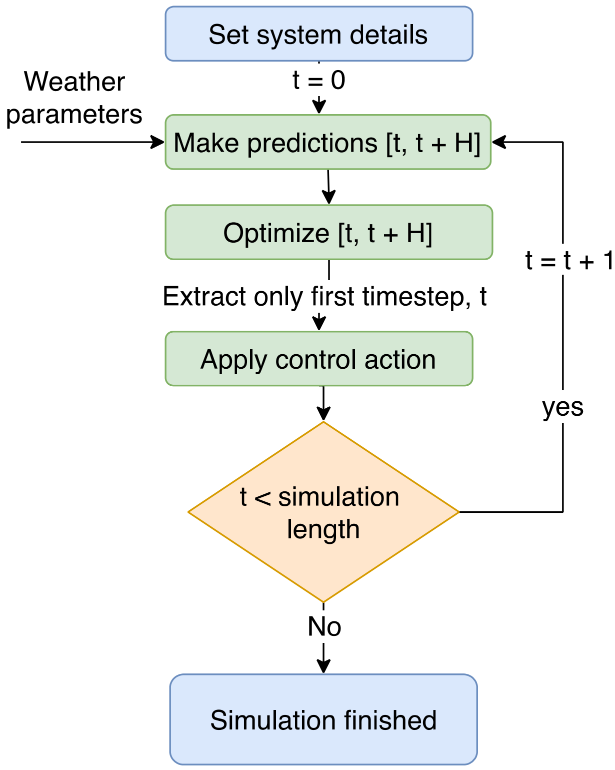
Approach

A case study is conducted on Rye microgrid in Norway, developed by TrønderEnergi. Predictions of the power from photovoltaic panels, a wind turbine and a load are made. The storage units in the microgrid are a battery energy storage system and a hydrogen energy storage system (electrolyser, tank and fuel cell). A diesel generator set is also included for backup. Two control system designs are implemented in python: one base case (the current control) and one new predictive design. A full year simulation with hourly resolution is performed with both control systems, and their performance compared.



Model

The new design is inspired by Model Predictive Control. Power predictions are made, based on basic machine learning concepts. The prediction models are trained on historical measurements of environmental data and time stamps. In every time step, the predictions are made for a certain control horizon. These predictions are input into an optimisation, that is executed to determine the power of all involved components. The first time step of the optimisation result is applied to the microgrid. In order to do so, a balancing of powers is done, to make up for inaccuracies in the predictions. The process is repeated for every hour of a year.



Results

The power predictions had a varying accuracy, the Normalised Root Mean Square Error was (among other parameters) used to evaluate the models. Solar panel (PV) predictions had an error of 2.54%, the wind turbine model an error of 5.34% and the load power an error of 6.88%. However, due to a limited amount of data in this analysis, these are likely to be unrealistically accurate. When comparing the new operational design to the base case the diesel consumption is heavily reduced. The amount of energy delivered by the diesel generator is 48.71% lower with the predictive approach. The run time of the algorithm is reasonable and the new operational strategy makes the microgrid more independent.

Conclusion

The results clarify the importance of having a good control system. The predictive control greatly influences the operation, and having an objective function makes the system strategy easy to alter. Comparing the developed model with the existing model, the energy supplied by the diesel generator was reduced by 48.71%. This brings the microgrid closer to meeting its goal of limiting the diesel dependence.

As a consequence, changing the operational strategy may have an impact on the microgrid success. It could be considered a valuable design feature in new and established microgrids. The final hope is for this thesis to contribute to renewable energy being available, even in remote locations.

Electric field distribution in layered polymeric HVDC insulation

Student: **Jens Fredrik Lunde**
Supervisor: **Frank Mauseth**
Co-supervisor: **Øystein Hestad**
Collaboration with: **SINTEF Energy Research (LowEmission Research Centre)**

Problem description

With an increased prevalence of HVDC cables for long range power transfer, the issue of trapped charges in DC applications becomes a greater problem. The trapped charges, called space charges, arise when a medium is stressed under DC conditions for long periods of time. As the discharge of the trapped charge depends upon the depth of the trap, the charge can remain in the insulation for long periods of time, even with no applied voltage. If the resulting field due to the trapped charges combined with the applied field exceed the breakdown voltage of the cable, a failure of the cable arises.

The task

The focus of the project is to measure trapped charges in layered cross-linked polyethylene (XLPE) samples using the Pulse Electro-Acoustic (PEA) method. The samples are layered to mimic a cable joint/termination as these are considered a weak point of a cable. One of the layers of the sample is cross-linked once, while the other is cross-linked twice. This is to create a discrepancy of the conductivity between the layers to facilitate charge build-up. The effect of temperature has on the trapping of charges is the main focus of the project. The applied voltage over the samples are 10 kV, while the ambient temperatures are 20, 40 and 60°C. Finally, the viability of using an equivalent RC-circuit to represent the resulting field development is evaluated using calculations and simulations.

Model/ measurements

The samples are mounted in a climate chamber to regulate the ambient temperature alongside a measurement electrode and a sensor electrode belonging to the PEANUTS (Pulsed ElectroAcoustic NondestrUctive Test System) used for measurements. The raw signal is recorded by the sensor electrode and sent to an amplifier. The amplified signal is sent further to the oscilloscope which displays the signal. The signal is recorded by a computer connected

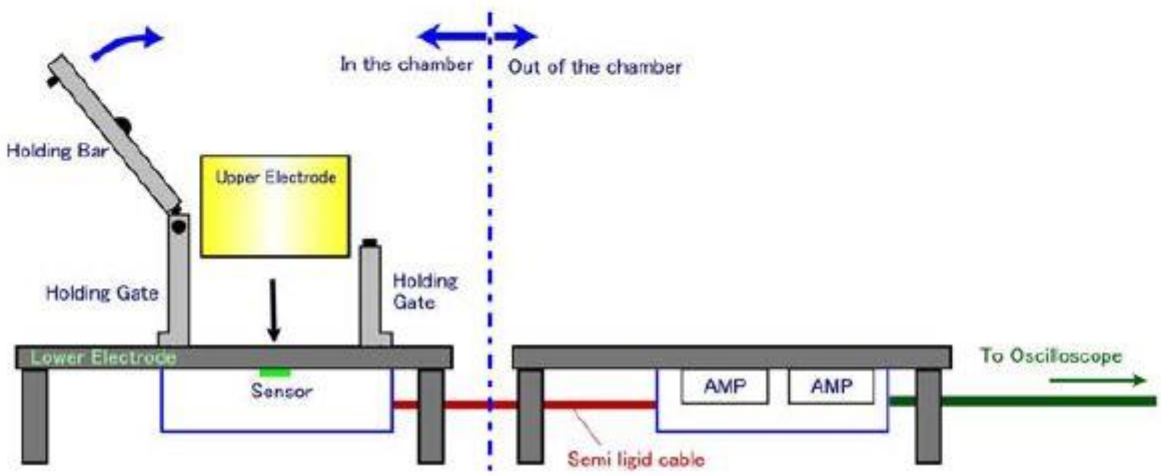


Figure 1: Representation of the measurement setup. Figure courtesy of the PEANUTS combined manual by FiveLab.

to the oscilloscope. Data processing and analysis is performed in MATLAB. The RC circuit consists of six parallel RC components in series. Each parallel branch corresponds with a section of the sample. The circuit is created and simulated using Simulink and compared with the measured results.

Results

The measurements revealed that homocharges (charges with the same polarity as the adjacent electrode) always accumulated at the anode regardless of temperature, while heterocharges (charges with opposite polarity as the adjacent electrode) accumulated at the cathode after a while. The charges at the cathode initiated as homocharges at 20 and 60^{o}C and changes polarity to heterocharges, while at 40^{o}C only heterocharges could be observed. At the dielectric interface, charges of opposite polarity as the applied voltage could be observed regardless of temperature, while more charges with the same polarity as the applied voltage could be observed with increasing temperature. More charges were trapped at 40^{o}C than at 20 and 60^{o}C. This may be due to the space charge formation rate increasing slower than the charge detrapping rate with increasing temperature. This means that the amount of trapped charges increases up to a certain temperature, after which the accumulation would begin to decrease.

The RC-equivalent circuit generally predicted the field distribution of the samples correctly, however at higher temperatures more mechanisms were observed in the field development which reduced the accuracy of the model. This meant that the model was quite accurate at 20^{o}C, but failed to predict the development rate of the field at 40 and 60^{o}C to a certain extent. More RC components could be added in parallel to the circuit in order to rectify this, however at the cost of making the model significantly more complex.

Conclusion

Increased charge accumulation in layered XLPE samples was observed at 40^{o}C compared to 20 and 60^{o}C. This may be due to the space charge formation rate increasing slower than the charge detrapping rate with increasing temperatures. This may in turn be due to increasing mobility of the charge carriers with increasing temperature. Other mechanisms such as the charge injection, sample morphology, charge transport in the samples and electrode material may also affect the charge accumulation. As all these mechanisms affect the samples at the same time, the system is regarded as quite complex and attributing the charge accumulation to a specific mechanism is difficult.

The RC circuit generally predicts the field development of the samples well at low temperatures, however as more mechanisms can be observed at higher temperatures the model fails to predict them and loses accuracy.

Price formation and market balancing in a local flexibility market using Model Predictive Control

Student: **Hannah Magnussen**
Supervisor: **Olav Bjarte Fosso**
Collaboration with: **FME CINELDI**

Problem description

Flexibility is broadly defined as the willingness and ability to change production or consumption. A market platform is proposed as a mean of accessing flexibility in an effective and economically efficient manner. An ongoing discussion addresses optimal price formation in such local flexibility markets. Optimal price calculation is related to minimising balancing costs and resolving capacity issues in the grid.

The task

Further investigate the potential for a future realisation of flexibility markets through developing an exemplified local platform for flexibility exchange, by using the Model Predictive Control (MPC) methodology. The example system is illustrated in Figure 1. The market model's performance is analysed through two physical situations. An assumed, small-scale energy community is subject to the example analyses. Finally, the market design will be assessed from the perspective of possible improvements and alternative extensions.

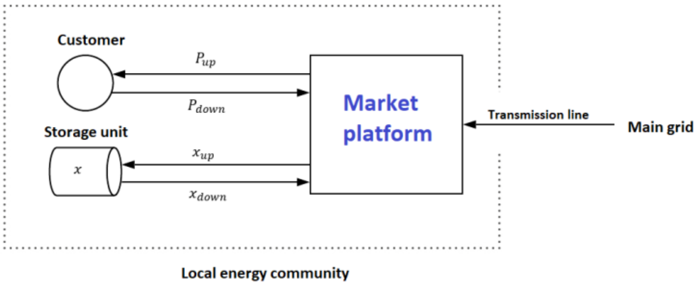


Figure 1: Example system for local flexibility market, with a single customer and a single storage unit.

Model/ measurements

The market algorithm is programmed in Python by using the linear programming package Lpsolve. The proposed design is based on the methodology called MPC. In the centre of this approach lies the ability to predict information based on system behaviour and historical data. This way, the market can arrive at optimal decisions for the present, based on anticipated system development. An important parameter in this methodology is the prediction horizon, *h*.

The market platform determines the market balance through optimising the use of resources over time, thereby achieving an optimal flexibility dispatch and local electricity price in every time step. The market algorithm consists of an optimisation problem being executed every hour, and for a set of hours into the future. A local price is found by determining the shadow price of the energy balance constraint in the optimisation problem, hence computing the marginal worth of an additional unit of electricity demanded in the community.

Simulation tests were performed for a 24-hour day. Two different situations were chosen; normal operating conditions, and a day where an outage causes reduced transfer capacity in some hours.

Calculation

In Figure 2, local price curves for h = 2, 6 and 12 are plotted against the assumed price curve in the distribution grid. These are assessed alongside the optimal schedule for flexibility activation computed by the market. The selection of a prediction horizon strongly affects the timetable for flexibility activation, and thereby the balancing costs in different parts of the day. A market algorithm with a somewhat short prediction horizon (h = 2) has a limited overview of the upcoming load profile, hence less opportunity to schedule flexibility long-term. A market algorithm with a somewhat long prediction horizon (h = 12) produces a more evenly distributed flexibility dispatch, including preparation for anticipated capacity issues.

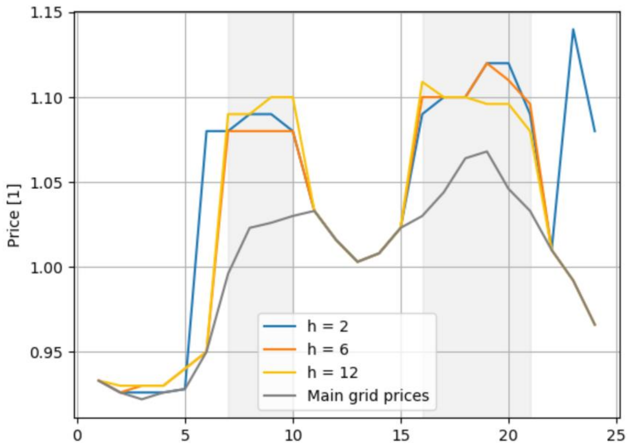


Figure 2: Computed local price curves for h = 2, 6, 12. Normal operating conditions.

These indications become even more visible when analysing a day where the grid faces a four-hour outage arising in hour 09, as in Figure 3. Both profiles jump to a higher price when the fault occurs. However, when long-term preparation is possible, computed price sets show the least volatility, even when an unforeseen event occurs. The price curve for h = 12 is therefore more even than for h = 6. When optimising for only a few hours at a time, on the other hand, the fault becomes difficult to handle, hence forcing the utilisation of any currently available resources. This can induce sudden and high price peaks, i.e. less predictable electricity bills for customers. For example, the curve for h = 6 has a high price peak in hour 20.

Even though the market algorithm produces the most economically efficient results when it is scheduling flexibility for the longest set of hours, this might still not always be the optimal choice. For example, when distribution grid prices are difficult to predict, there is no use in making long-term plans. Also, when unexpected events occur close to real-time, already performed computations are wasted and must be redone.

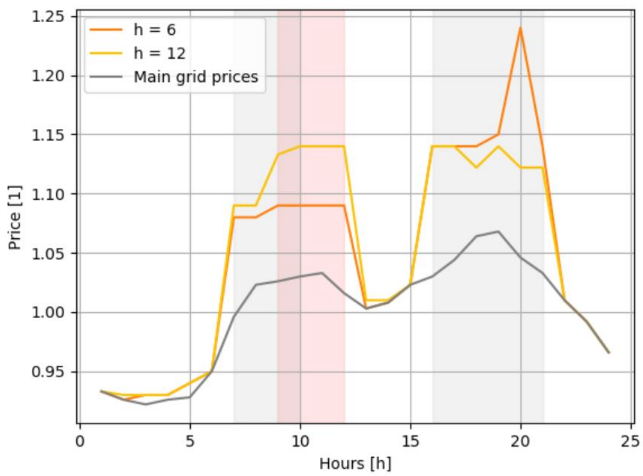


Figure 3: Computed local price curves for h = 6, 12. Reduced capacity in hours 09-12.

Conclusion

A general experience from the thesis work is how MPC can be a useful method in relation to flexibility market balancing. With for example Advanced Metering Systems (AMS) there will be more information on which to base predictions about future load curves. As for flexibility markets in general, there is definitely a potential to utilise flexibility for both balancing and grid purposes. Since the formation of an efficient market platform requires many participants to be active already from the beginning, the initial start-up phase might be the most challenging. However, the example analyses performed in this thesis indicate a significant potential once a market-based flexibility platform is in operation.

Partial Discharge Testing and Prediction Modelling at High DC Voltage

Student: **Jaume Martí Cascalló**
Supervisor: **Frank Mauseth**
Co-supervisor: **Pål Keim Olsen**

Overview

Internal partial discharges can be the cause of irreversible insulation degradation in High Voltage components, which can ultimately cause breakdown. Furthermore, they could become a condition indicator of the components, hinting a possible accelerated ageing due to other degradation mechanisms. Thus, acquiring a better understanding of the Partial Discharge mechanisms is of great interest. AC Partial Discharges have been widely studied, whereas DC Partial Discharges are a lesser-known phenomena.

The main purpose of this thesis is to provide a better understanding of the DC Partial Discharge behaviour. In order to achieve theoretical and practical comprehension, computer modelling and laboratory experiments were carried out during the present thesis. Two High Voltage DC Partial Discharge prediction models were developed and two different cavity sizes were compared for each model. The first model was based on the deterministic theory and the second model was created considering a stochastic starting electron generation rate. Both models were based on the ABC circuit model for internal partial discharges from voids in the insulation.

The laboratory work consisted of improving the sensitivity of an existing Partial Discharge measuring set-up and performing Partial Discharge measurements in polyethylene terephthalate (PET) samples with different size disk-shaped cavities in the centre of the test object employing the improved set-up.

Concordance among the experiments, the High Voltage DC stochastic model and the theory for the time between discharges (*tbd*) behaviour was found. The time between discharges increases with decreasing cavity diameter due to smaller starting electron generation rate for flat cylindrical cavity geometry. The discharge magnitude was shown to have a similar trend as the time between discharges, thus with a decreasing cavity size the discharge magnitude increased.

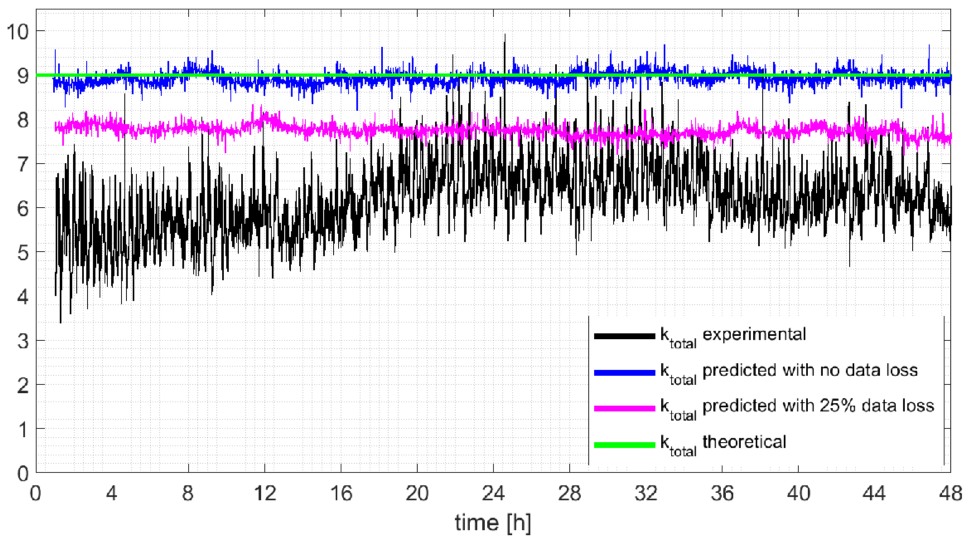


Figure 1: k_{total} found experimentally at 77 °C compared with the predicted value from the stochastic model with and without data loss and the stochastic theoretical value.

Conclusion

The conclusions extracted from the results and the discussion in this thesis are presented as follows:

- A successful set-up for measuring Partial Discharges under DC has been achieved and Partial Discharge measurements for High Voltage DC have been performed with the improved set-up.

- High Voltage DC Partial Discharge prediction models have been successfully generated in Matlab for a relative comparison of different cavity sizes following the deterministic and the stochastic theories.

- A correlation between the cavity diameter and the time between discharges has found to be present during the laboratory tests, with a similar behaviour as predicted in the models and presented in the theory. When the cavity diameter is smaller, the starting electron rate is smaller, therefore the time between discharges increases. For the bigger diameter a similar behaviour has been observed, since a bigger cavity has a higher starting electron generation rate, thus the time between discharges decreases. The High Voltage DC deterministic model is unsuccessful at describing the behaviour, however the High Voltage DC stochastic model provides a proper relative prediction, with a similar behaviour but distinct value.

- The discharge magnitude has a similar behaviour as the time between discharges regarding the cavity diameter. For a decreasing cavity diameter, the discharge magnitude increases in view of the fact the starting electron generation rate decreases. The High Voltage DC stochastic model and the experimental results are in consonance. However, the experimental results differ in the magnitude of this correlation.

- The temperature affects the time between discharges and the discharge magnitude. A reduction in temperature reduces the conductivity of the PET, thus increasing the time between discharges and the discharge magnitude. A prudent approach has to be taken for this conclusion, considering when the different temperature tests were performed, the nature of the cavities was intrinsically different and the limitations from the measuring devices were also a factor.

- From the two High Voltage DC models created for this thesis, the stochastic model has provided a more accurate relative prediction of the analysed parameters to the laboratory results than the deterministic model, even though it is not possible to have an absolute comparison between the models and the empirical tests.

- The nature of the samples used for measuring DC Partial Discharges were different for each test object, which hindered the reproducibility of the experiments.

Control Design of a Low-Cost Hybrid Converter for HVDC Connection of Offshore Wind Farms

Student: **Mona Martinsen**
Supervisor: **Olimpo Anaya-Lara**
Contact: **Raymundo Torres-Olguin**
Collaboration with: **SINTEF**

Problem description

Offshore wind farms are more and more often connected to the grid through HVDC. Until now HVDC links based on voltage source converters (VSC) have been used, but these are expensive and have high losses. In this thesis, a new topology for HVDC connection is investigated, based on a hybrid VSC-DR converter. The hybrid converter consists of a diode rectifier in series with a VSC is used on the offshore side. AVSC is used on the onshore side. The transmission system will be able to reduce the cost and improve the efficiency, and the system can still be controlled by the VSC. This thesis investigates the feasibility of this system and looks at challenges related to control design, harmonic cancellation and sizing of the VSC in the hybrid converter.

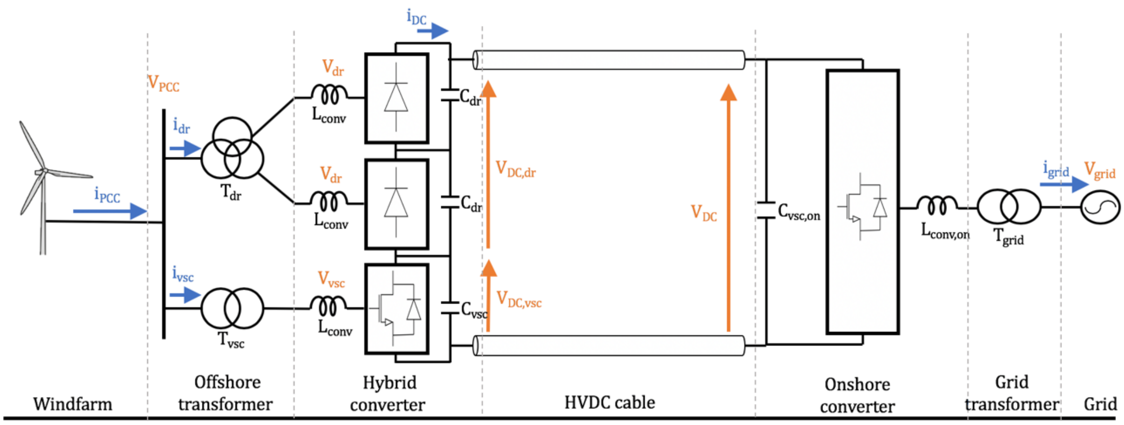
The task

The main objectives of this master's thesis are:

1.) To design a control system for both the offshore and the onshore VSC.
2.) To implement control loops for an active power filter in the offshore VSC to cancel harmonics from the DR.
3.) To make initial steps towards finding the optimal size of the VSC and the DR in the hybrid converter.

