Masteroppgaver 2021

NTNU
Norges teknisk-naturvitenskapelige universitet
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Summary of Master's Theses 2021

Department of Electric Power Engineering

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Fakultet for informasjonsteknologi og elektroteknikk
Institutt for elkraftteknikk

Summary of Master Theses 2021

Another year has passed, and a new class of Master students have completed their education at the Department of Electric Power Engineering here at NTNU. And what a year it has been – with lock downs and restrictions that have made it difficult both for students and supervisors.

With this backdrop it is very satisfactory to be able present this summary of Master Theses from our 2021 class. I would like to take the opportunity to congratulate each and every student with completing the Master thesis and by that also the educational journey at NTNU.

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

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

Enjoy the reading!

Anngjerd Pleym
Head of Department

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Co-Simulation of an IPMSM Drive Using Comsol and Simulink

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Supervisor: **Robert Nilssen**
Contact: **krsandersson@gmail.com**

Problem description

Regular drive simulations are using the idealized LPM motor representation, where the parameters are omitting spatial harmonics, cross-coupling, and saturations. Co-simulations with the advanced FEM model representation of the motor can be a way to mitigate the mentioned limitations with the LPM in future design.

The task

It is made a co-simulation model of a three-phase IPMSM drive with the software package Comsol LiveLink for Simulink. The control system is using MTPA modulus optimum for the current controllers and symmetrical optimum for the speed controller. The linearized converter model is enabling to decouple the machine spatial harmonics from the PWM current and torque ripples since the reference signal, in principle, is sinusoidal. The results of the FEM model are compared with the lumped parameter model (LPM) in the co-simulations. It is included a list in the chapter "Introduction" about previous work/references.

Model/ measurements

The IPMSM is from the NTNU-laboratory. The IPMSM was taken apart to take geometric measurements. Subsequently, one sector was made shown in Figure 1. Extensive testing in the FEM software was made to reverse engineer the proper of number of turns and magnetic remanent flux density to obtain the nameplate data per phase BEMF of 214 V RMS/kRPM, rated current of 4.93 A RMS and rated torque of 28.7 Nm. The IPMSM in Comsol is however Y-connected, while D-connected in the lab, implying not equal inductance parameters. To obtain a correct co-simulation set up, it is important that the d-axis is aligned with Phase A shown in Figure 1. This is needed to get the equal current wave trend in the FEM model compared to the LPM-model depicted in Figure 2. Input parameters and output variables defined in Comsol and exported to Simulink is shown in Figure 3.