Model/ measurements

The offshore VSC controls the AC voltage in the offshore grid and indirectly determines the power balance between the DR and the VSC in the hybrid converter through the transformer design on the DR terminals. The control system is a cascaded voltage control with an inner current loop, and an outer loop for the AC voltage carried out in the synchronous reference frame. The control system also included SRF-based active power filter for the 11^{th} and 13^{th} harmonics. The onshore VSC is controlling the DC voltage in the HVDC link and the reactive power delivered to the grid, and the same method is used as in conventional VSC-HVDC.



Calculation
The system is fist tested when the VSC makes up 1/2 of the power rating in the hybrid converter. The simulations prove that the control system is able to fulfil all the control objectives in normal operating conditions, including variations in wind power and start-up of the wind farm. The active power filter is able to eliminate the filtered harmonics completely. The size of the VSC is then reduced to 1/4 of the active power rating, which is calculated to be the optimal size for minimizing the apparent power rating of the VSC. The system is still able to fulfil the control objectives, and the active power filter is able to cancel most of the 11th and 13th harmonic component.

Conclusion

The proposed system topology and the control system is working, and this indicates that a hybrid VSC-DR converter could be used in offshore wind integration. The system is only tested during normal operating conditions, and more work will be needed in the future to test fault conditions. The size of the VSC is important because it determines the cost-benefit of using this transmission system over the VSC-HVDC, which is used today. In this thesis, the size of the VSC is reduced to 1/4 of the hybrid converter rating. This is smaller than what has been suggested in earlier studies, where 1/3 have been the smallest. This is a very promising result, which could indicate that the cost-benefit can be more than earlier anticipated.

Contribution of Energy Storage to Generation Adequacy

Student: **Håvard Dahl Mediaas**
Supervisor: **Vijay Venu Vadlamudi**

Summary

The objective of this thesis is to evaluate the contribution of battery energy storage systems to generation adequacy by applying Monte Carlo simulation and capacity value quantification. As a response to the increasing global energy demand and environmental problems, the installed wind power capacity has grown rapidly over the last years. The intermittent characteristics of wind challenge the reliability of the power system. With the recent advances in battery technology, battery energy storage systems may be an essential key in exploiting wind energy. Probabilistic power system reliability studies, a highly developed field for evaluating reliability of power systems with uncertain behaviour, are needed for efficient planning of complex power systems, especially the ones with high penetration of renewable energy resources. The introduction of intertemporal characteristics due to the presence of renewable energy resources and battery energy storage will introduce new considerations to the reliability assessment, requiring sequential Monte Carlo simulation techniques. This thesis explores these aspects.

The thesis focuses on incorporating quantification of capacity value in generation adequacy assessment of power systems consisting of traditional and wind power generation with the inclusion of battery energy storage systems. Probabilistic generation adequacy indices (LOLE and EENS)[1] are applied to obtain the capacity value metric ELCC[2]. The algorithmic approaches for calculating ELCC have been implemented in existing indigenous MATLAB scripts for generation adequacy assessment using the Monte Carlo state transition simulation method, while scripts for wind speed sampling, and battery energy storage modelling together with operation strategies have been developed. The scripts are tested on two test systems - the Roy Billinton Test System (RBTS) and the IEEE Reliability Test System (RTS).

Four different energy storage operation strategies and two methods of calculating the ELCC metric are evaluated. It is clearly observed that strategies aiming to improve the system reliability provide considerably higher capacity value of battery energy storage systems. Due to EENS considering the severity of LOL[3] events rather than the mere occurrence of LOL, it was found that the EENS is the preferred method of obtaining the ELCC.

[1] Loss of Load Expectation, Expected Energy Not Served
[2] Equivalent Load Carrying Capability
[3] Loss of Load

Analysis of Micro Hydropower Plant Connected to Microgrid in Island Mode Operation Consisting of Pump-as-Turbine, Self-Excited Induction Generator and Induction Generator Controller

Student: **Ragnhild Petterteig Mo**
Supervisor: **Elisabetta Tedeschi**
Co-Supervisor: **Trond Leiv Toftevaag & Torbjørn Kristian Nielsen**

Abstract
The aim of this thesis have been to analyze a cheap, robust, and simple micro hydropower plant consisting of a pump-as-turbine (PAT), a self-excited induction generator (SEIG) and an induction generator controller (IGC) connected in an islanded microgrid, supplying a varying single-phase village load. The long-term aim has been to prepare the evaluated system for implementation in decentralized villages in developing countries without connection to the main grid.

Some of the main obstacles when using an induction generator (IG), directly connected to an uncontrolled PAT, in stand-alone operations in an islanded microgrid are the difficulties of determining the excitation capacitance requirements, as well as ensuring stable voltage and frequency as the village load connected to the system varies. The objective of the IGC is to ensure a constant total consumed power seen from the generator, by dissipating surplus power to a ballast load, for the purpose of keeping the voltage and frequency deviations within a limited range. The necessary theory of the different components of the evaluated system is presented. The operating conditions of the tested system were defined so that it could be tested with the components which was already selected. Additionally, the power quality requirements of the microgrid were defined, under the assumption that the village load is purely resistive.

The IGC was first tested in the Electrical Machine Laboratory at the Norwegian University of Science and Technology (NTNU) without the PAT, to characterize its behavior. Thereafter, the whole stand-alone system was tested in the Waterpower Laboratory at NTNU, with the PAT as the prime mover. A simulation model of the tested system was also created in the Simscape environment in Simulink and MATLAB, for the purpose of verifying the laboratory test results. By creating a realistic, yet simplified simulation model, the system can, as further work, be analyzed for different topologies and with different parameters, for instance for other load power factors or with distribution lines.

The three-phase IG used, is converted to a single-phase IG by connecting the excitation capacitors in a C-2C connection. Depending on the operating frequency and the operating voltage, there exists one total load power ensuring a balanced operation of the generator in such a connection. The operating conditions for the tested system were therefore set mainly for obtaining a balanced operation of the IG. Both the laboratory tests and the simulations show that the tested system is able to supply a single-phase resistive load within the voltage and frequency requirements defined for the tested isolated system, at the defined operating conditions. However, the components used are not optimal. The test results show that the excitation capacitors integrated in the IGC cabinet are oversized. Both the PAT and the SEIG were operating in overload. The PAT has to operate far from the best efficiency point (BEP), because the BEP at the required head, is at a speed which is much higher than the operating speed. However, the behavior of the PAT seems good. As a result of the overloading of the generator, the line currents were measured to be up to 43 % higher than the rated current

during the laboratory tests. This results in extra power losses and a significant reduction of the efficiency. Overloading also result in a lower expected lifetime of the SEIG, which would contradict the requirement of robustness of the system.

Another concern for the tested system is that the IGC does not manage to ensure exact 230 V across the village load, thus it does not manage to ensure constant power seen from the generator, when the village load is varying. Due to the characteristic of the PAT and the IGC, both the frequency, voltage, and total load power increases when both the village load and the ballast load are consuming. This results in an unbalanced system and a further increase in two of the generator line currents. However, the voltage variation is only measured to be 2.6 % from the rated voltage, 230 V. The maximum frequency deviation is measured to be 6.6 % from the rated frequency 50 Hz, but the system frequency is never below 50 Hz. Because of the phase angle control method of the IGC, there are significant harmonics in the signal when both the ballast load and the village load are consuming. The maximal total harmonic distortion (THD) of the village load voltage and village load current is found to be 4.34 % and 4.33 % respectively. This is also within the power quality requirements defined.

Both the laboratory tests and the simulations show that the tested system, consisting of the pre-selected PAT, the pre-selected three-phase SEIG and the available IGC, is able to supply a varying single-phase resistive load within the voltage and frequency requirements defined for such isolated system, at the operating conditions defined. However, it is proposed to either reduce the excitation capacitor size in the IGC or that the SEIG in the tested system should be changed to a SEIG with a different magnetizing curve or higher rated current, in order to reduce the overloading of the SEIG and increase the efficiency.

Evaluating pathways for hydrogen produced from low-carbon energy sources

Student: **Marius Moldestad**
Supervisor: **Magnus Korpås**

Drastic measures are required in the transformation of the European economy towards climate neutrality, and hydrogen is expected to play an integral part in the decarbonisation process, with a political climate growing in favour towards the expansion of hydrogen-based technologies. This master’s thesis has the objective to analyse the influence of large-scale deployment of hydrogen in a future European multi-energy carrier system. The analysis is conducted with the use of a least-cost capacity investment model developed for this purpose, which co-optimises investments in electricity generation and hydrogen production infrastructure. The model is applied to a developed scenario in 2050, comprising of the North Sea countries aggregated into nodes.

The main findings are that hydrogen produced from electrolysis is the dominant production pathway, with 65 % of the production share in the base scenario. The deployment of a CO2 price of 60 €/t, favours CCS-based H2 production from steam-methane reforming (SMR), constituting the remaining share. Storage facilities see high utilisation, as 30 % of the electrolytic hydrogen is transported via storage before consumption.

The combination of technology cost-reductions and hydrogen production integration effectuates deployment of large shares of onshore and offshore wind. The system flexibility provided by the integration of hydrogen production and storage in the energy system is found to increase the net share of renewable energy sources (RES) in the electricity mix from 63.5 % to above 70.9 %, reducing CO2 emissions by 6 million tonnes.

Moreover, the CO2 price is found to be highly influential of the energy and hydrogen production mix, as CCS-technology is introduced in power generation at 30 €/t CO2, and in SMR between 30 and 60 €/t CO2.

The average hydrogen production price is estimated between 1.57 and 2.6 €/kg, with price levels seen between 1 €/kg and 2.6 €/kg for varying future electrolyser and renewable energy costs.

The system is also found to be significantly impacted by natural gas prices, with a 38 % share of power generation from fossil fuels at a 50 % price reduction from the base case natural gas price of 11.5 €/MMBtu, with no CO2 cost. The cost parity between electrolysis and SMR with CCS is found at a price natural gas price around 8.1 €/MMBTU with a CO2 price of 60 €/t.

The study should be complemented with research of higher temporal and spatial resolution, considering additional hydrogen pathways, to provide more robust results.

Nonetheless, the findings indicate that integrating large-scale hydrogen production into the energy system can facilitate renewable energy penetration and that the deployment of a CO2 price is a pivotal measure towards decarbonisation.

FPGA-Based Real-Time Emulator of Permanent Magnet Synchronous Motor

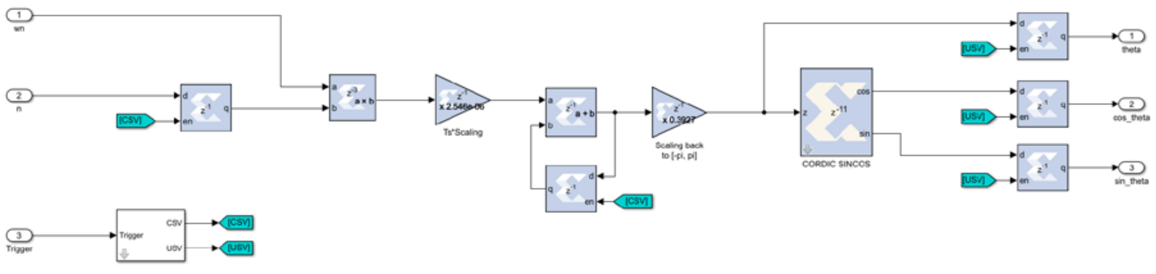
Student: **Anders Moldskred**
Supervisor: **Roy Nilsen**
Co-supervisor: **Aravinda Perera**
Collaboration with:

Problem description
Real-time emulation of motor drive systems allows for development and testing of digital drive control systems without requiring any hardware test setup, which reduces the cost and equipment needed for development. With advancements in FPGA technology and high-level synthesis tools for HDL programming, this is becoming an increasingly popular and accessible development tool for motor drive control systems.

A common control platform for motor drive systems is under development at the Department of Electric Power Engineering at NTNU, called the NTNU Control Platform. The platform hardware is made up of a control board from Avnet and a process interface board developed by SINTEF. The control platform software consists of a drive routine which runs on a CPU and is written in C++ and an FPGA, which is programmed using Vivado. Vivado is a programming tool developed by Xilinx which lets the user develop IP cores for the FPGA without having to learn hardware description languages, such as VHDL.
This control platform is intended to serve as a foundation for future master and PhD projects in the field of electric motor drives.

The task
The aim of this thesis is to develop and test IP cores for use in a real-time emulator of a permanent magnet synchronous motor. The IP cores are developed using Xilinx System Generator for DSP and tested in Simulink. These IP cores will in further work be implemented as part of a complete real-time emulator of a PMSM drive system, running on the NTNU Control Platform.
IP cores for simulation of both three-phase and six-phase PM synchronous motors as well as mechanical load are designed. The IP cores are tested by implementing them in previously developed Simulink models for three-phase and six-phase motor drive systems, replacing the continuous-time Simulink motor and mechanical load blocks. The outputs from the models containing the discrete-time IP cores are compared to the original models, which are used as reference. The motor torque and speed outputs from the models using the System Generator IP cores are compared to the outputs from the reference models to test the accuracy and performance of the IP cores.

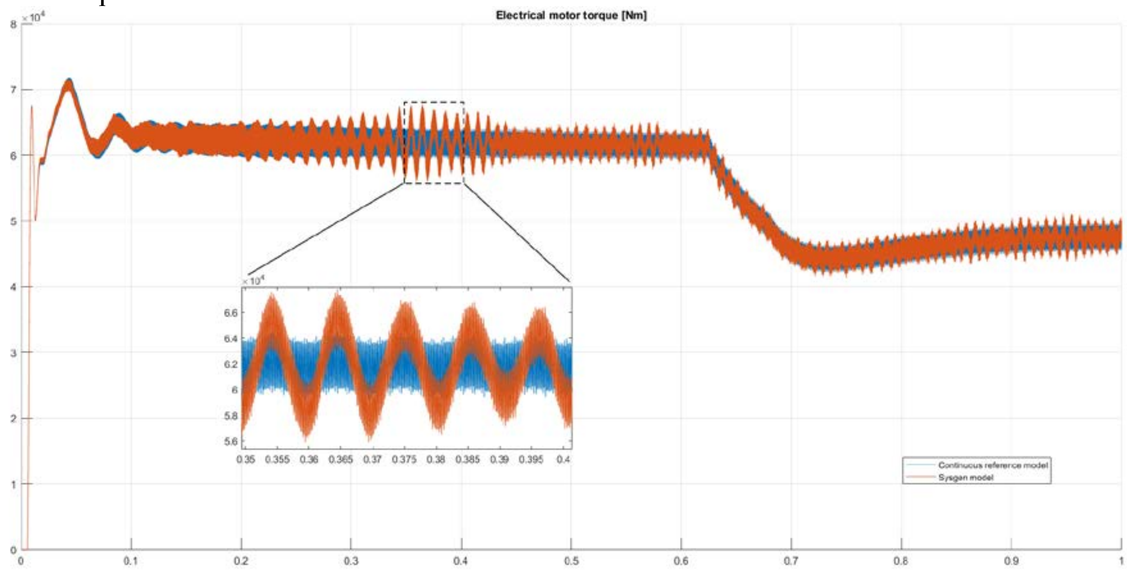
Model/ measurements
In order to model the PM motors and mechanical load, the dynamic behaviour of the systems is described as a set of first order differential equations. These equations are then discretized using the Forward Euler method and implemented in System Generator IP cores. In addition to these, IP cores for calculation of rotor angle based on motor speed and transformation between stator reference frame and rotor reference frame are designed.



1: System Generator IP core for calulation of electrical angle and sine cosine of angle based on motor speed

Calculation

The electrical torque, mechanical load torque and speed of the models are compared to test the performance and accuracy of the discrete-time IP cores, as shown for the six-phase model motor torque below.



2: Electrical torque plot of 6-phase continuous reference model and SysGen model

Conclusion

The results from the simulations show that the three-phase motor drive system model containing the discrete-time IP cores perform very similar to the continuous-time reference model. In the six-phase model however, there are some oscillations in the electrical torque of the IP core model which are not present in the reference model. The amplitude of the oscillations is reduced by reducing the discrete sampling time on the IP cores.
Increasing the FPGA clock period from 10ns to 100ns, thereby reducing the clock frequency, also seem to dampen the oscillations somewhat. An analysis of the eigenvalues of the motor models show that the discrete system is stable, but may be poorly damped. Comparing the frequency of oscillations to the damped frequency of the eigenvalues at different motor speeds, it is found that they are similar, which indicates that the oscillations are linked to the eigenvalues.

Analysis and Implementation of Energy Management System on Concept Design of Gløshaugen Microgrid

Student: **Syed Mohammad Mujtaba**
Supervisor: **Irina Oleinikova**

Problem description

Distributed Energy Sources (DERs) have been the focus of the modern power industry as they are proven to be a more efficient and reliable source of energy supply. Renewable Energy Sources (RES) and other DERs are integrated into the grid at the distribution level to set up a Microgrid (MG). The main objective of this thesis was to develop a concept design of NTNU Gløshaugen campus as a microgrid; implement energy management system with PVs and batteries to achieve peak-shaving; and improve the stability of the microgrid during load variations and after fault clearance. Data from the existing grid network was used to model the campus on ETAP-16. Time-based AC/DC Load flow and transient stability simulations were performed to analyze the system behaviour under different conditions. The burden on the utility grid was reduced significantly after the integration of PVs and batteries during peak hours. The adequate operation of batteries resulted in achieving a flat utility output power curve when the demand was high. The stability of the system was improved with the generator's exciter AVR control for the worst-case scenario. As a result, the bus and generator parameters were reaching their steady-state values within a reasonable time.

Dynamically Simulating Power Systems Using a Self-Adaptive Time Step Method

Student: **Erik-Anant Stedjan Narayan**
Supervisor: **Olav Bjarte Fosso**
Co-supervisor: **Jalal Khodaparast Ghadikolaei**

Problem description

The growing use of renewable energy sources and power electronic converters requires simulation tools capable of handling the increased system complexity. Gear's method has previously been shown to perform well for differential-algebraic equation (DAE) systems with ranging time constants, making it a promising candidate for dynamically simulating the future power system. Despite this, few published implementations exist, and strategies to improve the method have yet to be fully explored.

The task

The thesis presented a modeling of four separate power system cases with varying characteristics in terms of stability, size and complexity, saturation effects, topology changes and discrete system events, and degree of power electronic integration. Following this, Python implementations of Gear's method for each of the cases were developed, including comparisons with a commercially available DAE solver.

Implementation and Results

Figure 1 shows the simulation results of one of the investigated cases. The system consisted of three generators connected via a six-bus system to an infinite bus (3MIB), including two dynamic loads. The generating units each consisted of a synchronous generator, exciter, and hydro turbine and governor. Figure 1 shows how, by applying the appropriate improvement strategies, the performance and accuracy of the method could be improved notably. The result in Figure 1b was produced by the best performing strategy combination, namely, simply preventing the step length from changing more than for every 15 steps.

The remaining three cases consisted of a single generating unit connected through a transmission line to an infinite bus, two generators connected via a three-bus system to a load bus with a static compensator and dynamic load, and a multi-terminal direct current (MTDC) system consisting of three interconnected voltage source converters.

Conclusion

The method was shown to perform well for the three systems dominated by synchronous generators. In addition, of the examined strategies, fixing the step length for at least 15 consecutive steps was shown to result in the largest improvement in terms of performance and solution accuracy. However, the method failed to successfully simulate the investigated MTDC system. Even with the best performing strategy combination, Gear's method was unable to accurately capture the MTDC system voltages following a line outage.

To conclude, Gear's method performed well, both in terms of computational resource use and solution accuracy, for systems dominated by synchronous generators or with limited power electronic integration. If the poor results obtained for the MTDC system were a result of some underlying modeling nature of power converters, or simply a feature of the particular formulation used in the thesis, could not be concluded.