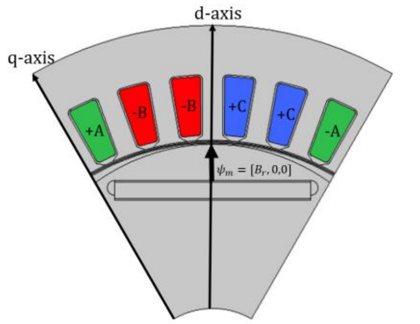


Figure 1 Alignment of the d-axis with Phase A

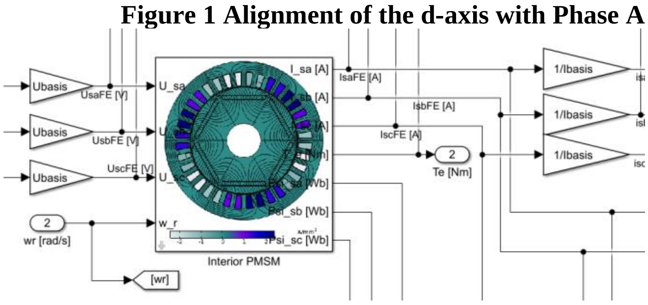


Figure 3 Co-Simulation Block in Simulink

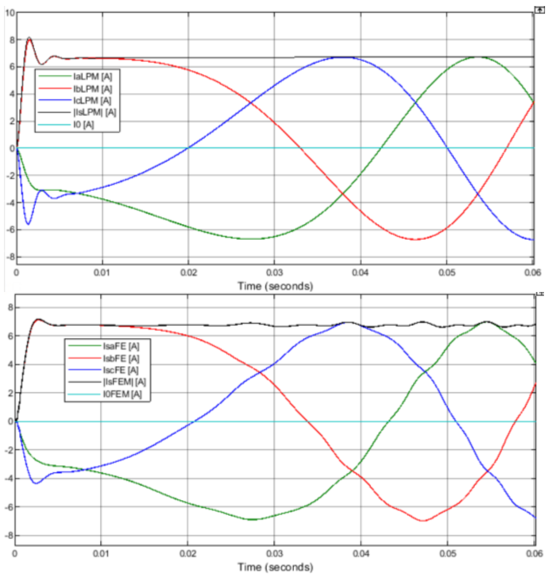
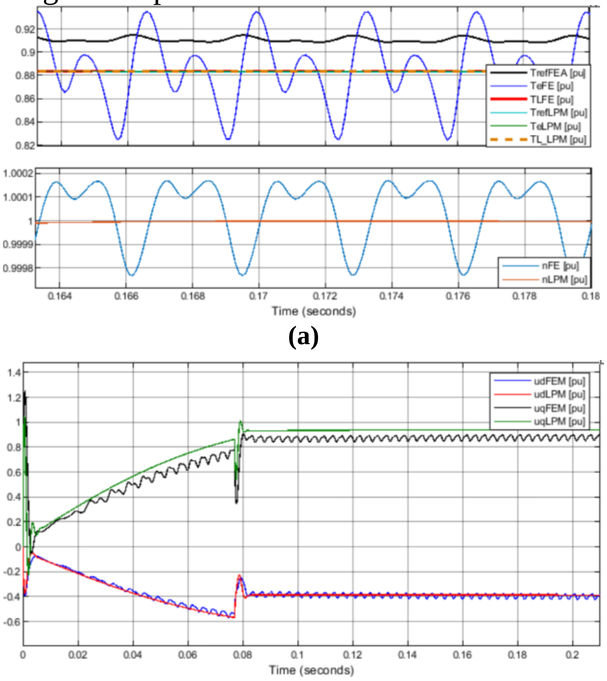


Figure 2 Current waves with the LPM model and FEM model, respectively.

Calculation

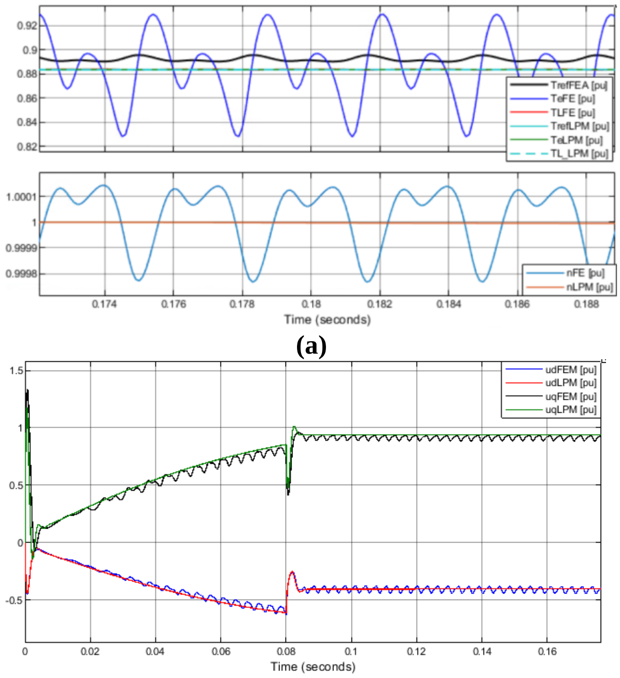
In the co-simulation results the FEM model was compared with the equivalent regular LPM model. It is clear that cogging torque due to slotting, spatial harmonics, saturation and cross coupling is influencing the drive system depicted in Figur 4 and Figur 5. It was discovered that the co-simulation results were computed with a saturated parameter late in the study shown in Figur 4. The co-simulations with the new parameters are shown in Figur 5, with an improvement in FEM torque estimation error shown in (a) and q-axis voltage estimation error shown in (b) compared to the LPM. This shows the significance of obtaining a correct magnetic representation of the FEM machine in the drive.



(a)

(b)

Figur 4 Results with the saturated d-axis inductance.



(a)

(b)

Figur 5 Results with unsaturated d-axis inductance.

Conclusion

It is described how to perform a co-simulation drive system of an IPMSM with the software Comsol LiveLink for Simulink in detail. The co-simulation results are comparing the FEM model with the equivalent LPM model. The impact of the spatial harmonics, saturation, and cross coupling from the motor on the drive system are investigated. Although co-simulation is have limitations with a handful of references due to a relative new field, this approach with newly released software, better computer capacities and expanded knowledge from the past few years in the field, can offer accurate designs in the future and reduce the amount of protypes in the design phase, especially for fault cases.