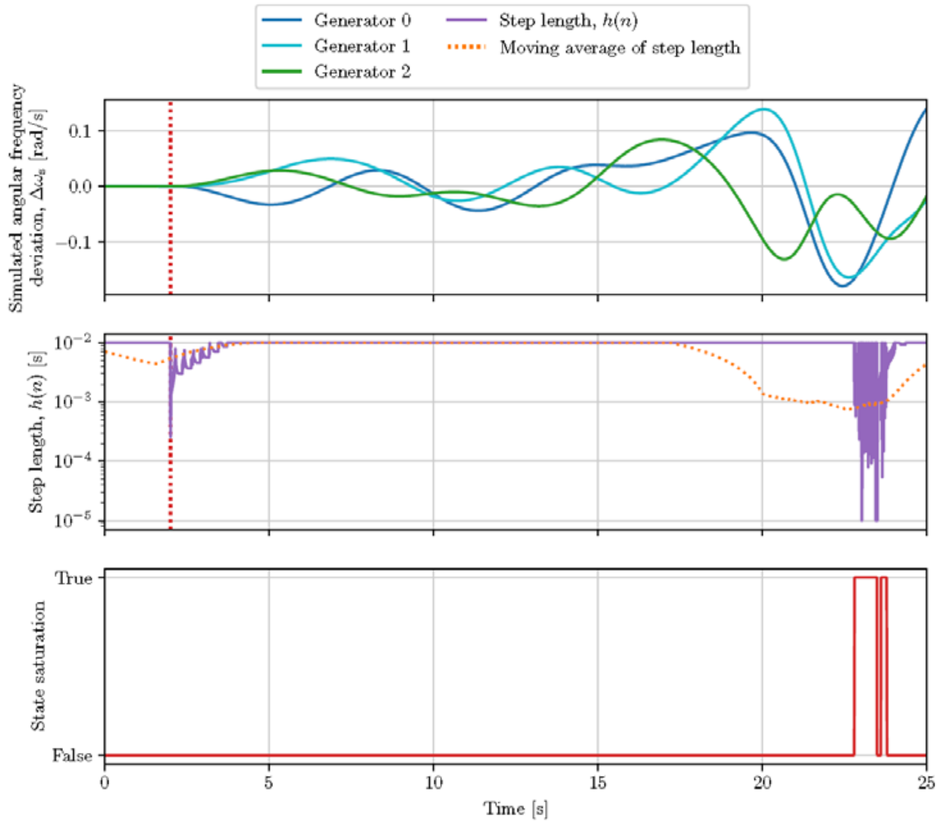


Figure 2a: *Base case simulation of 3MIB system for t ∈ [0, 25] s, with voltage reference change at t = 2 s. From top to bottom: Simulated state variable, step length, and indication if state saturation was enforced.*

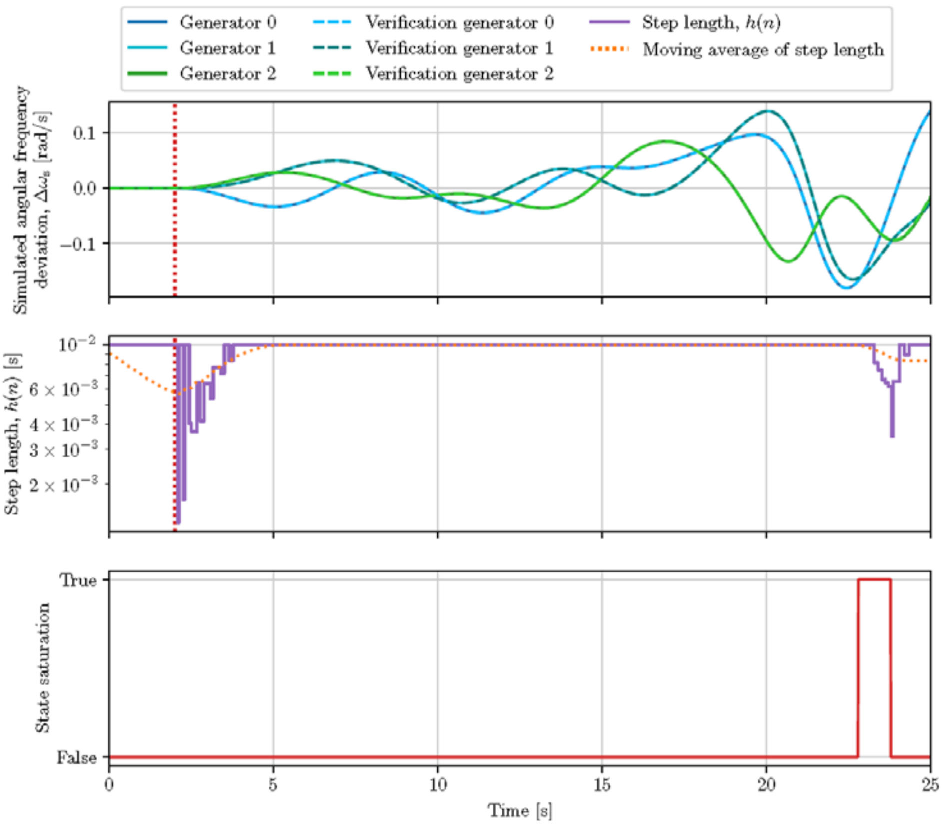


Figure 1b: *Overall best case simulation of 3MIB system for t ∈ [0, 25] s, with voltage reference change at t = 2 s and verification. From top to bottom: Simulated state variable and verification result, step length, and indication if state saturation was enforced.*

Introduction of Silicon Carbide in High-Power Converters Using a Hybrid Si-SiC Switch

Student: **Lars-Kristian Njåstad**
Supervisor: **Dimosthenis Peftitsis**
Contact: **Jonas Sjolte**
Collaboration with: **Siemens AS**

Problem description

The master thesis has investigated the use of wide bandgap (WBG) semiconductors in high-powered converters. In comparison to the traditionally used semiconductors, like silicon (Si), WBG semiconductors like silicon carbide (SiC) enable the production of devices with larger breakdown voltages, lower conduction losses, and faster switching. All of these attributes are desirable for use in high-powered converters, but because of the immaturity of SiC technology there are cost and reliability issues. These deficiencies makes full SiC integration a nonviable solution for the industrial market. Therefore, novel solutions, like the hybrid Si-SiC switch (HyS) seen in Figure 1 needs to be employed. The HyS consists of a parallel connection of a Si IGBT and SiC MOSFET. The Si IGBT takes care of the steady-state conduction, enabling the use of a low-powered SiC MOSFET as an auxiliary switch in order to handle the hard switching actions of the converter.

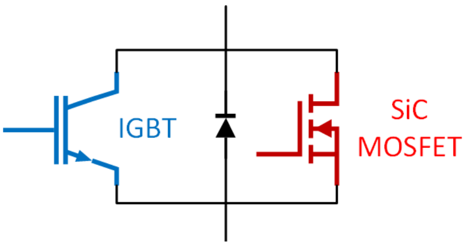


Figure 1: The Hybrid Switch

By using this configuration, the desirable features of SiC can be integrated into high-powered converters for a reasonable cost. Namely, increasing the switching speed of the converter is desirable as it would lead to a decrease in the size of passive components like inductors and capacitors, decreasing the bulk of the system. Therefore, it was deemed necessary to investigate the use of the HyS solution in a high-powered converter in order to establish if, and potentially by how much, the use of the HyS would increase the maximum achievable switching frequency, $f_{sw,max}$, of the given converter. Furthermore, the most pertinent practical challenges for realizing the HyS solution needed to be identified so that proper mitigation techniques could be put into place.

Model/ measurements

In order to verify the use of the HyS solution, the electrical and thermal performance of the HyS was assessed using simulations. Using the Simscape library in Simulink, the dynamic electrical performance of the HyS and its constituent components was assessed using a double-pulse test circuit. From these simulations, several approximations of the dynamic behaviour of the HyS that would be used during the thermal simulations were established. Then, steady-state analysis of the thermal performance of the HyS in a half-bridge converter was conducted using PLECS. During these simulations, a parametric sweep was conducted in order to assess how different operating conditions affected the $f_{sw,max}$ of the converter using the HyS solution

Results

The relationship between the $f_{sw,max}$ of the half-bridge converter and the respective swept variables is shown in Figure 2. The colour of the lines and/or markers indicates if the HyS was limited by junction temperature or power losses: If the line/marker is green, it was limited by power losses, while if the line/marker is orange, it was limited by the SiC MOSFET's junction temperature. The power loss limit is based on an IGBT in a half-bridge circuit with a switching frequency of 3 kHz.

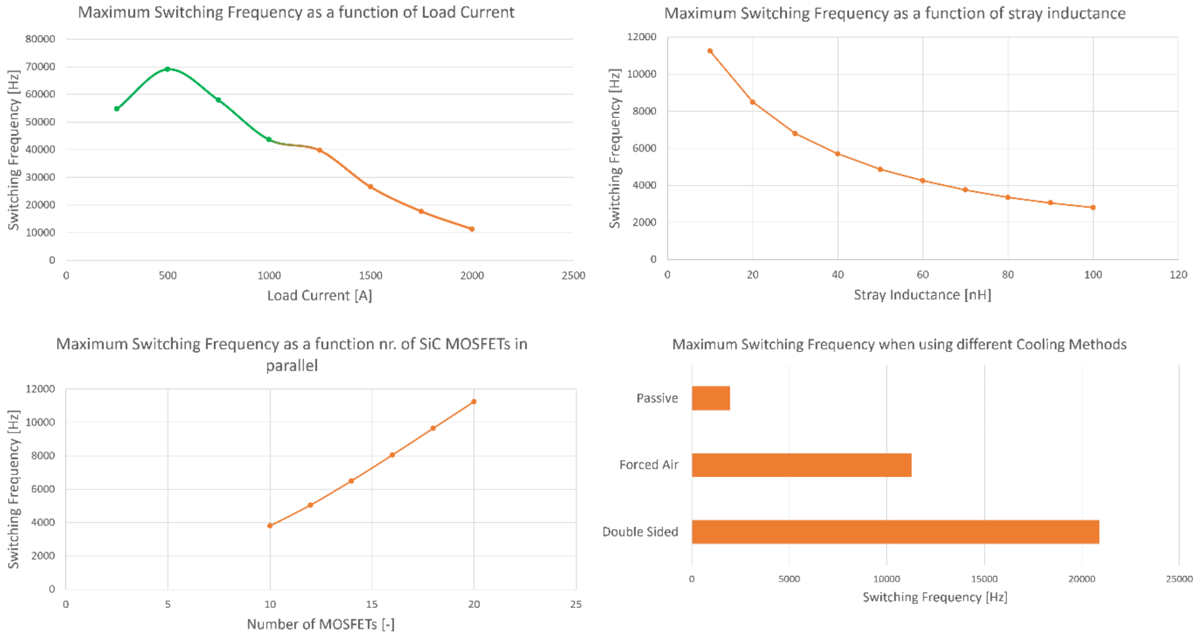


Figure 2: The results of the parametric sweep

Conclusion

The simulations uncovered that by using the HyS solution instead of a solo IGBT in a high-powered converter, $f_{sw,max}$ could be increased significantly. However, this was dependent on resolving several practical challenges, and therefore the thesis proposes a design process for an HyS custom module in order to combat the most pressing of these challenges. At the forefront of the custom module design challenges is parasitic inductance mitigation, since novel module design is required in order to reduce stray inductance to the levels necessary for the required HyS performance. This includes the use of planar interconnection techniques replacing the commonly used wirebonds. In addition, the low current ratings of commercially available SiC MOSFETs forces the use of several SiC MOSFET chips in parallel to reach the desired current rating. In a parallel connected configuration, it is essential to achieve as close to uniformly distributed current as possible in order to avoid thermal breakdown. Therefore, the tolerance for inductance imbalance between the parallel connected SiC MOSFETs becomes lower with increased switching frequency, since inductance imbalances leads imbalanced current distribution. This necessitates the use of extremely symmetrical module layouts in order to uniformly distribute the stray inductance of the module. Furthermore, the thermal management of the HyS is an important challenge, since the thesis found that $f_{sw,max}$ of the HyS was limited by the SiC MOSFETs' junction temperature at heavy-load conditions. This means that there is a potential for increased switching frequency if more efficient cooling is employed. Again, this requires the use of novel techniques, such as double-sided cooling, which is only possible if wirebonds are eliminated, and direct liquid cooling which significantly reduces the thermal resistance between the heat sink and ambient.

The Future of Fuel Cell Technology in Maritime Applications

Student: **Birger Nordvi**
Supervisor: **Kjetil Uhlen**
Co-supervisor: **Trond Toftevaag**

Collaboration with: **Kongsberg Maritime**

Abstract
From the industrial age through the age of oil, humankind has created immense advancements in production, technology and quality of life. Unfortunately, the progress has come at the expense of the environment; and the need is greater than ever before for environmentally friendly technology that can lead to an improved balance between the modern society and nature.

Fuel cell technology is a viable and future-oriented solution to providing environmentally friendly electrical power production, both in general and for maritime applications.

In this master thesis, an expansive theoretical review of fuel cell technology, in terms of the characteristics, possibilities and limitations of various fuel cell types and of potential energy carriers, is presented – both separately and from a broader recommendatory system performance perspective.

Hydrogen is a popular energy carrier for fuel cells, but an analysis of hydrogen energy carriers like Liquid Organic Hydrogen Carriers (LOHCs), metal hydrides, ammonia (NH_3) and methanol (CH_3OH) shows that many of the disadvantages of hydrogen, particularly low volumetric energy density and challenging storage requirements, can be alleviated or avoided by choosing more suitable energy carriers.

A case study of an offshore wind turbine constructing Service Operation Vessel (SOV) is included. The case study is based on computer simulations of a realistic SOV load consumption profile in a hybrid, carbon-neutral, solid oxide fuel cell powered microgrid, with an electric battery functioning as an Auxiliary Electric Storage Component (AESC) for peak shaving and transient load buffering. The simulations indicate the performance and feasibility of deploying fuel cells in microgrids in onshore and maritime applications, and also show the effectiveness of using batteries to compensate for the limited dynamic response capability of fuel cells. The case study is further supplemented with a sensitivity analysis, with respect to fuel cell rated power, to study the effect that fuel cell system sizing has on the electrical power production efficiency, energy carrier consumption, hybrid load sharing and battery system scaling.

Clustering of AMS-data

Student: **Stian Norheim**
Supervisor: **Eivind Solvang**
Co-supervisor: **Maren Istad, SINTEF Energy Research**
Co-supervisor: **Karoline Ingebrigtsen, SINTEF Energy Research / The Artic University of Norway**
Collaboration with: **SINTEF Energy Research**

Problem description:
The last years it has been a massive rollout of advanced metering systems (AMS) in Norway. This is a part of the modernization and digitization of the power grid and the rollout makes large quantities of AMS-data available. This AMS-data is suitable for Big-Data techniques and clustering is a Big-Data technique used to divide a dataset without external labelling information into groups with different characteristics.

The task:
This master thesis investigates clustering on AMS-data, and presents a solid foundation of clustering theory, AMS and useful background information to use the clustering results most efficiently. The thesis presents a comprehensive clustering analysis on four datasets using 6 different clustering algorithms and 5 data representation techniques. Validation of the results is done with three cluster validation indexes (CVIs) and manual inspection to insure robustness of the results. A comparison with the practice used today and an analysis of capacity in the grid based on AMS-data are also performed.

Model:,
The thesis tests and analyses three partitional algorithms, two hierarchical algorithms and a neural network (SOM). The data representation techniques are Z-transformation, Min-Max normalization (normalise values in the range [0,1]), Principal component analysis (PCA), discrete wavelet transformation and average load profiles. The CVI scores are used to find the optimal cluster numbers for each dataset, and the cluster quality is calculated for the algorithms and data representation techniques on the four datasets using the optimal cluster numbers.

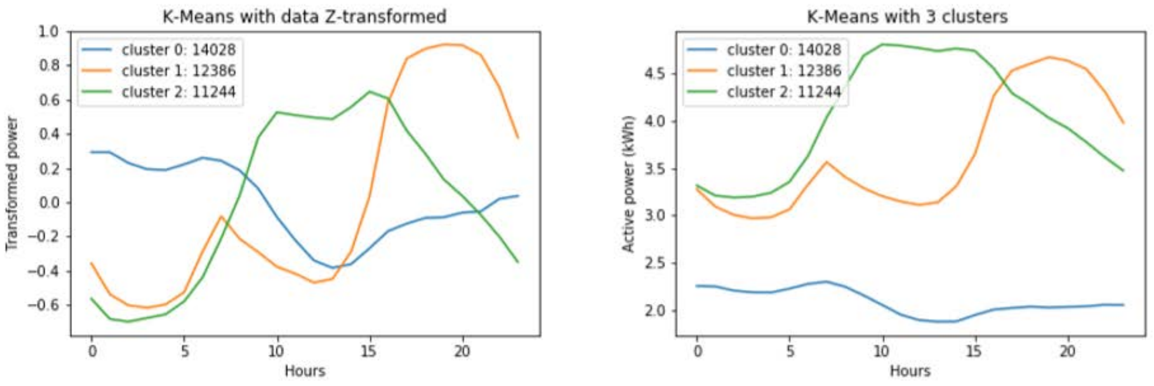
Calculation:
The results are shown in the figure 1:

Clustering approach	DB	SI	CH	Computation time
K-Means	1	1	1	11s
K-Shape	1,008	1,017	1,000	x57
K-Means + DTW	1,131	0,811	0,899	x1012
SOM	2,003	-0,559	0,123	x5
Hierarchical + single	1,109	-2,744	0,012	x52
Hierarchical + ward	1,277	0,444	0,581	x273
K-Means + PCA	1,027	0,962	0,989	x0,61
K-Means + wavelets	1,079	0,897	0,949	x0,56

Figure 1: Summary of results

The figure shows the three CVI indexes used, Davies-Bouldin (DB), Silhouette (SI) and Calinskz-Harabsz (CH). The lower DB value, the better clustering quality, and the higher SI and CH value, the better clustering quality. All the values are divided by the corresponding K-Means value. The clustering with Min-Max normalization and average load profiles use a different transformation of the dataset, which make the CVI scores not comparable. The clustering with average load profiles reduces the computation time with 95% on the datasets analysed.

Figure 2 shows a graphical representation of the results for one of the datasets using the K-Means algorithms with the data Z-transformed.



(a) Z-transformation representation **(b)** Original data representation

Figure 2: K-Means with 3 clusters on one of the datasets. Two different cluster representations.

Conclusion:

The results show that the partitional algorithms are the preferred choice. The old, simple and robust K-Means performs well and has a low computational cost. The K-Shape got similar CVI scores as K-Means, despite the CVI scores calculated being biased towards algorithms using Euclidean distance (ED) measures. The hierarchical algorithm using single linkage criterion shows interesting results, being able to isolate outliers. The data representation techniques show potential for a considerable reduction in time, and also clustering with different characteristics.

Analyse av lastendringer på nettstasjonsnivå som følge av solkraftproduksjon på privathus og næringsbygg

Student: **Mari Myrold Osnes**
Veileder: **Eivind Solvang**
Utføres i samarbeid med: **SINTEF Energi**

Sammendrag

Nettilknyttet solkraft har hatt en kraftig vekst i den norske solenerginæringen de siste årene. Det økende antallet plusskunder bidrar til en desentralisering av kraftproduksjonen, og kan skape utfordringer knyttet til kapasitet i fordelingsnettet.

Denne oppgaven har analysert lastendring på nettstasjonsnivå for to nettstasjoner i Stavanger-området. Forbrukskurver som inneholder gjennomsnittlig effektverdi per time fra Lyse Elnett er sammenlignet mot framtidig produksjon fra solanlegg. Solkraftproduksjonen baserer seg på tre ulike framtidsscenarier der ulike mengder kunder i Stavanger-området har solanlegg installert på eget tak. Gjennom en plusskunde fra Trondheim, som siden sensommeren 2019 har hatt eget solanlegg i drift, har det vært mulig å benytte reelle produksjonsdata fra et solanlegg. Disse dataene har blitt brukt som en referanse for kundene i Stavanger.

De ulike scenariene med solkraftproduksjon ga forskjellige utfall. Felles for alle scenariene er at plusskundene vil bidra til endringer i lastprofil. I timer med mindre produksjon enn forbruk vil produksjonen virke avlastende for nettet, og timene med overskudd av produksjon vil føre til større belastning på nettet. Det tredje scenariet skilte seg ut ved sammenligning av overproduksjon med merkeeffekten på transformator. For dette tilfellet vil det være henholdsvis 359 og 378 timer for nettstasjon 1 og 2 gjennom året der overskuddet av kraft vil overskride transformatoreffekt. Disse timene gjennom året med overskudd kan være utfordrende med tanke på potensielle overspenninger og overbelastning av linjer og transformator som kan skade komponenter i kraftnettet.

Mengden overskuddkraft som kan være utfordrende for netteiere er i stor grad avhengig av de ulike framtidsutsiktene. Her er det store variasjoner, men de aller fleste spår en enorm økning i installert solkraftkapasitet de neste 10-20 årene. Endringer i tariffer og kutt i støtte kan på den andre siden bremse utviklingen.

Agent-based modelling of EV charging scheduling towards optimized operation in Smart Grids

Student: **Manuel Pérez Bravo**
Supervisor: **Olav Bjarte Fosso**

Transport and energy sectors are source to the majority of greenhouse gas emissions in Europe. Electric vehicles are regarded as an effective alternative towards the optimisation of the transport energy efficiency, the introduction of low-emission energies, and the shift to zero-emission vehicles. Simultaneously, there is the need of accelerating the uptake of renewable energies, with a special focus on the electricity generation. Electric vehicles can indeed also contribute to their introduction, by making the demand more flexible and adding energy storage to the system, thus tackling the variability of some renewable sources such as wind or solar.

Nevertheless, the growing adoption of electric vehicles is not only an opportunity but also a challenge. A larger fleet of vehicles, together with the tendency of increasing their battery capacity and charging rates, compromises the safe operation of the distribution grid and limits its hosting capacity. With the purpose of avoiding the physical upgrade of the network, the concept of Smart Charging arises, aligned with the principles of the Smart Grid: integrating the behavior of all users to assure the economically efficient and sustainable operation of the power grid. Among the Smart Charging set of techniques, Smart Pricing seeks fostering an efficient charging behavior by means of sending the consumers economic signals that reflect the actual cost of energy. Locational Marginal Pricing (LMP) is a market design, already in use, that enables the wholesale electric energy prices to reflect the actual cost of energy in different locations, accounting not only for the system price but also for the congestion and losses costs in the network.

In this thesis, the introduction of a pricing scheme based on LMP for the charging stations is studied. The purpose is to assess its efficiency in relocating the demand in both time and space, i.e., encouraging drivers to charge during periods of higher generation thus lower prices, while distributing the load among the stations with fewer congestion and losses costs. For this purpose, a real-time cooperative simulation tool has been developed, integrating an Agent-Based Model of the drivers' behavior, and the Optimal Power Flow of the network constraints, based on a real Norwegian local network with 856 consumers.

By analysing the response of agents to the dynamic local pricing over several days, and in comparison with two other reference scenarios, results show how the charging operation can be optimized in the short and long terms, by relocating the demand in space and time respectively. Comparing the proposed pricing scheme with the current situation in Norway, the cost of charging energy sees a reduction of up to 35 % for the grid and 18 % for the drivers while increasing the profit margins to the infrastructure provider, hence making the charging of electric vehicles more advantageous for all the parties involved.

An investigation on modeling principles and ageing behaviour of the lithium ion battery

Student: **Fredrik Pettersen**
Supervisor: **Roy Nilsen**

In this thesis the battery technology and lithium ion cells in particular is studied. Lithium ion batteries are the dominant battery technology on the marked today and serves a variety of applications ranging from small electrical devices such as mobile phones to electrical energy storage in the distribution grid. The lithium ion battery offers high energy density relative to competing technologies, which is one of the main reasons for its popularity.

A comprehensive literature review of modeling principles for state of charge estimation and battery degradation is performed, and the mathematical framework for the electrochemical representation of the lithium ion cell is detailed.

The ageing behaviour of a lithium nickel cobalt aluminium oxide (NCA) cell is investigated for fast charging protocols. This is performed by computational simulation on an isothermal, one dimensional electrochemical ageing model in Comsol Multiphysics. The ageing is assumed to be caused by the formation and increased thickness of the so-called solid electrolyte interphase (SEI), which is highlighted in scientific publications as one of the main degradation mechanisms in lithium ion cells with graphite anodes. The growth of SEI consumes cyclable lithium ions and consequently, reduce the battery capacity (i.e. capacity fade).

The ageing simulations was performed for 10 cases, including 1C, 2C, 4C, 6C and 8C charge current for battery temperatures 25 °C and 45°C. The discharge current was set to constant 1C. Minimum and maximum voltage limits of 2.5V and 4.1V was used in the simulations. The best cycle life performance was found to be at 25°C and 1C charge current where the NCA cell was able to perform 16117 cycles before reaching end of life criteria which was set to 80% capacity fade. Each increase in charge current resulted in faster degradation and at 8C, the cycle life performance dropped by 23% compared to the best case. Moreover, at 45°C and 1C the cycle life performance worsened by 74.6% compared to 25°C and 1C. The worst performance was found to be at 45°C and 8C which showed a 79.3% reduction compared to the best case. Hence, the simulations indicated that fast charging and elevated temperatures significantly shortens life span of lithium ion cells.

Stability Assessment of a Microgrid

Student: **Marie Rønhaug Pettersen**
Supervisor: **Mohammad Amin**

Problem description

Environmental pollution from non-renewable energy resources such as coal and oil has made today's energy crisis and environmental issues more prominent. Because of this, an increased focus regarding making the energy sector greener has emerged. A larger proportion of renewable energy involves a technological shift in the power industry to enable a coordination between the grid and distributed generation.

Today's power grid is based on a centralized power generation from large power plants that often are located far away from the end-users. The most prominent advantage of centralized power is the ability to enhance the efficiency of energy use, while drawbacks are operational difficulties, high costs and difficulty in meeting the user's new requirements regarding reliability and safety. This emphasizes the need of a decentralized power generation, built up by several small power generators. This technology is called distributed generation, which is a general term for renewables and non-renewables that have smaller capacity than the traditional power plants. Some of the advantages of distributed generation are less pollution, reduction of line losses and operating costs, higher energy efficiency and improved performance and reliability of power supply.

While the number of distributed generation units are continuously increasing in today's power grid, new challenges for operating and controlling the power grid safely are created. The concept of microgrids emerged as a way to address these challenges. On the downside, the integration of power electronics to the power system will result in power quality and stability issues. There are several sources to instability in a power electronics dominated power system. Among others, a weak grid, brought by a high grid impedance can cause instability. It has also been proven that the control parameters might influence the stability and it can arise stability issues when connecting several converters in parallel because the control loops might interact with each other. This makes it necessary and important to get familiar with different stability analysis tools to understand the instability of a system dominated by power electronics.

The task

This thesis focuses on small-signal stability analysis in the frequency domain and introduces the impedance-based stability analysis as a method to predict the stability of a power electronics dominated system. The stability of the microgrid in Fig. 1 is analyzed for both grid-connected and islanded mode. The impact on the stability from control and system parameters are researched. Additionally, the thesis identifies the causes of instability and predicts the stability strength of the systems. The predicted stability is further verified by time domain simulations.

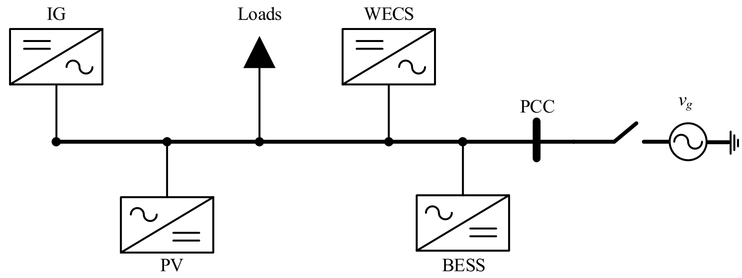


Figure 1: Topology of the microgrid.

Model/measurements
The main characteristics of the impedance-based stability analysis is that it divides the system into one source and one load subsystem as depict in Fig. 2. The source subsystem is represented by its Thevenin equivalent with a voltage source, $V_S(s)$ in series with an output impedance, $Z_S(s)$, while the load subsystem is represented by its input impedance, $Z_l(s)$. The stability of the system is determined from the impedance ratio, $Z_S(s)/Z_l(s)$, which must satisfy the generalized Nyquist stability criteria (GNC) for the system to be stable. A system is predicted to be stable if the Nyquist plot does not encircle the point $(-1, j0)$ and if the phase margin, which indicates the stability strength of the system, is sufficiently high enough, preferably over 35°

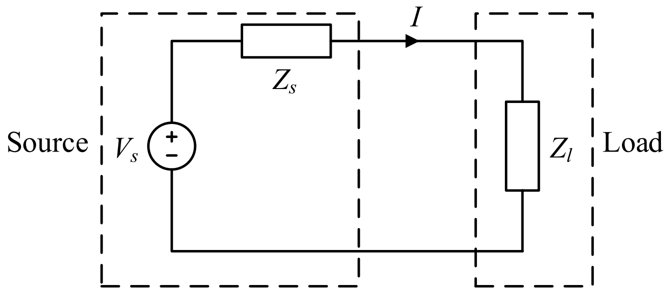


Figure 2: The small-signal representation of a voltage source system with load.

Calculation
Fig. 3a shows the Nyquist plot of the impedance ratio of the grid-connected microgrid when the grid impedance is increased to resemble a weak grid. Fig. 3b shows the Nyquist plot of the impedance ratio of the islanded microgrid when the current controller gain is changed. As can be observed the Nyquist plot encircles the point (-1, j0) for both cases and the impedance-based stability analysis predicts the systems to be unstable. The predicted instability is confirmed by time domain simulations in Fig. 3c where the top figure is the current of the grid-connected microgrid, while the bottom figure is the current of the islanded microgrid.

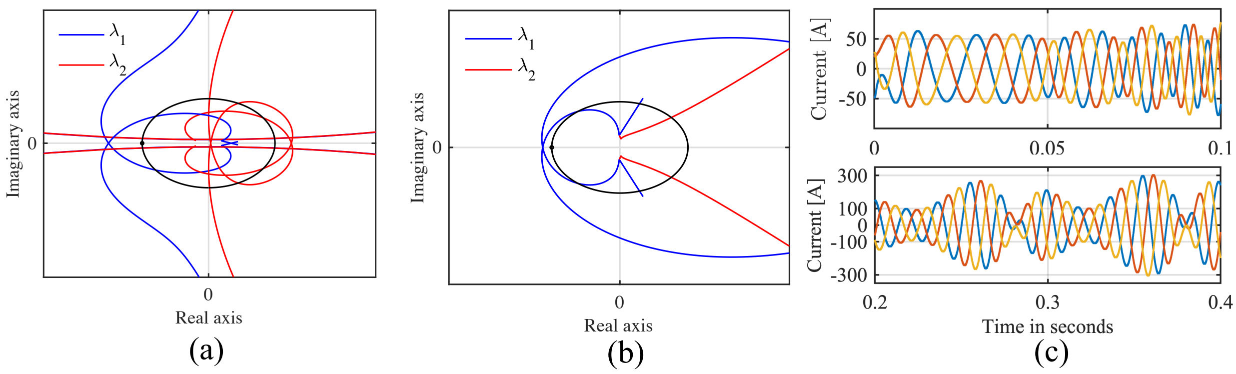


Figure 3: (a) Nyquist plot of the grid-connected microgrid, (b) Nyquist plot of the islanded microgrid and (c) time domain simulations of currents

Conclusion
The sources of instability of a grid-connected and an islanded microgrid has been investigated by applying the impedance-based stability method. It is discovered that a weak grid and changing the control parameters of the current controller and the phase locked loop lead to an unstable system when the microgrid is grid-connected. When the microgrid operates in islanded mode it is observed that the current controller and AC voltage controller gain affects the stability. Based on the result from the different cases, the method is proven to be accurate and useful as a tool to help assess the stability of the investigated systems.

Effect of a Non-Ideal Power Take-Off System on the Electrical Power Output of a Wave Energy Converter under Passive Control

Student: **Martine Furnes Pettersen**
Supervisor: **Olav Bjarte Fosso**
Co-supervisor: **Paula Garcia Rosa & Marta Molinas**

Real ocean waves are non-stationary by nature, which gives a challenge when designing and controlling wave energy converters (WECs). Many different control strategies have been proposed to increase the energy absorption of WECs under a variety of operating conditions. The performance of these control schemes have been verified through the use of hydrodynamic models, with the assumption that the power take-off (PTO) system is ideal. Generally, the PTO system can either be tuned on a constant frequency characterized by a local spectrum or continuously tuned after the wave frequency. Recent studies with a passive control (PC) method based on the Hilbert-Huang transform (HHT), that tunes the PTO on a wave-by-wave basis, have shown promising results with an ideal PTO for increasing the energy absorption from the waves. In this thesis, these studies have been extended to include a fully-coupled wave-to-wire model that includes the physical limitations and efficiency of an electrical PTO system. Through numerical simulations and comparisons with a passive loading (PL) method tuned at the mean centroid frequency of the excitation force spectrum and the case when only the hydrodynamic model is considered, the effect of the PC strategy on the electrical power output of the WEC is studied. Simulations with the hydrodynamic model only showed that the PC scheme absorbs more energy from the waves than PL. For instance, for sea states characterized by a wideband spectra, PC obtained a performance improvement in the absorbed energy of up to 32% compared to PL. From the wave-to-wire results, it was observed that PC averagely generates 10% more electrical power than PL, supporting the results with an ideal PTO. However, PC also requires 84% more power from the grid compared to PL in order to operate correctly. Even though PL results in more average power losses than PC, PL still averagely give around 6% more electrical power output than PC. This shows that the physical limitations and non-linearity of the PTO reduces the benefit of a time-varying PTO damping.

Condition Monitoring of Power Transformers in Digital Substations

Student: **Lars Ivar Ulvestad Raanaa**
Supervisor: **Hans Kristian Høidalen**
Collaboration with: **SINTEF Energy Research**

Problem description

Ageing Power Transformers in the power system increase the need for maintenance and reinvestments. There is currently a shortage of adequate systems for estimation of condition and residual lifetime, to facilitate asset management purposes. The aim is to move from time-based monitoring to condition-based monitoring, automating monitoring practices. The aim is that the approach will predict when faults occur and suggest maintenance and reinvestments actions needed to be performed in a timely manner to avoid these incipient faults from happening.

A new type of substation referred to as digital substation, introduces a new substation automation system that is based on digital technology. The substation design features a process bus and a station bus which are two LAN networks for communication between substation devices. Communication is defined by the IEC 61850 standard, that aims to achieve interoperability and is compliant with future technologies. Technically this is not easy to achieve, and there is no common method among grid utilities or industry today on how to set up condition monitoring systems. There is also the need to merge condition and operational data, which is currently restricted by regulations.

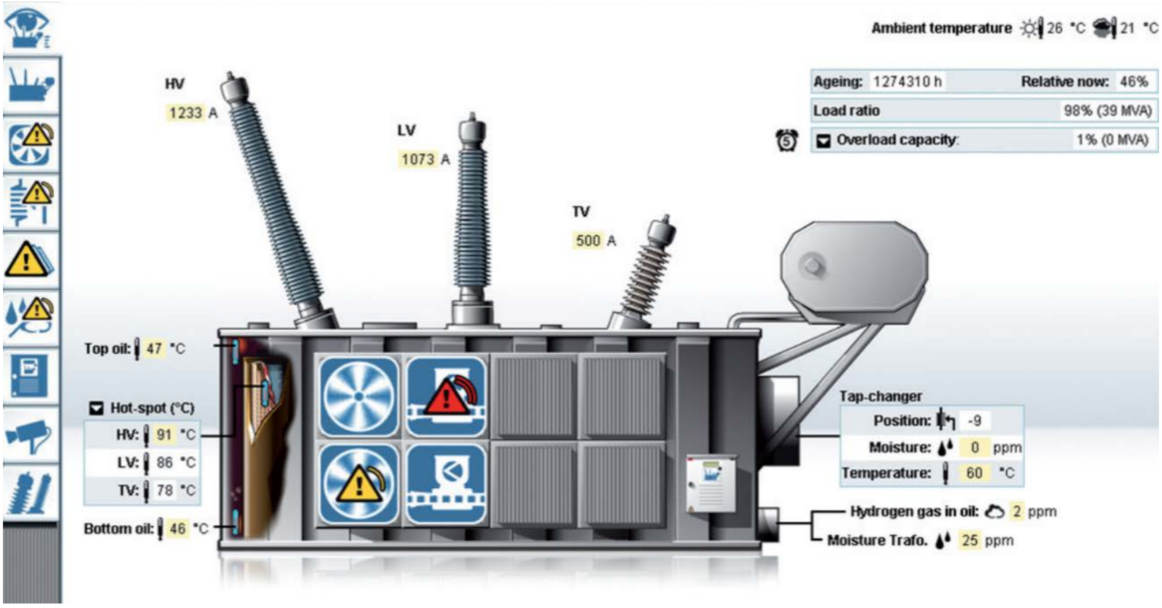
Any type of systems consists of a range of components that are interconnected in a hierarchical order. At the bottom, sensors acquire condition and operation parameters from power transformers using various facilities. The sensor data is transferred and processed in the substation automation system by different components that depends on the system design and are typically, central monitoring units, IEDs, servers and computers. These possess one or several processing algorithms and programs that can relate certain condition parameters with fault conditions. The systems present the condition on a screen and can show the condition of each monitored power transformer. The system may also be able to suggest descriptive actions needed to be taken, such as turn off a unit, check cooling, oil treatment, bushing replacement, etc.

The task

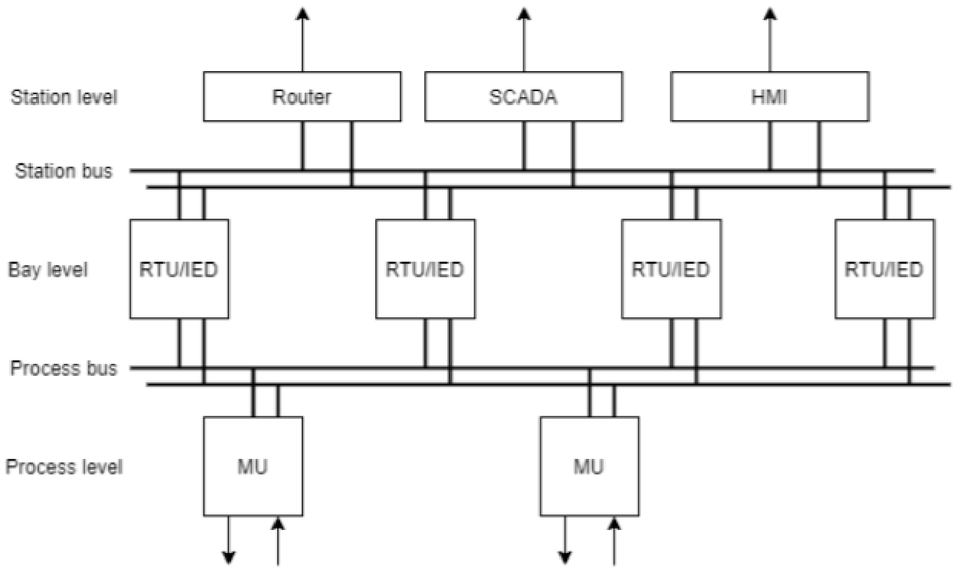
Obtain a deep understanding of condition monitoring of power transformers, digital substations, and the IEC 61850 standard. Based on the knowledge, develop a substation automation system that integrates condition monitoring into the digital substation and enable operational data to be harnessed for condition monitoring purposes.

There are several types of condition monitoring systems and it is important to find out what type of system should be applied to what type of transformer in what specific operational circumstance. It is also important to find out what monitoring facilities should be implemented and how the data should be processed and presented to provide an accurate and user-friendly system.

Condition monitoring may not necessarily be the most cost-efficient approach, however, it is an alternative that is worth investigating, as it may yield higher cost-efficiency in addition to many other benefits, such as fewer faults, fewer outages, increased security for personnel, increased power transformer lifetimes, etc.



Figur 1: Example of a condition monitoring system with several sensors.



Figur 2: Digital substation automation system design, featuring process bus and station bus.

Conclusion

Condition monitoring of power transformers is a well-developed field within electrical engineering, but digital substation and implementation of IEC 61850 are in the development phase and little experience has been made so far on how to integrate condition monitoring. In spite of this, condition monitoring is a suitable approach with high potential of becoming a success.

Electrothermal design of medium voltage high power DC/DC converters

Student: **Evangelia Rigati**
Supervisor: **Dimosthenis Peftitsis, NTNU**
Contact: **dimosthenis.peftitsis@ntnu.no**

Problem description

So far the electrical energy distribution is achieved by utilizing the MVAC infrastructure. However, the increasing power demand, the electrification of the transportation sector and the increased interest towards the interface between RES, energy storage systems and the existing grid resulted in the investigation of more complex networks. The remarkable progress in the field of power electronics and the lower cost of the DC technology nowadays compared to previous decades played a crucial role to the evolution of MVDC distribution grids. The DC/DC converter is the most promising candidate for DC grids, suitable for high power applications. The DAB DC/DC converter, in particular, seems to be the front runner among the proposed DC/DC converter topologies, due to its simple structure, impressive efficiency of approximately 99% and the fact that it allows bidirectional power flow and galvanic isolation between the input and output.

The task

The scope of this thesis is to investigate the basic block and modularized DAB DC-DC converter in terms of structure, operating principles and control strategies. Modularized DAB converters have been developed and employed to interconnect PVs and batteries to the MVDC distribution grid. For this reason, two different configurations of the hybrid PV-BESS system have been designed, a centralized and a distributed power system. The electrical and thermal performance of the converter switching devices have been investigated under source and load variations in order to assess the reliability of the converters.

Model/ measurements

All the system models have been developed in PLECS simulation software. The electrical models of the converters have been investigated and developed for both scenarios, the centralized (Fig. 1) and the distributed system (Fig. 2). The thermal model has been developed only for the centralized configuration, as shown in Fig. 3. Each full bridge of the converters consists of four 1.2-kV class, 90 A current rating SiC MOSFETs (Wolfspeed C2M0025120D, TO-247-3 package), which are mounted on the same heatsink. The most proper selection of heatsink was found to be the LAM 5 D K 100 24 by Fischer Elektronik. The transformers are considered ideal with transformation ratio 1:1. Finally, the selected PV module in both cases is the multicrystal KC200GT Kyocera model.
In order to verify the hybrid system operation a daily solar radiation profile has been simulated for the 139th day of the year, referring to $63^{0}26'48.5772''$ N and $10^{0}25'18.8616''$ E. A stochastic load profile for one day of operation has also been considered.

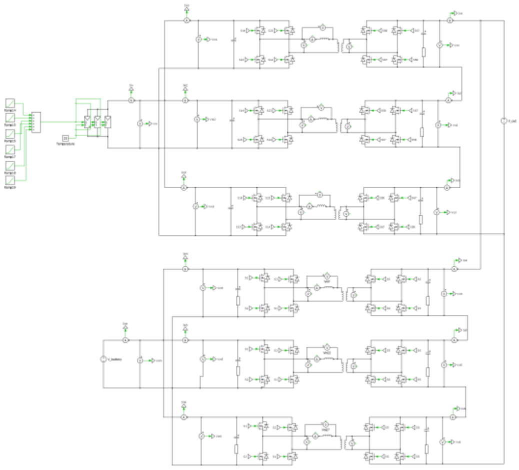


Fig. 1: Centralized model

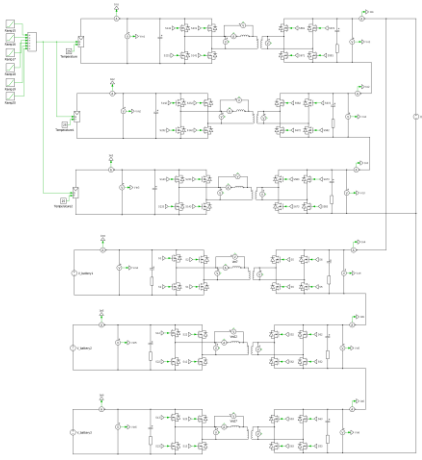


Fig. 2: Distributed model

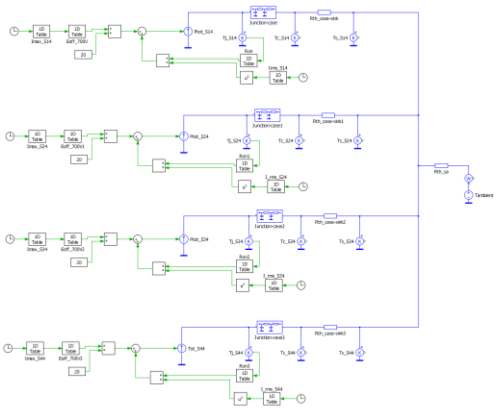


Fig. 3: Thermal equivalent circuit for the MOSFETs of one full bridge

Calculation

The devices' current has been captured under maximum power flow, i.e. under maximum solar radiation for the PV-DAB connection and maximum power transfer from the batteries for the BESS-DAB connection. This instantaneous value of current is illustrated in Fig. 4. Fig. 5 shows the temperature swings of one MOSFET, due to the generated PV power and the load power-demand profile.

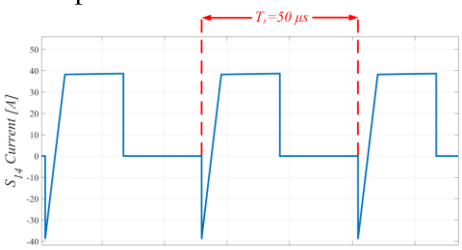


Fig. 4: MOSFET current under maximum solar radiation

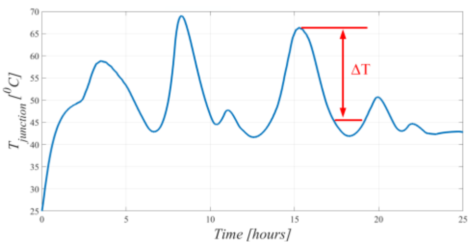


Fig. 5: Junction temperature variations of one MOSFET

Conclusion

The electrical results show that the converters and controllers of both systems operate within acceptable design limits. However, the distributed configuration is more reliable, because in case of a change in solar radiation or a fault in PVs and/or batteries the system will keep operating and will not collapse. The temperature stress is the main reason that reduces the operating lifetime of the MOSFETs. Reliability tests along with the implementation of lifetime models are necessary to assess the lifetime of the switching devices.

TIMES-LYR – a long-term deterministic scenario analysis of the future energy system in Longyearbyen

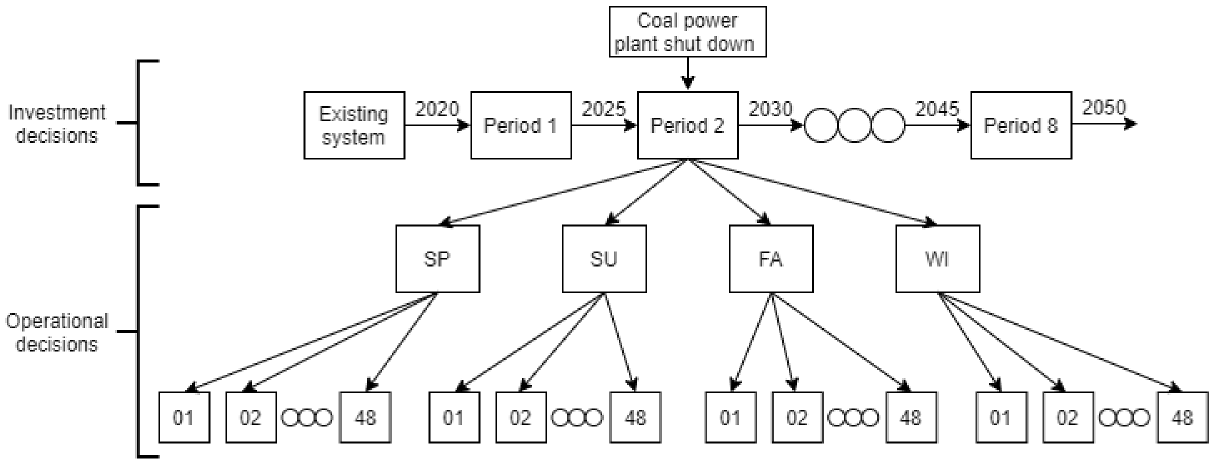
Student: **Einar Boman Rinde**

Supervisor: **Karen Byskov Lindberg**

Problem description

The objective of this thesis is to use an existing energy system modelling tool to investigate a transition from the fossil-based energy system in Longyearbyen to a renewable one. This is done by developing a TIMES-model from scratch of the Longyearbyen energy system.