Case Study: Self-Interest for Microgrids in Providing Peak Shaving and Congestion Management Services

Student: **Elias Heimland and Aasta Gran Andreassen**
Supervisor: **Gro Klæboe**
Co-supervisor: **Stine Fleischer Myhre**

Problem description
This thesis investigates if there are drivers in the current market structure that encourage microgrids to provide peak shaving and congestion management services. The study is motivated by the ongoing development in the distribution grid and the potential in exploiting available resources. The case study is based on Rye Microgrid.

The task
The case study in this thesis regards a microgrid and the operation of its flexible resources. The objective is to determine if the existing Norwegian market model and regulations facilitates for the self-interest of market players in providing peak shaving and congestion management services. The self-interest lies in the economic gain from utilising storage systems for power trading that exploits price fluctuations. The study aims at identifying in which areas the objectives of a microgrid owner and the DSO coincide.

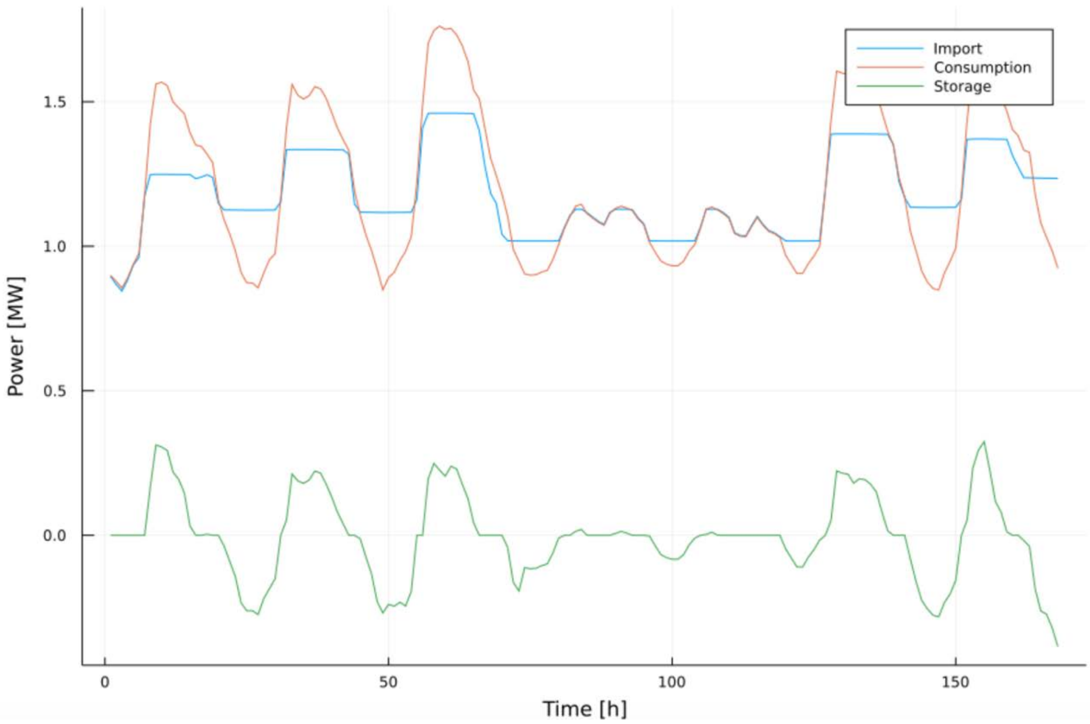
Model
The system model consists of Rye Microgrid and an electrically confined area of the surrounding distribution grid. The simulations use measured power production and load demand data from Rye Microgrid, as well as historical electricity prices from NordPool. The optimisation models are based on a deterministic and nonlinear approach to multi-period optimal power flow (MPOPF). The optimal energy storage system scheduling is found for three different cases. By simulating these cases for two periods, the seasonal variations in DER production, electricity price, and consumption levels are taken into account.

Calculation
The following case summary is given:

- *Case 1 - Non-Weighted Maximum Profit*
  This strategy will largely profit the microgrid owner. It produces the highest earnings from battery operation and total revenue among all cases. The indifference to ancillary services is, however, obvious and will to a little degree reflect the objective of the DSO.

- *Case 2 - Weighted Maximum Profit*
  The microgrid owner profits from the operation, a somewhat smaller profit compared to Case 1, but will largely support the grid infrastructure with peak shaving. The strategy is evidently agreeable with the aims and objectives of either party involved.