Model



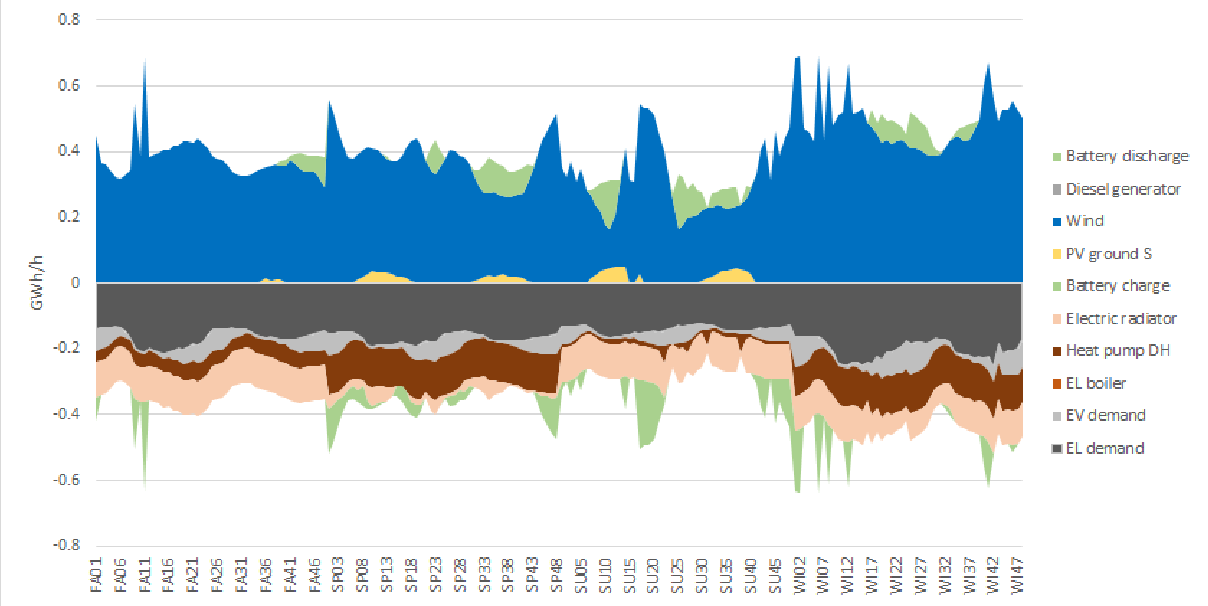
Breaking the TIMES model framework down its core, the model seeks to fulfil a demand in all defined time steps. The modelling horizon is set from 2020 to 2050, divided in five-year intervals where investments can be made. Each year is divided into four seasons with one weekday and one weekend over 24 hours, totalling to 192 time-slices annually as seen over.

Technologies or processes represent physical devices who transform one commodity to another. These technologies represent for instance steam turbines or solar PV but also demand technologies like electric radiators or cars. The commodities are energy carriers, like electricity or coal, greenhouse gas emissions or end-user heat. A technology either consumes or produces a commodity, and the commodity flows represents the links between technologies and commodities

The existing energy system is modelled along with various investment decisions, focusing on renewable energy sources and storage technologies. Five scenarios were investigated.

Conclusion

The results from the solved scenarios clearly indicate that a renewable energy system in Longyearbyen is feasible. Four out of five scenarios make large investments in renewable energy sources, and wind power is preferred as the main source of energy to minimize the costs. Seasonal storage is not found economical, and there is therefore curtailment of energy in all scenarios.



The figure shows the flow of electricity in the base scenario in 2050, where wind is clearly supplying most of the electricity. A battery is used to “flatten the curve,” and all heat is covered by heat pumps and electric radiators.

Grid Impact from Increased Prosumer Penetration in the Norwegian Distribution Grid

Student: **Liv Ringheim**
Supervisor: **Gerd Hovin Kjølle**

Problem description

This master thesis is a study of the grid impacts from an increased penetration of prosumers in the Norwegian distribution grid. A survey among DSOs has shown a large groth in the amount of prosumers during the last year. Simulations have been carried out in the simulation tools Netbas and DIgSILENT PowerFactory. The simulations are based on different penetration levels of prosumers with 8kW PV systems. Some simulations are also done with a combination of PV and battery energy storage, to see how this affects the results.

The simulations have shown that high production combined with light load can lead to voltages above the tolerated limit an overload of equipment in the grid. Through the simulations, it has been shown that an increased penetration of prosumers in the Norwegian distribution grid is especially challenging in weak grids, where minimum short-circuit currents are low. It has been shown that grid strength and apparent power rating of transformers are the limiting factors for the allowed penetration level of prosumers.

Grid improvements, such as increased transmission capacity in power lines and transformers, can reduce the grid impact from prosumers. Simulations of PV combined with BES has also proven to be an efficient way to reduce the grid impacts from prosumers.

Metodikk for etablering og analyse av reinvesteringsscenarier for distribusjonsnett

Student: **Erik Log Rogne**
Faglærer: **Eivind Solvang**

Problemstilling

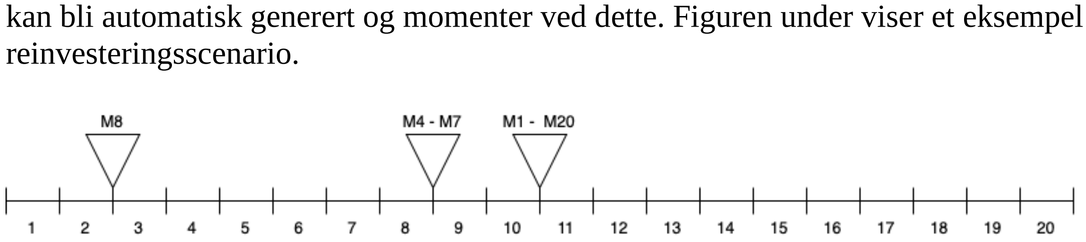
Formålet med denne oppgaven er undersøke hvordan reinvesteringsscenarier kan brukes som et alternativ til nettplanlegging for nettselskap. Dette gjøres ved å ta for seg ulike momenter som påvirker reinvesteringsscenarier. Dette handler blant annet om påkjenningsfaktorer på distribusjonsmastene, hvordan levetidskurve kan brukes i oppbygning av reinvesteringsscenarier og hvordan forventede kostnader i analyseperioden kan beregnes.

Oppgaven

I denne oppgaven blir reinvesteringsscenarier testet som et enkelt verktøy istedenfor komplisert optimalisering. Ved bruk av reinvesteringsscenarier er det ønskelig å få et bilde over hvordan situasjonen er i en analyseperiode. Dette handler både om tekniske faktorer på nettet, men også om det økonomiske aspektet. For å undersøke disse aspektene ble det først laget noen eksempler for å få et innblikk i hvordan ulike reinvesteringsscenarier kan se ut. Deretter ble ulike momenter testet for disse eksemplene. Et punkt er hvordan levetidskurven påvirker reinvesteringsscenariet sin oppbygning. Et annet punkt er hvordan kostnadene i løpet av analyseperioden regnes ut. Et annet viktig element er hvordan slike reinvesteringsscenarier kan bli automatisk generert og momenter ved dette.

Modell/målinger

I denne oppgaven blir reinvesteringsscenarier testet som et enkelt verktøy istedenfor komplisert optimalisering. Ved bruk av reinvesteringsscenarier er det ønskelig å få et bilde over hvordan situasjonen er i en analyseperiode. Dette handler både om tekniske faktorer på nettet, men også om det økonomiske aspektet. For å undersøke disse aspektene ble det først laget noen eksempler for å få et innblikk i hvordan ulike reinvesteringsscenarier kan se ut. Deretter ble ulike momenter testet for disse eksemplene. Et punkt er hvordan levetidskurven påvirker reinvesteringsscenariet sin oppbygning. Et annet punkt er hvordan kostnadene i løpet av analyseperioden regnes ut. Et annet viktig element er hvordan slike reinvesteringsscenarier kan bli automatisk generert og momenter ved dette. Figuren under viser et eksempel på et reinvesteringsscenario.



Beregninger

Ved undersøkelse av eksemplene viste det seg at utarbeidelsen reinvesteringsscenarier ved hjelp av levetidskurven er ganske intuitiv. Det blir gjort på en enkel måte, og sannsynligheten for at det beste reinvesteringsscenariet blir tatt i bruk, når tekniske betraktninger blir tatt hensyn til, er stor. Det kommer imidlertid større utfordringer ved det økonomiske aspektet.

For reinvesteringsscenarier vil en kostnadsmodell være en utfordring. Etter at et reinvesteringsscenario er laget vil alle planlagte reinvesteringer være planlagt i løpet av analyseperioden. Dermed kan nåverdiberegninger for disse reinvesteringene foretas. Det vil også bli beregnet en forventet kostnad for svikt. Denne er avhengig av tilstanden til mastene. Ved en høy tilstandskarakter for masten vil kostnaden være høy og ved lav tilstandskarakter vil kostnaden være lav. Dette kommer av at jo lavere tilstandskarakteren er, jo lavere vil sannsynligheten for svikt være, noe som igjen fører til lavere kostnader for svikt. Dermed er det viktig for nettselskapet og få så nøyaktige verdier for levetidskurven og 10-persentilet som mulig, slik at kostnadene for svikt blir så presise som mulig.

I tabellen under vises resultatene av totale forventede kostnader for ulike scenarier som er testet i denne oppgaven.

Eksempel	Total forventet kostnad
1	443 667.88 kr
2	228 503.19 kr
3	217 637.76 kr
4	338 449.08 kr
5	290 401.46 kr

Konklusjon

Bruk av reinvesteringsscenarier i denne sammenhengen har flere viktige elementer ved seg. Det er viktig å kunne bygge opp en reinvesteringssplan som nettselskapet kan stole på. Dette danner hele grunnlaget for bruk av reinvesteringsscenarier. Deretter er det nødvendig å gjøre vurderinger for nettselskapet med tanke på tekniske og økonomiske momenter. Dette går på hvilken grense som skal bli satt for utskiftning, og hvordan et reinvesteringsscenario kan bli gjennomført på en mest økonomisk hensiktsmessig måte.

Online Condition Monitoring of Synchronous Generators Using Vibration Signal

Student: Gaute Lyng Rødal
Supervisor: Arne Nysveen
Co-supervisor: Hossein Ehya

Problem description

Synchronous generators with salient poles are the supreme design of the electromechanical energy conversion device in a hydropower plant. Hydropower is among the cleanest sources of energy and accounts for 16% and 95% of the total energy production worldwide and in Norway, respectively. The duty of salient-pole synchronous generators is in this was indispensable. A defect in the machine can cause serious consequences in terms of economic losses from production stoppage, expensive reparations costs and dangerous situations and, thus, online condition monitoring that allows for detection of incipient faults is highly valuable. As most electrical and mechanical faults in a generator affect the machine's vibration behavior, using vibration signals for diagnosis is a powerful tool. However, compared to asynchronous or round-rotor machines, the salient-pole synchronous generator has not been explored to the extent it deserves, causing an urgent need for research.

The task

The objective of this thesis was to investigate whether and how vibration signals can be utilized for online condition monitoring and fault detection in salient-pole synchronous generators. Two faults, that is static eccentricity (SE) and inter-turn short circuit (ITSC) in one of the rotor poles, in no load and loaded operation were studied and compared to healthy condition at several fault degrees in order to determine if the fault severity can be recognized from the vibration. 2D and 3D finite element (FE) analyses were conducted on a generator located the National Smart Grid Laboratory at NTNU with detailed examination of the air-gap flux density, force density and total force, as well as the stator vibration caused by the air-gap forces. Figure 1 depicts the models used for the FE simulations. A novel analytical model for description of the magnetic parameters in the air-gap was formulated. Due to the university shut down caused by the outbreak of the coronavirus SARS-CoV-2, laboratory vibration measurements that were meant for verification of the theoretical analyses were discarded from the scope of the thesis.

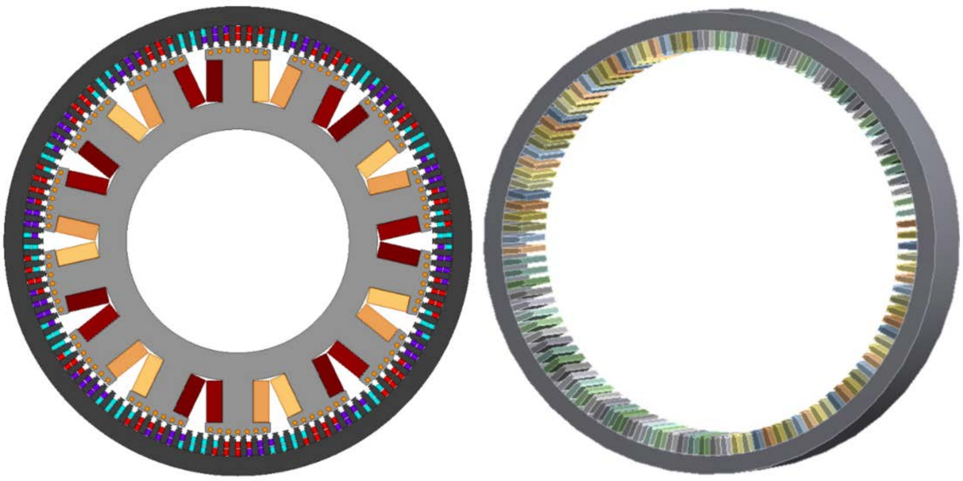


Figure 1: 2D-model (left) and 3D-model (right) used for finite element simulations.

Results

The simulations revealed that the ITSC fault excites time harmonics and spatial harmonics in the radial force density at every multiple of rotor frequency which causes a dramatic elevation in low-frequency vibration, particularly at rotor frequency. SE also induces unnatural spatial harmonics in the radial force density while the time domain harmonics are more or less unaffected by this fault. Consequently, SE increases low-frequency vibration as well, in particular at rotor-frequency, however, to a lower degree than ITSC. Figure 2 shows how the stator vibration, expressed in terms of logarithmic deformation, is affected by the two faults. The leftmost dot in the graph represents the rotor frequency and each dot is a multiple of this.

It was also found from the FE analyses that the tangential component of the air-gap magnetic flux density is relatively very small compared to the radial component and inconsiderable in production of the vibration-producing forces. Moreover, the harmonic orders of the radial force density formulated by the analytical model to appear as a result of the two faults are in good agreement with the simulation results.

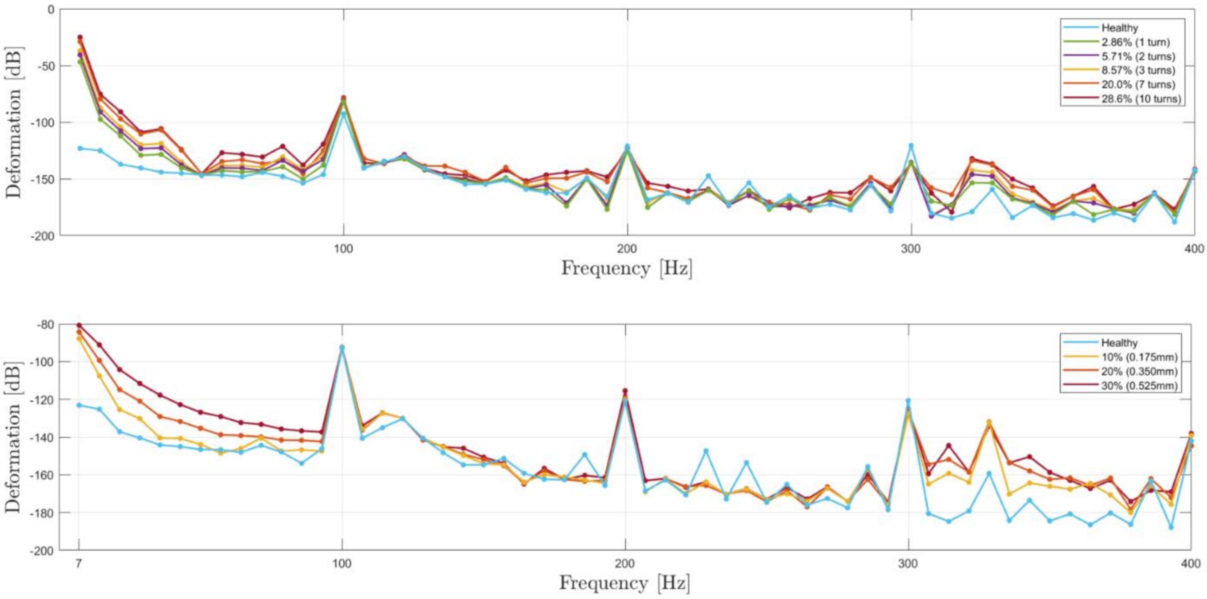


Figure 2: Frequency spectrum of the stator vibration during ITSC in the rotor (top) and SE (bottom) for various fault severities.

Conclusion

The thesis shows how vibration signals can be used for fault detection of SE and ITSC in the rotor winding by examining low-frequency stator vibration. Accurate classifiers to detect and distinguish the two faults form healthy condition and from each other have been presented, and a method for estimation of the fault severity has been deduced. The predictions made by the novel analytical model form reliable expectations of vibration in salient-pole synchronous generators during the two faults.

Real vibration measurements should be conducted on the investigated generator in order to examine the validity of the theoretical results in a practical point of view.

Impedance-Based Stability Analysis and Adaptive Control of Grid-Connected Converter

Student: **Fabian Skarboe Rønningen**
Supervisor: **Olimpo Anaya-Lara**
Co-Supervisor: **Raymundo E. Torres-Olguin**
Collaboration with: **SINTEF Energy Research**

Problem description

Over the last several decades, the penetration of power electronics connected to the grid has increased dramatically, and the trend is expected to further accelerate in the years to come. The main reason is the increased integration of renewable energy sources, as the majority are connected to the grid through power electronic converters due to the converter's ability to transform the energy from the source to a suitable form for injection to the power grid. The resulting impact in mitigating climate change problems is expected to be enormous, and it means that both generation and transmission, but also the consumers, are increasingly dependent on the power electronics technology. Accordingly, as the number of grid-connected converters continues to increase, so will its impact on power system dynamics and stability. Recently there have been several unexpected events of instability in power electronics dominated grids, apparently due to resonance between the converters and the grid. Therefore, to ensure the continued integration of renewable energy sources, the instability problems should be analyzed, and measures should be taken to avoid similar instability problems in the future.

Conclusion

There are several ways to assess the stability of the interaction between the grid and the converter, and
one of them is the so-called small-signal impedance-based stability method, which is studied in this thesis. The first part of this thesis is dedicated to developing appropriate models for a specific converter and the grid so that this method can be applied. Then follows the main contributions of this thesis, two novel adaptive control methods based on changing the control parameters for the current controller and the phase-locked loop depending on the grid impedance. After the necessary methods were developed, they were implemented in simulation.

The simulation software Matlab was first used to implement the converter and grid models, then the adaptive control methods. The result of the first method, which only adapts the phase-locked loop parameters, proved to be effective in increasing the stability limit compared to other static methods. However, it also showed poor behavior under certain grid conditions, even compared to simple static methods. The second method adapted both the phase-locked loop and the current controller, and the implementation proved to be superior to all other static and adaptive methods tested. Finally, both the methods were implemented in the time-domain in f a Simulink model. In general, the results he small-signal model translated well to the Simulink model, and also in this case, the second adaptive control method was highly effective under all grid conditions, until the stability limit was reached.

form o from t

Title Transient temperature estimations to facilitate dynamic current rating of power cables

Student: **Ragnhild Skjoldli**
Supervisor: **Erling Ildstad**
Collaboration with: **Statnett SF**

Problem description
Today the maximum current load capacity of power cables is rarely fully utilized. This is however about to change, as the increasing need for electric energy and power calls for more efficient use of the installed reserves in the power grid. Provided that the expected maximum temperatures of a cable system can be estimated, longer periods of current overload can be allowed during certain service conditions.

The maximum current load capacity of a cable system is limited by the maximum allowed temperature of the insulation. In order to estimate the transient temperature of the cable, the type of installation, its present and expected current load as well as the temperature, heat capacity and thermal conductivity of the cable and its surroundings needs to be realistically modelled.

The task
The main purpose of her MSc study is to develop a model for transient temperature calculations and to compare results from computer simulations with measured data from both laboratory experiments and an installed High Voltage XLPE Insulated Power Cable.

The thesis is expected to constitute:

- A literature survey, including theory, forming the base for the suggested methods for estimating transient temperatures of installed cables.
- Implementation of the IEC transient temperature model as well as an alternative model based upon the principle of superposition for estimation of the effect of variable load.
- A laboratory experiment, if possible, aiming at testing the validity of proposed models for transient temperature estimation.
- A case study based upon interdependent measured data of current load, environment and cable jacket temperatures provided by Statnett SF.
- Comparison of the measured and simulated results, including discussion of the validity of the approach used and suggestions for further work.

Model/measurements
The calculation methodology is establishing a thermal ladder network. The network aims to determine an analytical solution using IEC standards for heat transfer from the conductor to the outer cable surface. The calculation method is used to establish a simulation in MATLAB that calculates the temperature response due to a specified current change.

The experimental methodology mainly intends to be used in comparative analysis with the results from the calculation method represented for the calculation methodology. The experimental methodology includes a laboratory setup established at NTNU. The tests completed studies cases of temperature rises due to a load increase as well as temperature responses due to variable loads applied in order to study the effect of the superposition principle. The tests measured the temperature at two different laying conditions: 1) Cable placed on a concrete floor with air as surrounding medium. 2) Cable lifted from the floor in free air.

Results and conclusion

- The simulation established with the basis of the calculation methodology had a positive correlation with the cable installation from the experimental test. The correlation applies for both laying conditions: in free air and for cable placed on the floor. Both simulated sheath and conductor temperature interact with the logged temperatures from the laboratory setup. Especially the simulated steady-state temperature has been found to be similar to the logged temperature for both sheath and conductor.
- Utilizing the superposition principle in order to determine the temperature response has turned out to give results that correspond with the logged temperatures. The simulation has highlighted the importance of utilizing the principle of superposition when the temperature does not reach a steady-state before a new current is applied.
- An overloading example was simulated for the cable installation from the laboratory setup. The results show, among others, that an overload of 30% above maximum permissible current can be applied for 24 minutes.
- Simulating the load history impact on the power cable from the experiment has found that after switching off a 150 A load, the reference ambient temperature was reached after 2 hours and 45 minutes assuming a temperature margin of 0.05°C.
- The simulated sheath temperature for a high voltage cable tuned out to correspond well with the sheath temperature logged from the high voltage cable owned by Statnett.
- A case-study has revealed results considering the potential of the underutilized capacity of the high voltage cable installation. For instance, in April 2019, the cable could be overloaded with 150% more than it did for 6 hours under normal operation and 8 hours under emergency operation for the high voltage cable in free air as well as in a culvert. Furthermore, an overload of 150% to the cable installation in culvert may be applied for 1 hours longer under normal operation and 2 hours under emergency operation for a week in January than a week in June. The seasonal changes is found to have a great impact on the potential of dynamic cable rating.

The Influence of Local Energy Tariffs on a Norwegian Local Market

Student: **Olav Henrik Skonnord**
Supervisor: **Jayaprakash Rajasekharan**

Problem description

The transition to a clean and renewable consumer-centric energy system is expected to increase the electricity consumption in Norway. An increase in distributed generation (DG) is an expected outcome of this transition. Rapid spread of DG contributed to energy pro- duction and challenges grid operation. Combined with digitization it enables new market opportunities as local energy trading. Local energy trading is a key enabler to facilitate a smooth grid operation with high DG penetration. Along with a tariff structure fostering smart energy behaviour this may increase the grid stability and improve the quality of service.