- *Case 3 - Peak Shaving Import*
  The strategy formulation has superior peak shaving and congestion management capabilities to the other cases. The microgrid owner profits from this strategy as well.



Case 3, January: Peak shaving and congestion management abilities illustrated by the difference in total consumption in the distribution network (red) and the power flow over the import line to the distribution network (blue). The battery charging scheme is shown in green.

Conclusion

The thesis argues that a correlation between electricity prices and congestion tendencies in the local distribution grid makes power trading implicate congestion management.

The quantitative results from the simulation of the case study model suggest that there are economic incentives for storage system operators to provide peak shaving and congestion management services in a system where they are strictly motivated by market-based drivers. Refers to a market that establishes price signals which encourage a certain interaction. It also indicates how implementing a nodal pricing model, compared to the existing zonal pricing model, would strengthen the correlation between electricity prices and congestion tendencies in the local distribution.

Utfordringer knyttet til overstrømsvern i mikronett, og behovet for kommunikasjon

Student: **Adam Ata**
Faglærer: **Eilif Hugo Hansen**

Sammendrag

EN av de mest drastiske endringene det elektriske kraftsystemet opplever i dag, er integreringen av små og mellomstore distribuerte energiressurser (DER-er), i det tradisjonelle distribusjonsnettet. Mikronett er blitt sett som en effektiv løsning som kan benyttes for å koordinere, integrere og drifte DER-er i det nye kraftsystemet. Mikronett kan defineres som uavhengig og kontrollbar små elektrisk kraftsystem drevet av lokale DER-er, laster og lagringsenheter med evne til å operere som nett-tilkoblet eller i øydrift-tilstand. Likevel integrering av DER-er gir flere utfordringer til overstrømsvernet i mikronett. Blant annet toveis effektflytt, variasjoner i kortslutningsstrøm, spenning og frekvens, samt overbelastning og tap av koordinering mellom effektbrytere ved overgang mellom ulike driftstilstander i mikronett. Disse utfordringene forverres i tilfelle ved flere inverterbaserte energiressurser, spesielt når mikronettet opererer i øydrift-tilstand. Derfor de tradisjonelle beskyttelsesstrategiene og konvensjonelle overstrømsvern ikke kan være tilstrekkelig lenger.

Det eksisterer flere forskjellige metoder og løsninger som er benyttet i ulike land i forbindelse med utfordringer knyttet til overstrømsvern i mikronett. ABB har utviklet mikroprosessorbaserte digitale effektbrytere kalt for Tmax XT2, som inneholder mange forskjellige funksjoner som kan benyttes for å løse utfordringene i mikronett. Noen av disse funksjonene er utforsket og analysert, og en optimal løsning er representert for hver utfordring. Følgende løsninger er presentert i oppgaven:

- Retningsbestemt soneselektivitet for å løse utfordrende selektivitetsoppgaver.
- Adaptiv beskyttelse (dual setting) for å løse utfordringer knyttet til variasjoner i kortslutnings-strømmer ved overgang fra nett-tilkoblet til øydrift-tilstand.
- ATS-funksjon, både for styring av overgangen mellom nett-tilkoblet og øydrift-tilstand, og for tilkobling av alternative kilder i øydrift for å dekke manglende effektbehov.
- Synkronsjekk for sikker tilkobling av en generator mot offentlig nett og alternative forsyninger.
- Laststyring (Load shedding) for å unngå store spennings- og frekvensvariasjoner forårsaket overbelastning i øydrift

Oppgaven har også undersøkt behovet for kommunikasjon i et mikronettsystem, og i den forbindelse ble det gjennomgått ulike kommunikasjonsmetoder i et mikronett. Kommunikasjonsrollen er sett som å være essensielt for å sikre en stabil, pålitelig og optimal drift av et mikronett med høy integrasjon av DER-er.

For å undersøke effektiviteten til Tmax XT2 effektbryteren i forbindelse med beskyttelse mot overbelastning, utførte forfatteren en laboratorietest for en enkelt tenkt mikronettmodell. Laboratorietesten har som målsetting å undersøke hvordan kommunikasjonsbaserte digitale reléer kan benyttes for å overvinne utfordrende overbelastningssituasjoner i øydrift-tilstand. Resultatet fra laboratorietesten viser at den enkle laststyringsmetoden kan løse utfordringen med overbelastning i øydrift-tilstand.