This thesis target is to investigate how increasing tariffs influences the local energy trade in a Norwegian neighbourhood consisting of multiple communities. Furthermore, the lo- cal energy trade's influence on current and future market participants is examined. This was achieved by developing an optimization model capable of Peer-to-Peer (P2P) and Community-to-Community (C2C) trading. The communities and the consumers within them have unique load patterns and different amounts of storage and DG. The tariffs tested are aligned with the current tariff structure for domestic homes.

Two cases with 10 scenarios each was created to test the neighbourhood ability to exploit local energy trading when introducing tariffs to P2P and C2C trade. The main distinction between the investigated cases is the introduction of component degradation. Component degradation is introduced to provide a more realistic image of local energy trades capabilities and to analyse its influence.

The results show that increased tariffs reduce P2P and C2C trade within communities and the neighbourhood. However, the neighbourhood's daily morning peak is straightened independent of the tariff structure, with minor variations. By aligning with the current tariff structure for domestic households in Norway, the neighbourhood's yearly load curve is unchanged with local energy trade. Combined with similar yearly peak import it implies that local energy trade is unable to reduce grid stress. Aggregators is a market partici- pant potentially able to relieve grid stress. However, it is uncertain to which extent the aggregators will be able to participate in the Norwegian electricity market, due to market competition. Preliminary results indicate a gradual introduction of aggregators and that aggregators has minor influence on other market participant.

Application of signal processing and machine learning tools in fault detection of synchronous generators

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Collaboration with: **No-one**

Problem description
Develop a fault detection system using machine learning and signal processing tools capable of detecting inter-turn short-circuits of the rotor windings.

The task
The thesis examines the application of machine learning to measurements taken of a salient pole synchronous generator for the purpose of detecting and diagnosing inter-turn short-circuits.

Model/ measurements
A data set for machine learning was built using signal processing techniques to extract features from measurements of a salient pole synchronous generator operated under several different severities of ITSC fault. The features extracted were the power spectral density of integer multiples of the generator's mechanical frequency extracted by fast Fourier transform (FFT), discrete wavelet transform energies, and time series feature extraction based on scalable hypothesis tests (TSFRESH). Using this data set, a wide range of classifiers were trained to detect the presence of ITSC faults. The classifiers evaluated were logistic regression, K-nearest neighbours, radial basis function support vector machine (SVM), linear SVM, XGBoost decision tree forest, multi-layer perceptron (MLP), and a stacking ensemble classifier including all of the aforementioned. The classifiers were optimised using hyper-parameter grid searches. In addition, some feature selection and reduction algorithms were assessed such as random forest feature selection, TSFRESH feature selection, and principal component analysis.

Calculation
Out of 475 features investigated, high decomposition level relative wavelet energy features, aggregate linear trend features, approximate entropy features, and change quantile features were the most useful features. FFT derived features performed poorly. Correlation to the target value was a strong indication that features will be useful in classification and could thus be used to screen a large number of potential features at the risk of missing features with non-linear relationships.

Conclusion
A general trend during optimisation was that linear machine learning models per-formed well and that the performance of non-ensemble classifiers increased as the complexity decreased. The best performance was yielded by a stacking classifier using the optimised Logistic Regression, SVM, MLP, and XGBoost classifiers as base-classifiers, and logistic regression as the meta-classifier. It correctly classified 84.48 % of samples in the hold-out data set, and 84.56 % of the faulty samples present were correctly classified as such. Of the samples that were classified as faulty, 92.74 % were correctly classified. The worst performance was exhibited by the K-nearest neighbours classifier, performing worse than random chance. This

demonstrates that ITSC faults are suited to be detected using machine learning, however, these results should be confirmed on larger data sets that include other incipient faults.

Estimering av transiente temperaturforløp for dynamisk strømbelastning av kraftlinjer

Student: **Piotr Daniel Soja**
Veileder: **Erling Ildstad**

Problemstilling
I dag utnyttes den maksimale strømkapasiteten til høyspentlinjer i liten grad. Dette er imidlertid i ferd med å endre seg, ettersom det økende behovet for elektrisk energi og kraft krever mer effektiv bruk av de installerte reservene i kraftnettet. Forutsatt at de maksimale temperaturene på kraftlinjene kan estimeres, kan lengre perioder med strømoverbelastning tillates under visse vedlikehold.

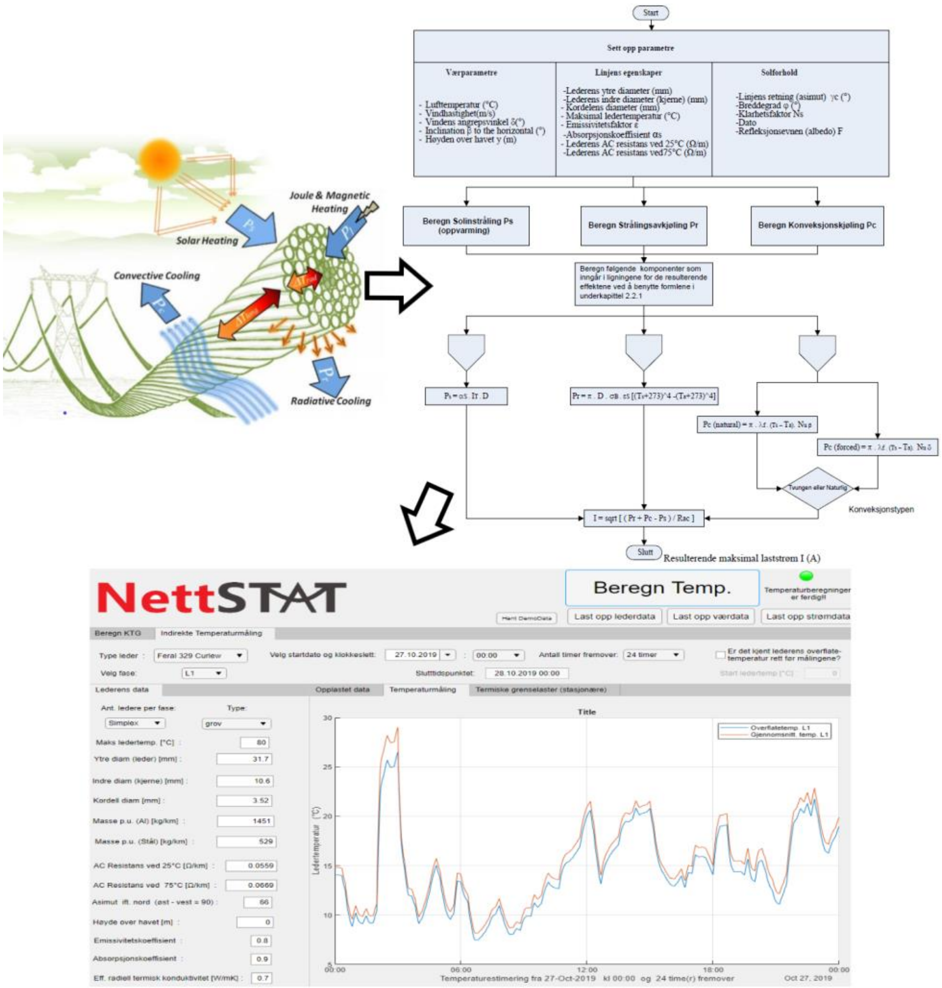
Konseptet med dynamisk estimering av termisk grenselast innebærer at kapasiteten til en komponent i en kraftledning varierer dynamisk som en funksjon av eksterne parametere som blant annet vindhastighet, lufttemperatur, vær og aktuell belastningshistorie for kritiske deler av kraftlinjen. I prinsippet kan denne nettreserven utnyttes mer effektivt, forutsatt at belastningsberegningen utføres ved bruk av en relevant termisk modell og sanntidsmålte verdier av lokale værforhold og belastningsstrøm.

Oppgaven
Hovedformålet med denne masteroppgaven er å utvikle en modell og et forenklet dataprogram for kortvarige temperaturberegninger av maksimale temperaturer og termiske grenselaster for kraftledninger.

Modell
Det har blitt utarbeidet et program i MATLAB App Designer ut fra varebalanseligningen og CIGRÉ sin beregningsmodell vist nedenfor. Programmet ble opprinnelig laget for å gi sensoren en mulighet til å gjenta foretatte analyser på en interaktiv måte og vise forståelsen av masterstudiet.
Stadig oppgradering og forbedring av programmet førte til at det også har potensial til å egne seg som et nytteverktøy for nettoperatører. Ved å oppgi værdata og strømmen er programmet i stand til å estimere termiske grenselaster ved å beregne temperaturendringen til overflaten og kjernen av lederen indirekte. Brukeren kan selv bestemme om det skal tas hensyn til kjernetemperaturen eller kun overflatetemperaturen. Programmet kan også utnyttes til å effektivisere de konservative kortvarige termiske grenselastene (KTG) som brukes i Statnett sine tekniske dokumenter. Det er også utviklet en eksperimentell funksjon kalt ”Dynamisk KTG” som i tillegg tar hensyn til faktiske værendringer som linjen er utsatt for.

For å oppsummere skal NettSTAT sørge for:

- Transient beregning av den maksimale strømmen ved oppgitt varighet og værforhold.
- Transient beregning av varigheten som linjen kan tåle ved en oppgitt strøm og værforhold.
- Dynamisk KTG beregning. Ved KTG beregning tas det hensyn til dynamiske endringer av værforhold.
- Temperaturestimering med mulighet for opptil 3 dagers predikering av stasjonære termiske grenselaster og transiente ledertemperaturendringer.



Beregninger
Resultatene viser også at bruk av de faktiske værforholdene i beregningen kan føre til at KTG kan benyttes i en kontinuerlig tidsperiode eller en 20% prosent høyere strøm sammenlignet med det tekniske dokumentet, selv om det er tatt hensyn til kjernetemperaturen.

Resultatene bekrefter også at dagens kraftledninger er utnyttet i minimal grad basert på vær- og strømdata oppgitt av Statnett. En 24 timers prognose viser at den maksimale kjernetemperaturen for den samme lederen ikke overskrider 12°C, selv om den er dimensjonert for 80°C

Konklusjon

- Den gjennomsnittlige ledertemperaturen som et resultat av lederens overflatetemperatur og kjernetemperatur utgjør en betydelig forskjell og begrenser den kortvarige termiske grenselasten til omtrent 6% lavere verdi sammenlignet med beregningene av overflatetemperaturen.
- Resultatene av KTG analysen bekrefter at dagens norske kraftledninger ikke utnyttes effektivt nok relatert til de værforholdene de er utsatt for. Det er mye høyere kortvarige termiske laststrømmer som kan påtrykkes uten at lederen blir termisk overbelastet.
- Den største suksessen var utviklingen av dynamisk KTG som er den mest effektive metoden for estimering og predikering av ledertemperaturen som en funksjon av varierende strøm, tid og værforhold. Det anbefales sterkt at Statnett benytter seg av denne metoden eller i det minste oppdaterer sin beregningsmetode.

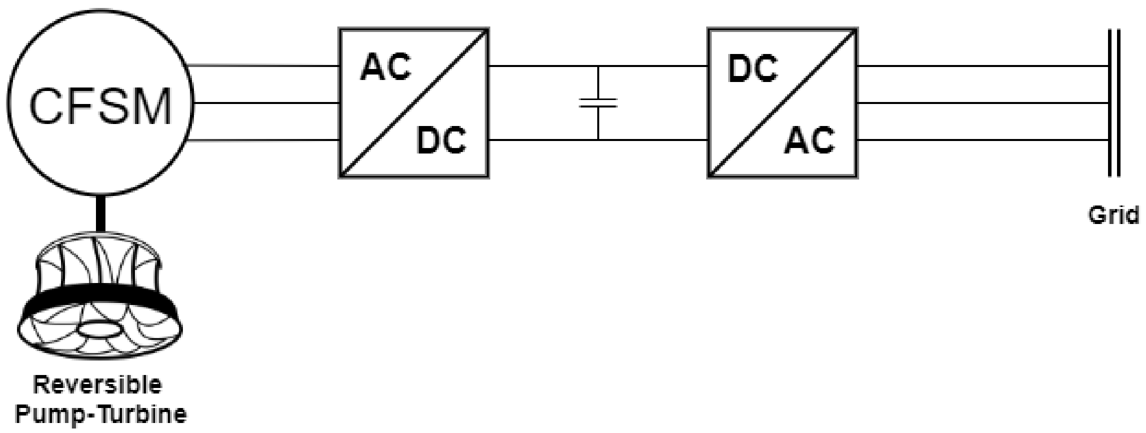
Control Strategies of a Converter-Fed Synchronous Machine for Variable Speed Hydropower

Student: **Jørgen Hagset Stavnesli**
Veileder: **Jonas K. Nøland**
Utføres i samarbeid med: **HydroCen**

Pumped-storage hydropower plants are one of the best solutions for efficient, large-scale energy storage, and have for a long time been used for balancing the supply-demand gap on an intraday basis. However, as the share of intermittent renewable energy sources is growing, there will be a need for more controllable power plants in the grid that are able to better compensate for fluctuations in the generation of power. The progress in power electronics has enabled synchronous machines to be fed by frequency converters with a rating of up to 100 MVA to employed for pumped-storage hydropower applications. By using full-sized converters, the hydro-electric plant is decoupled from the grid, thus bringing new possibilities for control of the plant.

This thesis examines the control of a converter-fed synchronous machine for a pumped-storage plant, studying the excitation system control and various forms of power control.
For this purpose, a model of an 8 kVA converter-fed synchronous machine was created in Simulink, where both pump-mode and generation-mode could be simulated. The excitation system controller was implemented with the objective of controlling the stator flux linkage to 1.0 pu, which had the effect of improving the torque-per-ampere ratio of the machine, while also avoiding operation of the machine in saturation.

Power control of the pump load, in the form of a load-following controller and a frequency controller, illustrated the potential for improved grid support when the pumped-storage plant can operate in variable speed. In addition, inertia controllers for the kinetic energy in the rotor and the stored energy in the dc-link capacitor were implemented. The inertia controllers indicated the ability of the converter-fed synchronous machine system to quickly respond to grid disturbances, without the need to start ramping of the prime mover. For further work, the model should be updated to include a MW-scale machine and explore the possibilities of virtual synchronous machine control in generation mode.



Model-Based Control of Plug-and-Play Grid-Connected Inverters

Student: **Rune Steig**
Supervisor: **Gilbert Beregna-Diaz**
Co-Supervisor: **Raymundo Torres-Olguin**
Co-Supervisor: **Santiago Sanches-Acevedo**
Collaboration with: **SINTEF Energy Research**

Problem description

Phase-Locked Loops (PLLs) are commonly used for grid synchronization and is a central part of the control system of a Voltage Source Converter (VSC). Substituting traditional fossil energy sources with renewable energy sources yields use of more power electronic components such as VSCs. The inertia of the grid decreases with increased renewable energy sources, which results in a more unstable grid. The PLLs used today are designed for a stiff grid, where the frequency is constant, and the grid is basically unaffected by disturbances. Hence, a PLL that are designed for a weaker grid will have to be designed.

The task

Three challenges related to the PLL are discovered. Two of the challenges are tried solving in this work. The first challenge is related to bilinear product nonlinearity and the fact that the PLLs are designed for simple systems but applied in complex systems. The second challenge is related angle difference state unavailability.

Three different PLLs have been designed and compared with a simple PLL used in industry today. The three PLLs are designed by use of Lyapunov stability theory as well as passivity theory.

Model/ measurements

The system analyzed is illustrated in the figure below. In this work, two angular frequencies are used to describe the system, and what angular frequency the different states in the different alternatives are related to are presented in the figure. The angular frequency provided by the PLL, ω_{PLL}, are treated as a control parameter and therefore different to the angular frequency of the grid, ω_g. Hence, two park transformations have to be used in order to represent the system in the synchronous reference frame.

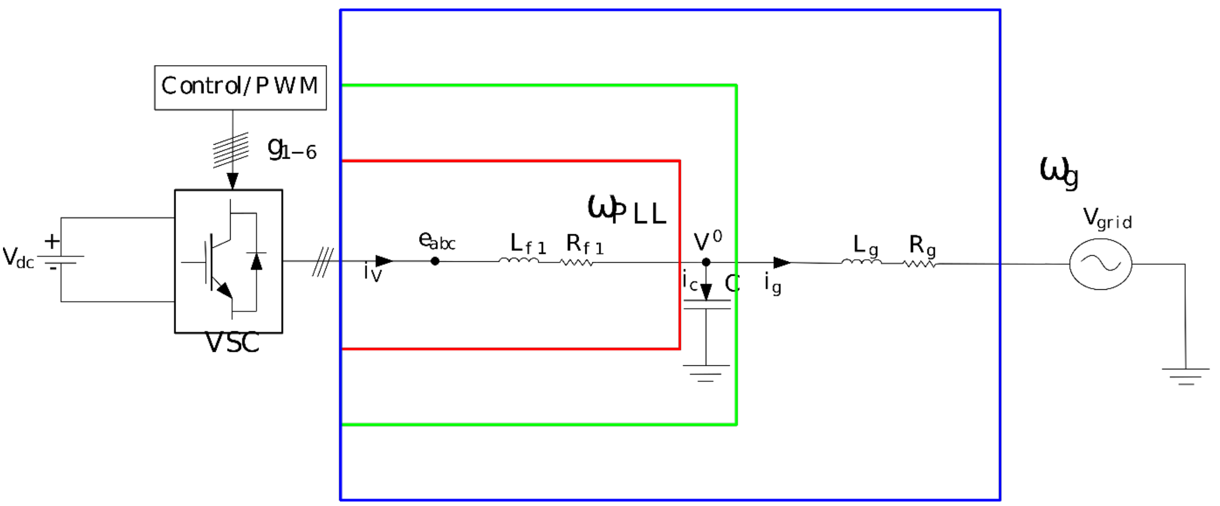


Figure 1: Illustration of what angular frequency the different PLLs are related to. Red box=Alternative 0, Green box= Alternative 1 and Blue box= Alternative 2

Calculation

Simulations comparing the designed PLLs and a traditional PLL with respect to performance indicates that the performance of the different PLLs are somewhat the same. Simulations challenging the different PLLs have not been conducted, meaning that further comparisons can be make.

Due to the fact that more simulations have done in order to determine if the designed PLLs are an improvement, the most interesting results of the thesis are the passivity outputs calculated. The passivity outputs are by help of PI stabilization globally asymptotic stable. Which implies that the PLLs designed comes with a stability certificate.

The equation under illustrates the most promising PLL in the thesis. The first row is related to the PLL, and the second and third rows are related to the current controller.

$$\tilde{\boldsymbol{y}} = \begin{bmatrix} \boldsymbol{L_f}(\boldsymbol{I_{v,d}}\boldsymbol{I_{v,q}^*} - \boldsymbol{I_{v,q}}\boldsymbol{I_{v,d}^*}) + \boldsymbol{C}\,(\boldsymbol{V_d^0}\boldsymbol{V_q^{0*}} - \boldsymbol{V_q^0}\boldsymbol{V_d^{0*}}) + \boldsymbol{\tau}\,(\boldsymbol{\delta} - \boldsymbol{\delta}^*) \\ \boldsymbol{V_{DC}}\,(\boldsymbol{I_{v,d}} - \boldsymbol{I_{v,d}^*}) \\ \boldsymbol{V_{DC}}\,(\boldsymbol{I_{v,q}} - \boldsymbol{I_{v,q}^*}) \end{bmatrix}$$

Where the values including *, are the calculated steady state values. τ is a tuning parameter and $\boldsymbol{\delta}$ are the difference between the two angular frequencies of the grid. The remaining parameters are illustrated in the figure. Today, a common way of estimating $\boldsymbol{\delta}$ is by the inverse tangential relationship between the d- and q-component of V^0. This approximation has also proven to be challenging.

Conclusion

In order to know if the designed PLLs are an improvement of the PLLs used in the industry today, more simulations have to be conducted. Even though two of the three challenges are solved, one remains. The third challenge is however, investigated in another work. Where conditions for obtaining global asymptotic stable are found and imposed in the tuning of the PI parameters.

Method for prediction of frequency drop following large generator outages

Student: **Amund Kulsrud Storruste**
Supervisor: **Kjetil Uhlen**

The near future energy system is expected to have a higher share of intermittent renewable energy sources and more distributed generation. This brings with it potential issues with regards to system stability in electrical transmission networks. By introducing a larger degree of controller interfaced generation the inertial properties of electrical power systems are diminished. Consequently, fault situations causing frequency deviations in the system will become harder to manage, with stricter time response demands for controllers. By simulating generator trips in the Nordic transmission system this project tests the accuracy of predicting the response of the system frequency of future disturbances through the use of aggregated turbine governor models, for the purpose of improving transmission system operators ability to accurately dimension availible primary reserves.

First, state-of-the-art of frequency control will be presented. This will be done by covering the different stages of frequency dynamics and control, and models for aggregating frequency system dynamics are presented. Then, the simulation software in terms of the PSSE Nordic 44 model and the ePHASORSIM real-time simulator will be covered. Additionally, a presentation on the development of aggregated turbine control will be presented. Finally, a case study will be completed for the the simulation and prediction of system frequency response. Four initial generator trips are simulated. Their frequency response is then used to tune the predictive transfer function models. Four new generator trips are then used to test the accuracy of the predictive transfer functions.

The frequency drop was predicted with an mean absolute error of 40 mHz and a mean absolute time deviation of 0.2 s. It is believed that the accuracy of predictions would improve given an inertia estimation process based on the initial rate of change of frequency of the case being predicted. Further work should tests should be performed for other values of system inertia based on available forecasts.

Vern av transformatorer i distribusjonsnettet mot lynoverspenninger

Student: **Arne Stevelin Hjelle Strand**
Faglærer: **Hans Kristian Høidalen**

Problemstilling

Transformatorer i distribusjonsnettet er spesielt utsatt for lynoverspenninger, og havari på grunn av lyn er en hyppig avbruddsårsak. Det norske distribusjonsnettet består i stor grad av transformatorer med isolerte nullpunkt, noe det ikke har vært laget modeller for simulering av overspenningsforløp på. I forskningsprosjektet ProTrafo har Bjørn Gustavsen, sjefforsker ved SINTEF Energi, høsten 2019 utviklet en slik modell for en 11 kV- 0.23 kV transformator. Denne modellen ble brukt sammen med egenutviklede modeller av vern i simuleringer av et eksempelnett i ATPDraw. Oppgaven svarer på hvordan distribusjonstransformatorer bør vernes mot lynoverspenninger, ved å gjøre flere tilnærminger. Først ble det utført laboratorietester på gnistgap og nullpunktsikring fra El-Tjeneste. Gnistgapet ble testet med lynimpuls for gapavstander på 5, 6, 8, 10 og 11.4 cm. Deretter ble modeller for gnistgap og nullpunktsikring laget ved hjelp av kurvetilpassing, og modellene ble deretter validert. Til slutt ble ulike vernkombinasjoner sammenlignet i simuleringer for et 20 kA direkte lynnedslag i en høyspentlinje 200 meter unna en transformator.