Feeder selection algorithms for high-impedance faults in resonance grounded distribution systems

Student: **Erik Sjøvold Aune**
Supervisor: **Hans K. Høidalen**
Contact: **Thomas Treider**

Problem description
The traditional Wattmetric algorithm utilized in resonance grounded systems has shown to inadequately identify faulty feeders. Typically, it is due to the fault impedance, but might as well be the result of unfortunate system parameters. Consequently, the protection scheme is unable to isolate the faulty feeder, causing hazardous situations, material damages, and possibly fail to adhere to regulations.

Due to the increasing utilization of cable infrastructure, resonance grounding has gained popularity in high voltage distribution networks. Therefore, optimal protection might prove crucial to maintaining a reliable power supply in the future. Companies such as A.Eberle, Siemens, and ABB are in the pursuit of developing new and better algorithms, which has led to the QU algorithm, the Directional algorithm, and the CPS algorithm, respectively. Three dissimilar algorithms, all transient based. But are they propitious, and do they provide advancements regardless of fault and system characteristics?

The task

With a single-line-to-ground (SLG) fault, the fault impedance might hinder the feeder selection with the traditional Wattmetric algorithm. Therefore, the scope of work is to recognize if the QU algorithm, the Directional algorithm, or the CPS algorithm might prove less influenced by the fault impedance. This requires an analysis of both traditional and new algorithms. However, a resonance grounded high voltage distribution system might compensate the system differently and the cable penetration may vary between systems. Characteristics of the feeder and phase subjected to an SLG high-impedance fault (HIF) may also vary. Consequently, the thesis will also investigate how these parameters affect the feeder selection with an SLG HIF.

Model/ measurements
The thesis utilized a Simulink/MATLAB implementation to numerically simulate a faulty feeder and to process the resulting zero sequence currents (ZSCs) and zero sequence voltage (ZSV) as required by the algorithms studied.

Calculation
By varying the faulty feeder characteristics (pure overhead line or mixed feeder), along side with a variation of fault resistance, over-compensation, and cable penetration of the system, the algorithms of interest are dissimilarly affected.

Conclusion
With the choice of algorithm, sensitivity differs, misoperation could be avoided, and healthy feeder selections achieved. Regardless, the new algorithms might advance the feeder selection in resonance grounded systems, but none of the new algorithms is superior in its entirety.

Comparison of internal balancing vs external balancing for a power producer located in NO3

Student: **Jens Rune Bellika**
Supervisor: **Gro Klaeboe**
Collaboration with: **TrønderEnergi**

Problem description
Recent studies have found a potential profit in shifting from separate intraday imbalance-clearing to a portfolio coordinated clearing-approach. A power producer with a portfolio of intermittent and flexible production units can take advantage of a portfolio clearing-approach. The extra revenue gain from a coordinated approach compared to an intraday market clearing approach is especially true when the intraday bid/ask spread are large and the market participants acts as price takers. The bid/ask spread are typical large in scenarios with low liquidity in the intraday market, e.g., periods with low transmission capacities between other price areas. The imbalances that has to be settled in the intraday market, are the difference between actual production/marginal cost and the day-ahead commitments.

The task
A rolling-horizon deterministic bid model has been built and connected to the hydropower production models. The model simulates through each time step of the intraday market, in total thirty-three time-steps, and takes trading decisions based on the real-time intraday order book in the stage. The bid model is connected with a reservoir hydropower model and a run-of-river hydropower model. Both plants use historical day-ahead commitments and must settle their imbalances in a pay-as-bid intraday market. A base-case scenario is obtained, where each plant clears their imbalances against the pay-as-bid intraday market. This scenario is compared against a scenario where the producer clears the imbalances with a coordinated portfolio approach. This means that the reservoir hydropower plant can cover the imbalance from the run-of-river hydropower plant if this is more profitable than trading the imbalance in the pay-as-bid intraday market. The run-of-river hydropower plant could also cover the imbalances from the reservoir hydropower plant, in this way the reservoir hydropower plant can store water for later usage when the market prices are expected to be higher.

Model/ measurements
The model simulates through each time step of the intraday market. In each stage the model has to decide if it should trade based on maximizing the revenues from the intraday market. The intraday market logic is illustrated in the figure below. The model will accept orders as long as they are profitable compared to the water value for the reservoir hydropower plant. For the run-of-river hydropower plant the intraday market is purely used for settling imbalances. With a common approach the plant with the lowest marginal cost of production will be used to cover the commitments as long as the plant has sufficient production capacity.

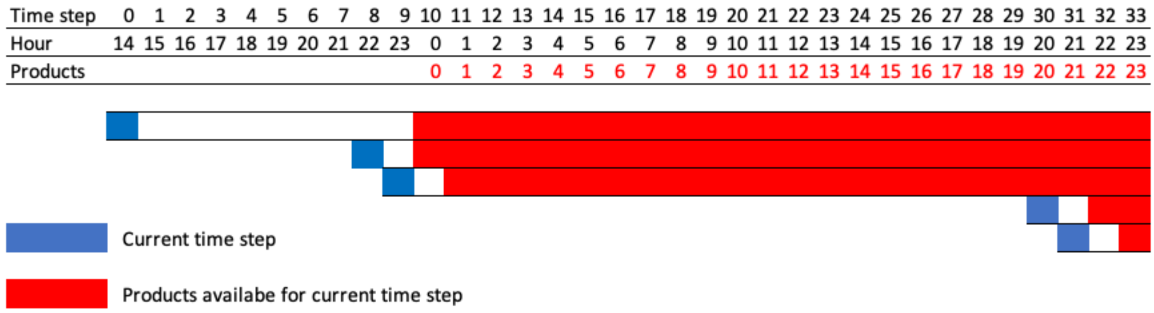


Figure 1 - Intraday market logic. There are in total 33-time steps. The market opens at 1400 CET the day before production, and the participant can trade until one hour before production in each product. The last bid must be placed before 2200 CET.

Calculation

The results are better for the portfolio coordinated imbalance approach. This can be due to the fact that the bid/ask spread are high several days in the modelled period. With this approach the reservoir hydropower plant can store additional water in some scenarios and use this water in periods with better prices, and the run-of-river hydropower plant can let the reservoir hydropower plant cover their commitments when the inflow are lower than anticipated and the bid/ask spreads are high.

Conclusion

This master thesis has investigated the value of internal intraday bidding coordination for clearing imbalances versus external clearing of the imbalances in the intraday market. The results from this thesis shows that internal intraday coordination is more profitable than handling the imbalances plant-wise in a pay-as-bid intraday market. A case-study on a power producer located in the price area NO3 with a portfolio of intermittent and flexible production units has been performed to find the value of internal intraday bidding coordination. The results from this study are hard to maintain in real-life since the model is fully deterministic, which means it will always have perfect insight into the order books and only take the best trades. Further research should include stochastic models and see what happens with the additional revenue from a coordinated intraday bidding-approach.

Investigating a LoRaWAN Communication Infrastructure for Cloud-Based Home Energy Management

Student: **Trym Johannes Berg**
Supervisor: **Ümit Cali**
Co-supervisor: **Murat Kuzlu**

Problem description

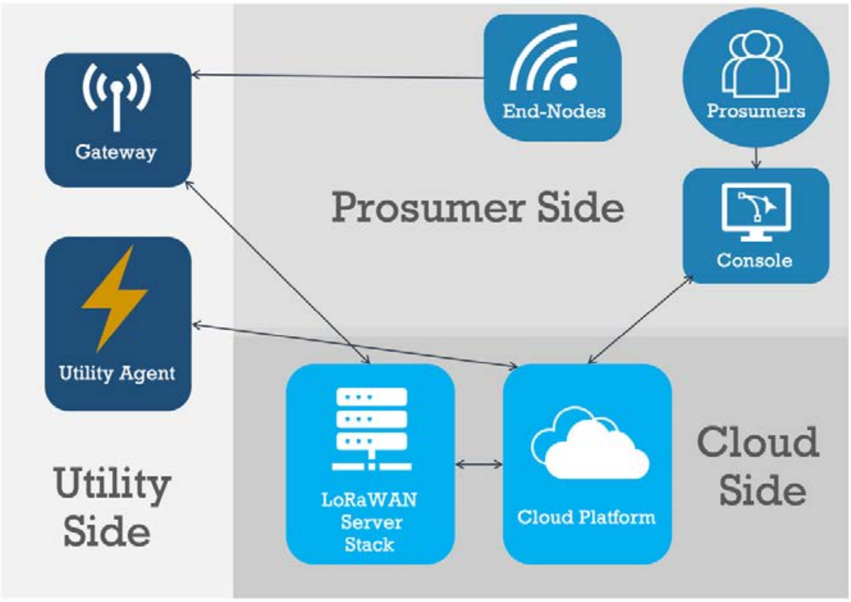
Increased focus on sustainable energy consumption and production has seen the rise of Home Energy Management Systems (HEMS) in residential homes. A HEMS is capable of monitoring and controlling the energy consumption and production in a home, based on signals from either the homeowner or a utility operator. To facilitate the communication infrastructure in large clusters of HEMS, it is necessary to use a long-range, low-latency communication protocol. LoRaWAN is an emerging Low-Power Wide-Area Network (LPWAN) protocol that offer flexible communication solutions with configurability. This thesis aims to determine if LoRaWAN is a suitable communication protocol for powering bi-directional communication in clusters of HEMS.