Resultatene viste at en kombinasjon av HS-avledere og LS-avledere var nødvendig for å oppnå tilstrekkelig vern. Bruk av LS-avledere bør anbefales selv for transformatorer tilknyttet LS-kabelnett. Gnistgap i nabomast ble funnet å gi noe tilleggsbeskyttelse i kombinasjon med HS-avledere og LS-avledere, men var utilstrekkelig alene. Ved å plassere gnistgapet 3 eller 5 spenn unna transformatoren i stedet for i nabomasten, ble spenningen mellom HS-terminalene og transformatorkasse hhv. tilnærmet doblet og tredoblet. Dette gjaldt også dersom lynet slo ned lenger unna og passerte gnistgapet før transformatoren. Det er derfor svært viktig å plassere gnistgap i nærmeste mulige mast. Gnistgapåpningen ble funnet å ha neglisjerbar effekt på resultatene. Det ble funnet gunstig å ha flere nedjordinger i nett med gjennomgående høyspentjord. En nedjording gav tilsvarende beskyttelse som gnistgap dersom impulsjording monteres. Bruk av adskilte jordingssystem på kassejord og nullpunktsikring har vært anbefalt mot lynoverspenninger, men simuleringene viste at det vil oppstå svært store spenningsforskjeller mellom LS-terminalene og transformatorkassen som vil føre til overslag. Årsaken er potensialhevning av transformatorkassen som oppstår under lynoverspenningen.

Electromagnetic Design of Modular Generators for Offshore wind Power Applications

Student: **Solveig Samseth Strand**

Supervisor: **Pål Keim Olsen**

Wind power production have become more and more competitive compared to traditional energy sources. Nevertheless, there are still many areas of wind power production that could benefit from increased efficiency and other improvements. A modular PM machine could be an important contribution for improving the overall wind power production system. Radial modular machines differ from traditional PM machines due to the segmentation of the stator, rotor, or both. This thesis is limited to a segmented stator structure. A modular stator structure facilitates a higher nominal voltage without an unsuitably low fill factor by distributing the voltage across the stator segments. The modular structure is for this thesis so called symmetric modularity. This entail a modular structure where each module has the same phase representation and can be closely linked to the base windings expression. The aim of the thesis is to explore the modular machine behaviour compared to non-modular machines. In addition to incorporating the modular structure in the design process.

Two machines were designed and tested, utilising FEM simulation software, a direct drive and geared machine. The FEM software utilised in this thesis was COMSOL Multiphysics. Both machines had to meet the same requirements and the only difference in the machine design premise was the speed. Design choices included were the same for both machines and they had to adhere to the same general machine limitations. Machine design and construction theory were explored, which included traditional design and the effect of modular structure on the machine design. The modular aspects were incorporated in the design process and influenced the slot and pole combination, winding structure, and fill factor. The machines designed were benchmarked against the same machine excluding modularity to observe the performance alterations. The machine aspects studied related to magnetic, electrical and loss.

General symmetric modular structures for the design of PM machines were studied, in relation to the effect of the number of segments, to categories the benefits and drawback of constructing a machine with a modular structure. Some of the findings related to the machine insulation requirements, pole and slot combinations, winding factor, and frequency. It was observed that the insulation reduction due to modularity converge when the number of segments increase. The minimum number of slots are continuously doubled as the number of modules increase. The possible frequency obtained for modular machines are limited by an increase in the number of modules, and a higher speed further limits the possible frequencies.

The FEM-simulation results for the modular machines were similar to the non-modular machine results. However, the machine performances were affected by implementing modular structures due to flux gaps between the stator modules, which had a significant deteriorating effect. Machine performance especially altered by physical modularity and flux gaps were among others phase back-EMF, torque, and core losses. The flux gaps between the modules resulted in the greatest deviation from non-modular machine performance for the geared machine. The reason behind the greater deviation for the geared machine with the same flux gap width as the direct drive machine could be linked to the machine size and the number of stator slots. The negative aspects of the flux gaps implemented between the modules increased with an increase in the flux gap width. Symmetric modular machine performance must be further explored to gain a better understanding. The core loss performance especially yielded unreliable results and should be studied further.

Topflow, a Toolbox for Specialized Power System Analysis

Student: **Åsmund Sælen**
Supervisor: **Olav Bjarte Fosso**

Problem description

Power system analysis is a branch of electrical engineering which is essential in designing electrical power systems. Simulations show if systems operate as expected, can withstand stress, and protect against failures. Many tools for power system analysis exist; one is a toolbox created by NTNU professor Olav Bjarte Fosso in the 90s. The toolbox consists of various FORTRAN-routines that do simulations such as Newton-Rapshon load-flow, continuation load-flow, contingency analysis, and security-constrained DC load-flow. Previous projects have worked towards making the toolbox available in Python, a popular object-orientated programming language. The speed and the functionality of the program is preserved by writing parts of the modernized code in C. The primary goal of this master's thesis is to update the simulation-function "acsolve" of that toolbox, which performs a Newton-Rapshon load-flow.

The specialization project "Toolbox for Power System Analysis" from 2019 by Åsmund Sælen purposed an initial implementation of acsolve. However, the implementation lacked functions for initializing the input-data; hence, the program could not run simulations on large power systems. This master's thesis presents Python-functions that communicates with Excel-files, and a more sophisticated way of initializing the parameters of the simulation-functions. An additional algorithm named "decsolve", which performs fast-decoupled load-flows, is implemented. The updated program is tested on various MATPOWER standard-cases to study the code's reliability and performance. Profiling-tools available in Python are used to optimize the initial implementations, and the module "timit" is used to benchmarks the speed of the program against open-source Python-projects.

The Newton-Rapshon load-flow function (acsolve) gave reliable results in all the tests, and Figure 1 show that the speed matches the open-source Python-projects "pypower" and "pandapower". The second simulation-function, decsolve, gave reliable results on small and medium-large power systems, but not on large. The master's thesis reached the primary goal of updating acsolve, and gave recommendations on how to resolve the apparent bugs in decsolve. Future contributors can use the documentations in this thesis to complete the translation of the original toolbox.

Comparing Optimization Strategies in Local Electricity Markets Applied to Large Industrial End-users in Norway and Residential Buildings in the UK

Student:	**Martine Halvorsen Sønju**
Supervisor:	**Kjetil Uhlen**
Co-supervisors:	**Pedro Crespo del Granado & Seyed Naser Hashemipour**
Collaboration with:	**Lyse Elnett AS**

Abstract
This thesis proposes two different optimization-based control system strategies, to be used on a local market level, and investigates the performance of the strategies based on the total cost of electricity during operation for the energy sharing region (ESR), or community, and for each end-user within the ESR. The strategies are also evaluated based on to what degree they can increase the self-consumption of power from DERs within the ESR, and derby decrease the energy consumption from the main grid. The peak demand of such ESRs, or of end-users with high energy demands, are of importance to the distribution system operator (DSO), as the DSO dimensions the local grid according to the highest measured peak power demand. To investigate the relationship between peak power demand and total electricity costs, a multi-objective optimization (MOO) approach based on the epsilon-constraint method is also implemented.

The first optimization strategy introduced is the decentralized control system strategy, which has as objective to minimize the total electricity costs for each end-user within an ESR. The second strategy is the centralized control system strategy, which minimizes the total cost of electricity for the whole ESR. In the decentralized strategy, the end-users can only utilize their own local production and/or storage units and the main power grid to meet their energy demands. The centralized strategy enables P2P energy trade among the end-users within the ESR, meaning that P2P energy can be used in combination with energy from local production and/or storage units and the main grid to meet the energy demand of each end-user within the ESR.

To examine the performance of the two optimization strategies, the strategies were applied to two different cases. The first case concerns a community of 25 residential buildings in London, UK, while the second case concerns three large industrial end-users at Forus, Norway. The two strategies make supply-demand decisions for each of the cases according to their objective function and associated restrictions.

The main results show that the centralized optimization strategy gives the lowest total costs for the ESR with a cost reduction of 1.0-8.0% compared to the decentralized strategy. The centralized strategy does also give the lowest costs for each of the end-users within the ESR, as the P2P energy trade increases the ESR flexibility in addition to reducing the amount of energy consumed from the main grid by 1.4-18.9%. It is observed that the difference in performance between the decentralized and centralized strategies is dependent on the amount of DERs and storage units in the specific case. A high amount of DERs and storage units minimizes the difference in performance between the two strategies. The results from the MOO show that there is a dependency between total electricity costs and peak power demand for the cases studied and that a small increase in cost can reduce the peak power demand by a significant amount.

Analysis and Optimization of a Passive Magnetic Bearing

Student: **Sindre Tungesvik**
Supervisor: **Jonas Kristiansen Nøland**
Collaboration with: **Sleipner Motor AS**

Abstract

The increasing application of high-speed rotating machinery gives rise to challenges related to friction losses, bearing lifetime and vibrations. A compelling solution to these issues is magnetic bearings, enabling contact-free levitation in one, or more, degrees of freedom. Through controllable magnetic field sources or combining permanent magnets and other types of bearings - losses, vibrations, and other mechanical bearing problems can be avoided. However, magnetic materials are expensive, especially permanent magnets. Hence, optimizing for minimal material usage in production and maximum lifetime is crucial.

The goals of the thesis was to present detailed finite element models (FEM) of a proposed passive magnetic bearing (PMB), perform analysis with emphasis on torque and force production capabilities, iron loss calculations and demagnetization risk, and present an optimized final design. The optimization was performed with the goal of reducing magnetic material cost while complying to set torque and demagnetization risk requirements. The tasks have been performed using COMSOL Multiphysics.

An approximated 2D axisymmetric model of the bearing was shown to be satisfactory for stationary studies, for example used in optimization algorithms. Hence, the analysis and optimization time reduced significantly.
At high temperatures, minor irreversible demagnetization occurred for the initial design, but this had a negligible effect on the bearing's performance. The demagnetized volume could be severe for specific geometric parameter variations, and constraints had to be imposed during optimization. Iron loss calculations showed 60 times higher iron loss for solid iron rings than for laminations, such that significant heating and increased demagnetization could occur if care is not taken. Using built-in optimization solvers in COMSOL, the magnetic material cost was reduced by 6.5 %.

Investigation of parasitics and thermal performance of a SiC MOSFET power module using FEM and LTSpice

Student: **Tobias Nieckula Ubostad**
Supervisor: **Dimosthenis Peftitsis, NTNU**
Co-supervisors: **Andreas Giannakis and Gard Lyng Rødal, NTNU**

Problem description

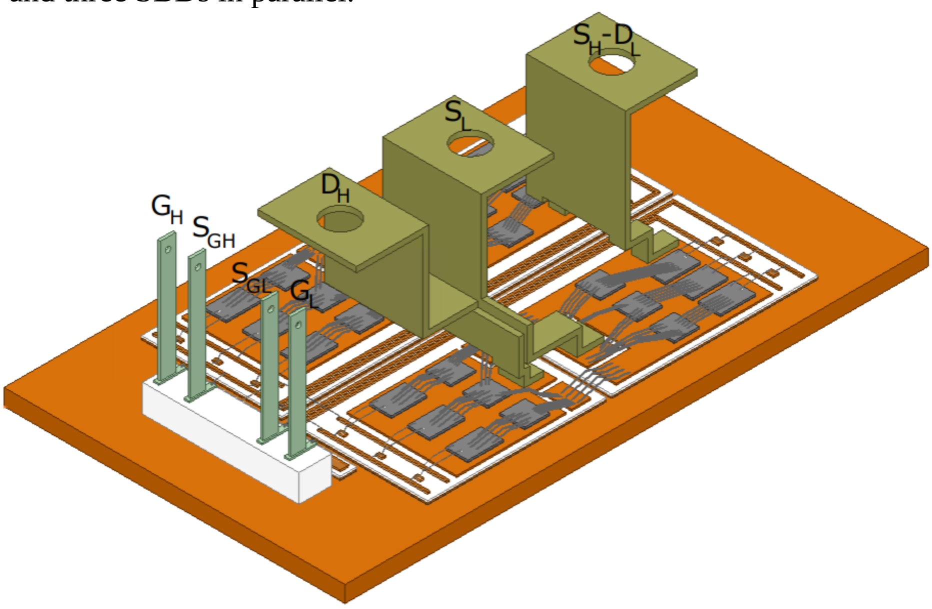
Current Silicon (Si) technology is reaching its theoretical limit in terms of switching and conduction performance. They have relatively high losses and and limited switchin speed, which limits any improvement to the power density as the passive elements are larger. However, recent development in silicon carbide (SiC) power semiconductors enables the design and implementation of more compact and efficient power converters. SiC devices can attain higher switching speed and junction temperatures, opening up for development of power modules with power densities that are not attainable with existing Si technology. However, commercially available power modules today are still based on designs similar to existing Si IGBT modules, which limits both the switching speed and thermal performance of the module. Furthermore, they have a unfavourable parasitic design, which induce overvoltages and oscillations due to the fast switching SiC devices, and thus limit the superior properties of SiC.

The task

In this thesis the aim is to recreate and simulate a conventional SiC MOSFET power module in FEM software. The selected module is the half-bridge CAS300M12BM2 from Cree. Its geometry will be realized in ANSYS EM. The parasitic components of the module will be investigated and extracted though FEM and incorporated into a SPICE circuit for analysis in LTSpice. Furthermore, some improvements will be made to reduce the inductance of the module. In addition, the thermal performance of the module will also be evaluated through FEM simulations.

Model

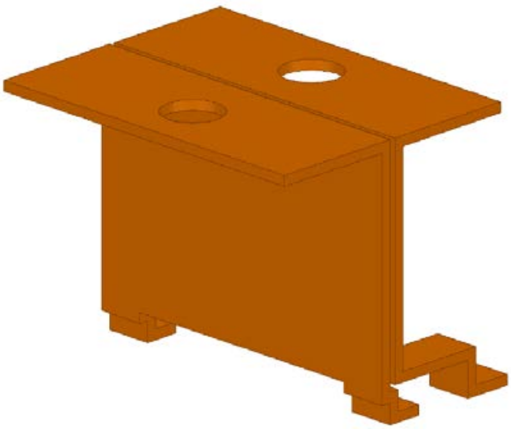
The 3D model of the power module is shown in the figure below, and is the basis for the whole thesis. Each switch consits of two in parallel pads, and each pad contains three SiC MOSFETs and three SBDs in parallel.

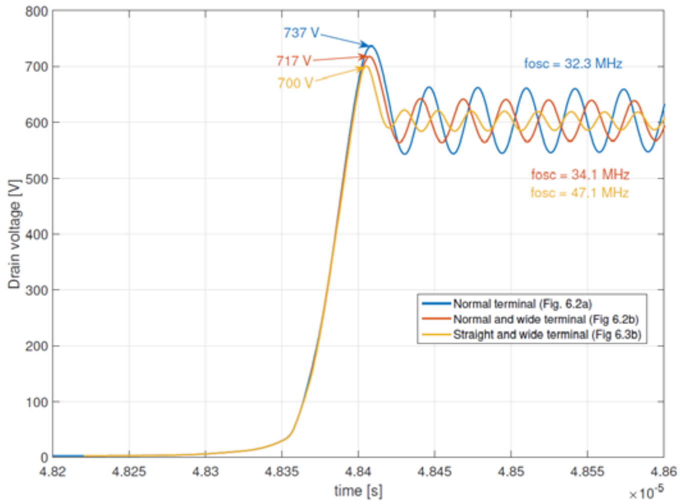


Simulation results

The parasitic extraction showed that a significant amount of the stray inductance in the module comes from the main power terminals, which will affect the switching performance of the device. LTSpice simulations showed significant voltage overshoots and ringing due to the stray inductance in the module. It was found that the simulated switching losses follow the same trend as the datasheet values of the physical module, but with some discrepancies, as the the simulated model has som limitation in how the LTSpice models of the SiC MOSFETs work and that the junction temperature was fixed. Furthermore, the thermal analysis shows that the middle MOSFET in each pad will experience higher temperatures, due to thermal coupling to the chips beside it. This is especially noticeable in the lower switch position as the dies as more tightly placed.

The power terminal design was improved so that a larger advantage is taken of the magnetic cancelling effect, which effectively reduce the stray inductance of the module. One of the improved power terminal designs is shown below, together with the improved turn-off voltage waveforms. The voltage overshoot has been reduced from 137 V for the normal module to 100 V with new improved terminal design. Furthermore, there has been a reduction in switching losses due to less overshoot in the voltage.





Conclusion

The thermal analysis revealed that the layout of the MOSFET dies is not well fit for high temperature operation, as the dies in the lower switch position experience much higher junction temperatures due to them being to more tightly placed. Moreover, the middle MOSFET in the lower switch is the bottleneck of the module and limits the maximum temperature to 150 °C.

The LTSpice simulations showed results that correspond well with datasheet, and it was revealed that significant voltage overshoots will be present.

Strip-line arrangement of the power terminals showed that the inductance of these elements can be reduced significantly, as the magnetic cancelling effects are taken advantage of to a larger degree. However, implementing such a design in a physical module might be difficult due to space restriction and low margins when it comes to distance between the positive and negative terminals.

Towards Energy Management of an MMC With PV and BESS

Design, Control and Operation Under Power Mismatches

Student: **Egil Viken**
Supervisor: **Gilbert Bergna-Diaz**
Co-supervisor: **Raymundo E. Torres-Olguin**

Problem description

A new promising grid interface for distributed energy resources (DERs) is the modular multilevel converter (MMC). The interest for MMC as a grid interface comes from its unique topology which consists of distinguishable submodules that can be connected in series. In previous MMC topologies, as seen in Figure 1, the submodules usually consist of only a capacitor for providing voltage steps to synthesize the AC voltage. However, DERs can be interfaced by connecting them in parallel to each of the submodule capacitors. The result is that the MMC can provide a distributed interface for DERs that are easily amplified to medium-high voltages. PVs are one of the fastest growing DERs, but due to its intermittency its power must be supported by battery energy storage system (BESS). Thus, specifically, the MMC can be used for interfacing PVs and BESSs.

The task

The distributed nature of DERs creates power mismatches in the MMC. The PV arrays of different submodules may not receive the same irradiance and the BESSs may be given distinct power references. Consequently, the power flow coming from each submodule may differ. These power mismatches must be mitigated in the MMC to provide balanced grid currents or else the converter becomes unstable. Power mismatch mitigating techniques are proposed and found successful, but are not tested for mixed power flows, that is, MMCs where there are submodules consuming power and submodules delivering power simultaneously. The MMC's ability to mitigate power mismatches during mixed power flows should be investigated to identify the necessary constraints of an MMC energy management system for grid-connected DERs.

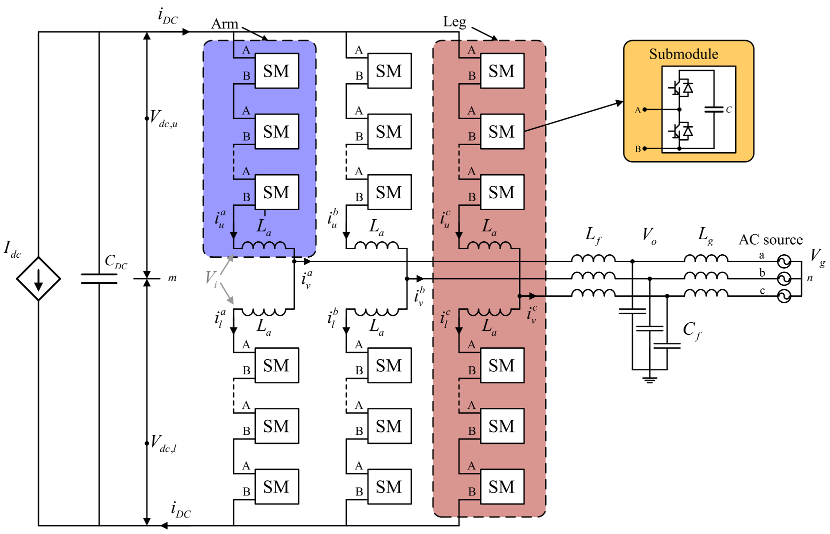


Figure 1 - An MMC topology

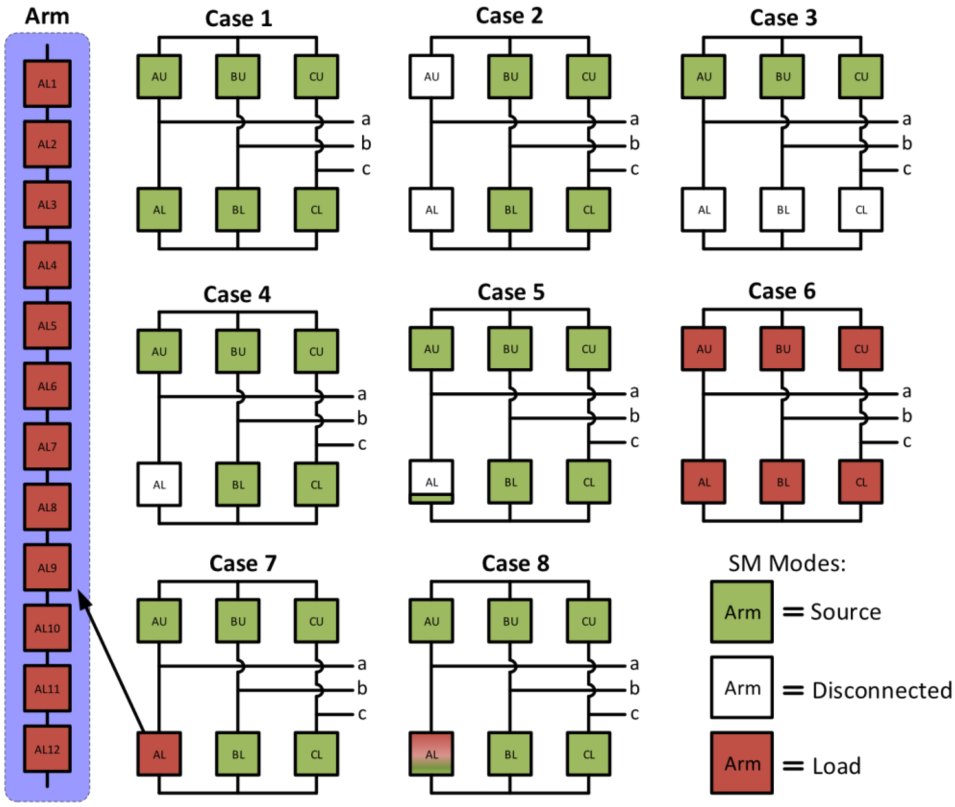


Figure 2 - Power mismatch scenarios for testing the MMC

Model/measurements

An MMC model was made to investigate the MMC during power mismatches. The methods for mitigating the mismatches was outlined and verified through simulations. A submodule was designed to interface the PV and BESS in each submodule. Beside from the DERs, converters were added for controlling the power in the submodules. A dual active bridge was used to set the maximum power point for the PV and a bidirectional boost converter to control the power flow. Each DER and converter were modeled, and steady-state equations was developed. The MMC was investigated using the cases defined in Figure 2. The figure illustrates the power coming from each arm and submodule in each case. The cases were evaluated and compared by defining key performance indicators (KPIs) which assessed the total grid current imbalance, the harmonic content of the grid current and the deviances of the submodule voltages from their rated values.