The task

To help answer the main research question stated above, this thesis proposes the following research objectives: Design, implementation, and validation of a cloud-based LoRaWAN communication infrastructure, capable of facilitating both uplinks to and downlinks from HEMSs. Extensive research on HEMS, LoRaWAN and cloud computing was first conducted to help with designing the communication infrastructure. The infrastructure includes nodes, gateways, a network/application server, and a cloud-based operating center (cloud platform). A test bed solution was then implemented based on the proposed design. Coverage, latency, and metering resolution assessments are finally conducted to validate the proposed solution. The validation process includes coverage (indoor and outdoor) and latency experiments performed on the test bed solution, and theoretical calculations of time on air for investigating the metering resolution. Note that this thesis considers HEMS for mainly prosumers, which is homeowners who produce renewable energy on-site.

Model/ measurements

The figure below details the system architecture.



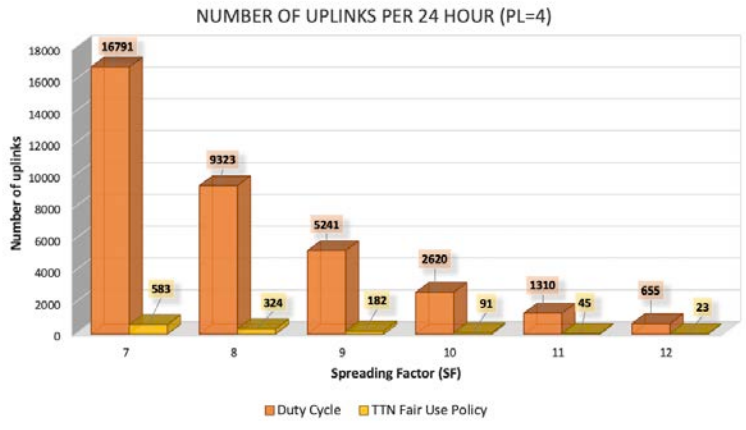
Prosumer side contains the end-nodes, which represents home appliances, smart meters, actuators, or any other device used for transmitting or receiving messages over LoRaWAN. The gateway is located at utility side, and it receives and transmits messages to and from end-nodes. Finally, the gateway then backhauls these messages to a cluster of network and application servers located in the cloud. These servers forward the messages to a cloud platform that acts as an operating center.

Calculation

Results from the outdoor experiments showcase the effects of line-of-sight. Although the GW to the right is located more than four times further away from location 1 than the GW to the left, it was still able to receive the signal with much better signal quality.

Signal qualities for GW connections from location 1 (Distance; RSSI; SNR; Data Rate)

The latency and metering resolution investigation provided the results displayed below. It shows that a LoRaWAN end-node can achieve a round-trip latency of around 1s, and a metering resolution (uplink-rate) of 5.2s.



AVERAGE ROUND-TRIP LATENCY	
LAN: Ethernet	LPWAN: LoRaWAN
93 ms	1284 ms

Conclusion

Results from the theoretical and experimental analysis show that a LoRaWAN-powered HEMS can achieve a large coverage area while still maintaining low latency. It was further observed that end-node configuration and gateway deployment played a key part in enabling low-latency communication. The findings in this thesis reveal that LoRaWAN is a suitable communication protocol for clusters of HEMS, however, it highly depends on the deployed solution. Further studies and experiments on latency and coverage in large-scale deployments are needed to better define the limitations of LoRaWAN.

Positive and Negative Streamer Propagation Along Profiled Dielectric Surfaces

Student: **Henriette Bilsbak**
Supervisor: **Frank Mauseth**
Co-supervisor: **Hans Kristian Meyer**
Co-supervisor: **Robert Marskar**
Collaboration with: **SINTEF Energy Research**

Problem description
SF_6 is the most commonly used insulation gas in MV switchgear. Despite its excellent dielectric properties and cost-competitiveness compared to other gases, it has a very high global warming potential. Research efforts to eliminate SF_6 by replacing it with other potential gases are currently being performed. The complex geometries of MV switchgear makes this a complicated task. This causes the need for a better understanding of the mechanisms of streamer propagation and breakdown to find better ways of controlling the electric field in these geometries.