Conclusion

The MMC was found to successfully manage mixed power flow between the arms. However, mixed power flows between the submodules could not be guaranteed. If too many submodules with power flows different from the overall MMC power direction were present, the voltages of these submodules would deviate from their rated values.

Power System Analysis on Electrifying Gina Krog from Shore

Student: **Krishna Raju Vulchi**
Supervisor: **Kjetil Uhlen**

Problem description

Gina Krog is an Oil and Gas field in the North Sea located about 65 km from Johan Sverdrup, and came on stream in June 2017. The project to prepare Gina Krog platform to import the main electrical power from shore via a 65 km long subsea cable from the Utsira High Power hub (UHP) at Johan Sverdrup.

The following elements studied for the Power from Shore import for Gina Krog.

- Load flow analysis
- Short circuit calculations
- Switching assessment and simulations
- Assessment of protection devices on Gina Krog
- Discussions and Conclusions for each element

Eddy current losses in transformer windings

Student: **Marianne Waagan**
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Contact: **mariannewaagan@hotmail.com**
Collaboration with: **SINTEF**

Problem description

Power transformers have very high energy efficiencies, typically more than 99.5%. The eddy current losses in the windings normally account for a small part of the total losses, of which the "DC-losses" in the windings constitute the major part. However, the eddy current losses are concentrated at the top and bottom windings and thereby they contribute to the creation of hot spots. Hot spots are particularly important for the paper insulation between the turns and windings as high temperatures increase the ageing of the paper and reduce the life-time of transformers.

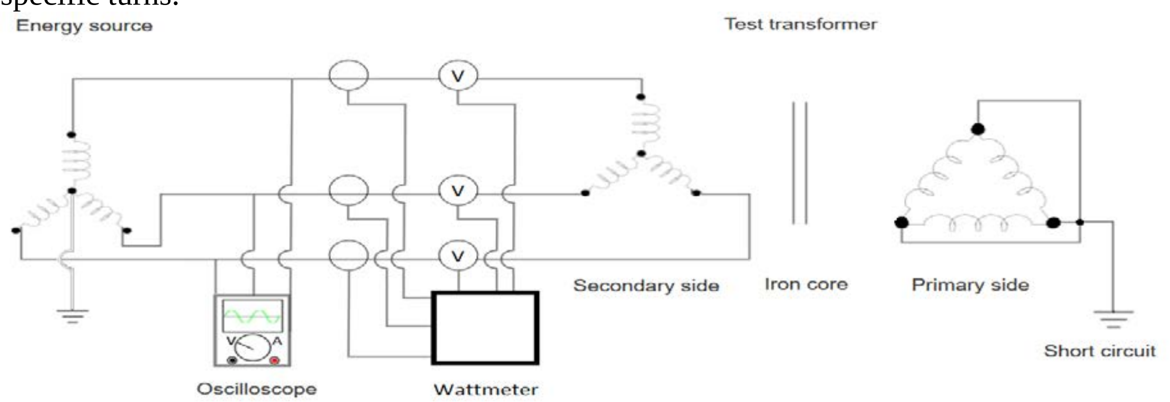
Methods to accurately determine the magnitude and distribution of the eddy current losses in the windings are therefore important for thermal analyses and life-time estimation of transformers. There are simplified methods to determine the eddy current losses in the windings. In this project, measurements of eddy current losses in windings were performed to evaluate whether the simplified methods are accurate. They were performed on a 230/400 V test transformer.

The task

The work in this master thesis includes:
- Evaluation of methods to directly measure eddy current losses in windings
- Design and building of a test set-up for loss measurements on a 3-phase transformer, including a method to measure the magnitude of eddy current loss in windings
- Model circulating currents in the transformer windings.
- Loss measurements on the transformer
- Evaluation of the accuracy of calculated eddy current losses in windings (based on a comparison with measured losses)

Model/ measurements

To do the mesurements in this master thesis, the set up presented in Figure 1 was used. In addition to this, thermocouples were placed on the windings to measure the temperature in specific turns.



Figur 1 The set up for the measurements

For the modelling, COMSOL Multiphysics was used. A 3D model was constructed to investigate the effect of circulating currents, and a semi-analytical loss calculation method was used in a 2D model to calculate the losses in specific turns in the test transformer.

Calculation
One of the comparisons done in this master thesis at nominal rms current between measured ansd simulated losses is presented in the table below. There were also measurements and comparisons done at half and twice the nominal rms current of 115 A.

Thermocouple	107	108	109	110	111	112	113	114	115	116
Measurements[W/m]	1.34	1.17	1.36	1.37	1.35	1.41	1.42	1.43	1.43	1.36
Simulations[W/m]	1.27	1.77	1.39	1.77	1.27	1.77	1.77	1.27	1.27	1.39
Difference in %	5.37	-33.8	-2.29	-22.4	5.55	-20.1	-19.8	12.5	12.8	-2.17

In addition to this, measurements of total loss, resistance, short circuit heat run test and measurements of circulating current were performed.

Conclusion
The three phase losses found at room temperature in the specialization project at 841.3 W increased to 931.7 W when taking into consideration circulating currents, causing the losses to increase with 10.7 \%. It is still not at 1.11 kW, which is the copper losses registered at room temperature for the transformer. When comparing the simulated circulating currents in the primary winding and the measured circulating currents, it becomes clear that the difference is rather small, both in amplitude and phase angle.

From the resistance measurement, it became clear that the primary winding has the largest resistance. There were some differences between the measured and calculated value of the resistance at room temperature, 7.648 \% in the secondary winding and 8.215 \% in the primary winding. This difference is assumed to be due to inaccurate geometry assumptions of the transformer and inaccurate data about the area and resistivity of the conductor. For the resistance after the heat run test, it became clear that the calculated average temperature of the primary winding matched well with the measured temperature.

For the temperature measurements, the linearity in the first 10 minutes of measurements showed that the assumption of approximately adiabatic heating was valid. It was noted that the higher the current, the bigger the temperature increase would be. When using these temperature increases to calculate the power loss in the turns, there were some differences between the measured and simulated result depending on the winding parallel, regardless of current being applied. The cause of this was not found and further research would be beneficial.

The comparison between the magnetodynamic and the semi-analytical loss calculation method when considering circulating currents showed minute differences between the methods, and it is therefore assumed that they can be used interchangeably at 50 Hz. For the comparisons between the loss calculation methods with and without circulating currents, differences became clear depending on position of the winding parallel and can be explained using the leakage field and the geometry of the winding.

Electric Utility Customer Segmentation from Advanced Metering Systems Data

Student: **Kari Walstad**

Supervisor: **Vijay Venu Vadlamudi, NTNU**

Contact: **Aina Romani Dalmau Serigstad**

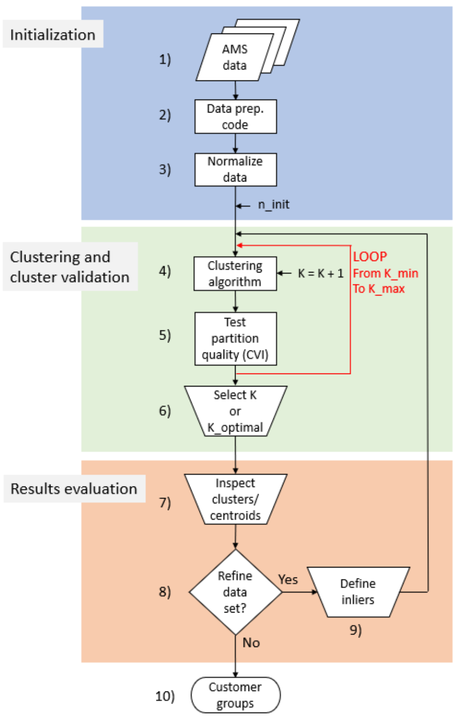
Collaboration with: **Lyse Elnett, CINELDI**

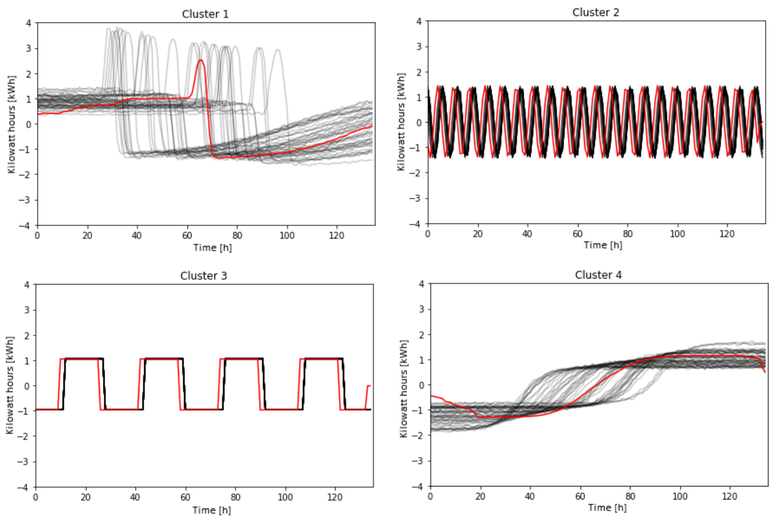
Problem description

The Norwegian Regulatory Authority for Energy have required all Norwegian Distribution System Operators (DSO) to install Advanced Metering Systems (AMS) meters at every point of measurement in the distribution utility grid by 1 January 2019. An AMS-meter is able to capture a wide variety of data types in real time. Analysis and evaluation of this data has the potential to benefit DSOs in several ways. The initial task of this work was to identify an area for analysis of benefit to DSOs, which could be based on the provided AMS consumption time series data. It was decided to develop a computer-based tool for customer segmentation. The ambition was to base the development of the tool on freely accessible programs and algorithms. Furthermore, it was a wish that the tool could be used by DSOs or other interested parties after the completion of this report.

The task

A synthesis computer programme for customer segmentation was developed in the coding language Python, using shape-based clustering (i.e. amplitude, offset and time invariant), and a Cluster Validation Index (CVI) algorithm. Additionally, an option to perform outlier analysis of the AMS input data was included in the programme.





The developed programme for discovering customer groups of similarly shaped power consumption profiles within a set of AMS-data is shown in the figure above (left). The assessment of the developed customer segmentation programme and the underlying methodology was first done through tests on a known data set to check whether the results that were known beforehand to be correct would be produced, see figure above (right). Following this, an assessment was made on the basis of actual AMS-data sets provided by Lyse Elnett.

Conclusion

On a known/defined data set the developed customer segmentation programme was shown to produce the results that were known to be correct beforehand. Outlier analysis methods, which the user can chose to apply, were shown to be able to sort out predefined outliers provided some user input and guidance.

An assessment was made on the basis of actual AMS-data sets provided by Lyse Elnett. When tested on the first AMS-data set, the programme showed a tendency to prefer segmenting based on similar periodicity of the time series. Additionally, AMS-data was more challenging for the algorithm to cluster than the known data set, as the AMS-data set contained less distinct time series groups and to some extent more irregular data. Outlier analysis was shown to improve the programme performance by removing irregular (i.e. flat) time series.

The developed customer segmentation programme was shown to produce a better partition compactness of the second AMS-data set than the standard DSO method when measured with a CVI. It should be remembered that the basis for the standard DSO segmentation method is not necessarily founded on segmenting for similar consumption shapes, but for similar customer types. For this reason, the developed customer segmentation programme may be used as a complementary method, which provides additional insight to the standard customer segmentation approach.

In this work, the computer-based programme has been developed based on openly available advanced data analysis tools, and is considered usable for a DSO engineer with a power systems background and an information technology interest. Experience with the programme indicates that runtime may be an issue when analysing large AMS-data sets.

Some potential improvements to the developed programme were also identified. One of these was the potential for the programme to take into account the standard DSO segmentation, in order to include amplitude and offset information in the analysis. Another area of improvement was the language in which the programme was written. Python is a relatively high-level coding language, and the efficiency of the programme and thereby calculation time may be improved if a lower-level language such as C++ were utilized.

Instantaneous Frequency Identification in Microgrids Through Adaptive Data Analysis

Student: **Erlend Westad**
Supervisor: **Olav Bjarte Fosso**
Co-supervisor: **Marta Molinas**
Collaboration with: **Department of Engineering Cybernetics**

Problem description

With the increased integration of power electronic equipment and distributed energy generation, the modern power system has become more prone to harmonic pollution. As isolated systems categorized by low inertia such as microgrids are more common, the presence of non-linear distortion is becoming an increasing problem. The most common methods used for surveillance in the power system are as of now based on average value calculations. They are thus not suited for the rising non-linearity caused by the harmonics in the evolving system. For monitoring and control equipment to keep operating with adequate performance, there is a need for alternative surveillance methods capable of instantaneous frequency and amplitude detection. However, using mathematical formulations to describe physical behaviour in large scale systems can be challenging. Controllers relying on mathematical models and approximations may lead to complex control schemes whose operations might be challenging to understand, and implementation might be costly due to their complex nature. As opposed to this high-fidelity modelling, this thesis explores the use of adaptive data analysis as an alternative method for frequency and harmonic monitoring in the power system. Using methods capable of handling both non-linear and non-stationary signals, available measurements are used to characterize the grid under investigation.

The task

This thesis's objective is to explore adaptive data analysis as an alternative to present methods used for monitoring and control in the power system. This is done by assessing the potential of Empirical Mode Decomposition (EMD) and online EMD when used in conjunction with the Hilbert Transform (HT) assisted by the Fast Fourier Transform (FFT). The main methods are a thorough review of existing literature, constructing synthetic signals to compare decomposition quality, and applying the detection methods to an actual voltage and current measurement to identify the harmonic content. Techniques for mode-mixing separation in the EMD are also explored, mainly focusing on masking signals constructed by the help of frequency identification through FFT and a boundary condition map. This technique is then adapted and investigated when used with the Online EMD.

Results and Conclusion

A comparison of the decomposition quality of the EMD and Online EMD is made through the analysis of synthetic signals. When applied to a three-tone superimposed signal, the decomposition quality of the Online EMD is seen to converge to the decomposition quality of the classical EMD using identical stoppage criteria. Results presented in Figure 1. For lower values of window size, the Online EMD has a slightly worse decomposition quality but is seen to outperform the classic version for $l = 13$. As a disturbance is added to the signal, there is no clear relationship between the online and classical versions. This is presented in Figure 2. However, Online EMD is seen to result in slightly better decomposition for lower window sizes compared to the classical EMD using identical stoppage criteria, but as the window size increases, the decomposition quality declines.

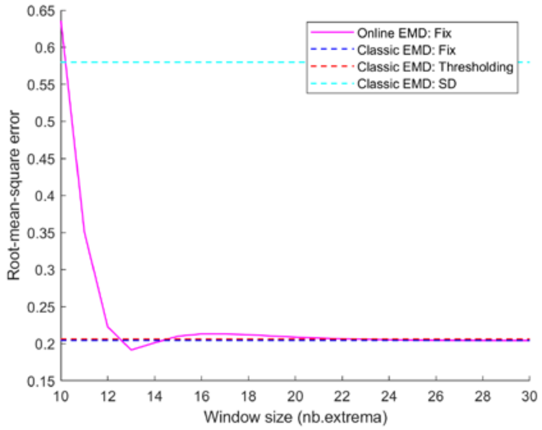


Figure 1: Average root-mean-square error for all IMFs as the widow size increases for the Online EMD.

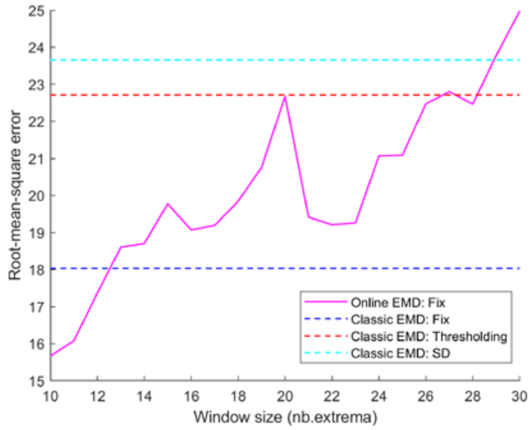


Figure 2: Average root-mean-square error for all IMFs as the widow size increases for the Online EMD with added gaussian white noise.

These methods are then used to identify the harmonic content in an actual voltage and current measurement taken from a wind-turbine. The measurements are decomposed using both EMD and Online EMD and are further analyzed by FFT and HT. The resulting decomposition of current L1 and voltage L12 using classical EMD can be seen in Figure 3 and 4 respectively. Using FFT for frequency identification to construct appropriate masking signals proved to be highly effective when used in conjunction with a boundary condition map. While there are traces of inter-harmonics in IMF 3 of current measurement L1, the separation of modes using classical EMD is deemed satisfactory. This is also the case for Online EMD. As such, the usage of masking signals for mode-mixing separation can be considered effective when adapted to the Online EMD. The findings based on classical and Online EMD proved to be similar enough to warrant an identical conclusion. Thus, the Online EMD is deemed to be a suitable alternative to the classical version when real-time identification or processing power is of the essence.

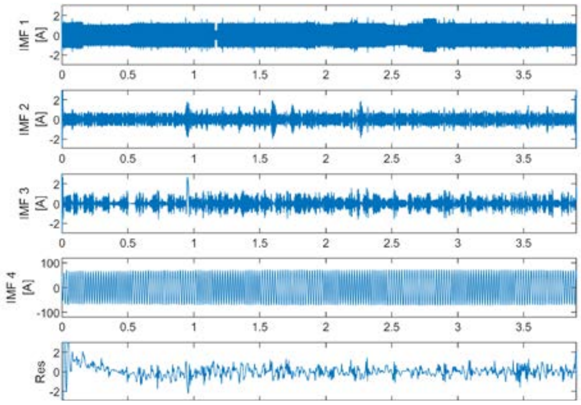


Figure 3: Final resulting IMFs for current measurement L1 using classical EMD.

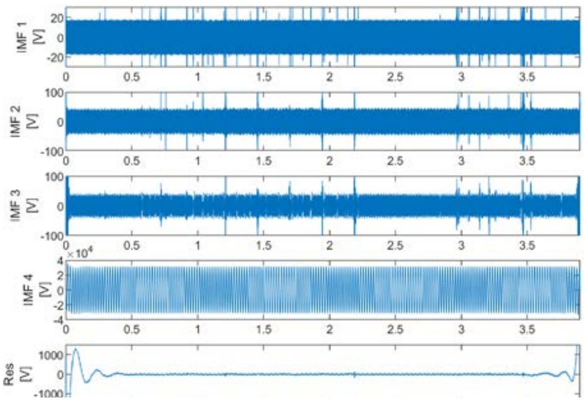


Figure 4: Final resulting IMFs for voltage measurement L12 using classical EMD.

The Impact of Offshore Wind Power Variations on Continuous-time Scheduling of a Hydrothermal System

Student: **Mari Lund Øvstebø**
Supervisor: **Hossein Farahmand**
Co-Supervisor: **Christian Øyn Naversen**

Problem description
As a part of the climate policy, a significant amount of offshore wind power is expected to be integrated into the Northern European power system in the coming years. The variable nature of wind power generation challenges the security of the power supply as the flexibility of conventional generators are pushed to their limits. Larger shares of offshore wind power result in more frequent and unpredicted changes in the power flow between connected areas, amplifying the structural imbalances in the system.

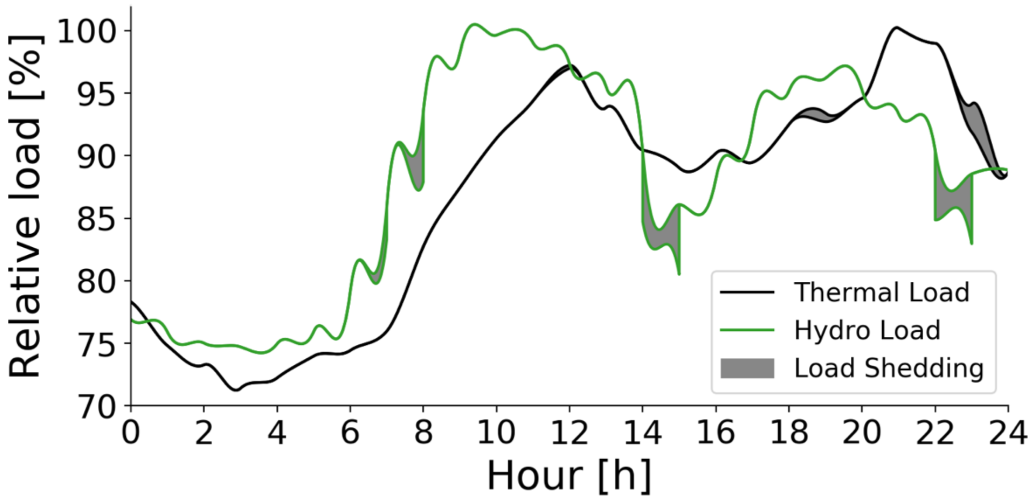
The task
The tasks in this thesis were to implement both a discrete-time and a continuous-time UC model for a hydrothermal system with integration of offshore wind power to look at how variable and uncertain wind power production would affect the coordination of thermal and hydropower production, and to look at the differences between the two UC models.

Model/ measurements
In this thesis, a stylized three-area power system representing parts of Northern Europe is considered. The power system consists of a hydro dominated Norwegian area, a thermal dominated German and Dutch area, and an offshore wind area in the North Sea, connected through HVDC cables. A continuous-time UC formulation is used to model the Northern European system operation. The cost of covering the structural imbalances in the system is quantified by a cost comparison to an analogous discrete-time model for different cases.

The work was performed with Pyomo, a Python-based optimization modelling language. Below, the objective function for the continuous-time UC model is presented, where different costs of the system are included. In addition, both UC models exist of several operational constraints for both thermal and hydropower production. The constraints for the continuous-time UC model are formulated with the use of Bernstein polynomials, where the Bernstein polynomial coefficients are the decision variables in the optimization problem.

$$Z = \alpha + \frac{1}{4}\sum_{h\in\mathcal{T}}\delta_h \mathbf{1}^T \cdot \left(C^c\boldsymbol{\rho}_h^c + C^s\boldsymbol{\rho}_h^s\right) + \frac{1}{4}\sum_{m\in\mathcal{M}}\sum_{h\in\mathcal{T}}\delta_h\mathbf{1}^T\cdot\left(C^b\mathbf{q}_{m,h}^b + C^o\mathbf{q}_{m,h}^o\right)$$
$$+\sum_{i\in\mathcal{I}}\sum_{h\in\mathcal{T}}\left(\frac{1}{4}\delta_h C_i\mathbf{1}^T\cdot\mathbf{g}_{i,h} + C_i^{start}SU_{i,h} + C_i^{stop}SD_{i,h}\right) \tag{4.29}$$

The continuous-time UC model was used as a simulator for real-time operation to investigate where the discrete-time model overestimates the flexibility of the system. This was done by fixing the binary commitment variables for the continuous-time model to be equal to the commitment decisions from the discrete-time UC model. This resulted in load shedding, shown as gray areas in the figure, which is load that the system is not capable of covering



Conclusion
If the discrete-time unit commitment is implemented for real-time operation, load shedding will be introduced since the demand in periods with high net-load ramping cannot be met. The simulation results demonstrate that the proposed framework reduces system balancing costs and the events of ramping scarcity in real-time balancing of the power system.