Model/ measurements
Three different dielectric surfaces have been investigated in a rod-plane air gap. Lightning impulses of 35 kV have been applied the test objects and streamer activity has been recorded by two high-speed cameras. A plain surface profile, a circular surface profile and a square surface profile have been used in the experiment. Electrostatic simulations have been carried out in COMSOL to investigate inception voltages and the effect of surface charge. The streamers are recorded with two different high-speed cameras. Breakdown voltages are detected with voltage measuring equipment and the 50% breakdown voltages are estimated by the up-and-down method.

Calculation
Streamers captured along the two profiled surfaces are shown in Figure 1 and Figure 2. The streamer along the square surface does not follow all the grooves to the bottom, while the streamer along the circular surface follows the whole surface path.

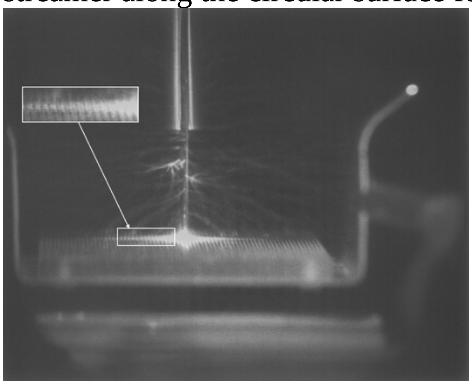


Figure 1: Streamer propagation along the square surface.

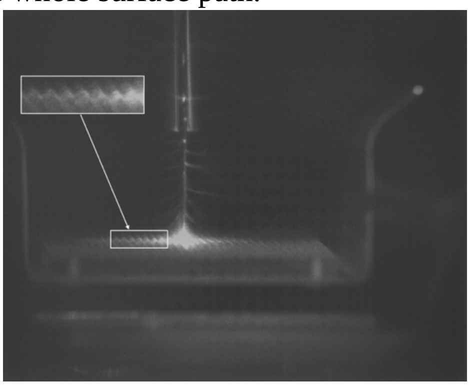


Figure 2: Streamer propagation along the circular surface.

Breakdown voltages with standard deviations are shown in Figure 3.

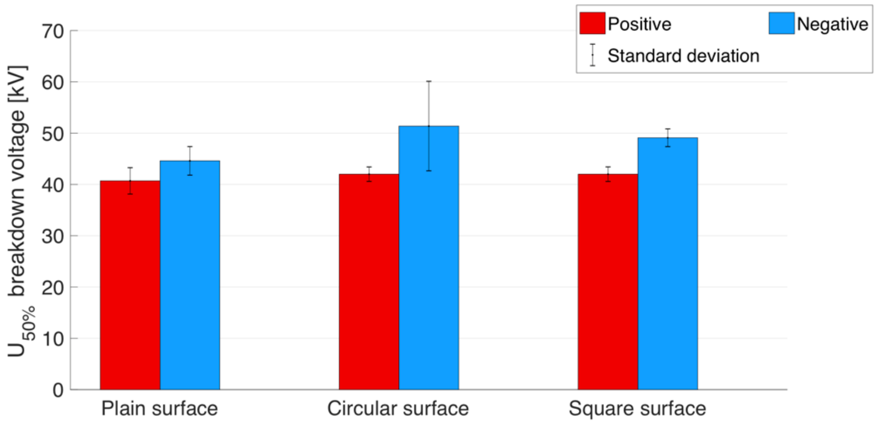


Figure 3 Breakdown voltages of the three dielectric surfaces.

Conclusion

Streamers propagate shorter and slower along profiled dielectric surfaces for both polarity streamers. Typical engineering tools are inadequate when estimating streamer ranges along profiled dielectric surfaces, and it is likely that the geometry and electric field distortion are contributing factors for limiting the streamer propagation. The breakdown voltages increase when introducing profiled dielectric surfaces, and the introduction of these types of profiles could possibly be implemented into MV switchgear insulations systems to increase the withstand voltages.

Breakdown strength of oil-impregnated paper insulation at DC with superimposed lightning impulse voltage

Student: **Andreas Birkeland**
Supervisor: **Erling Ildstad and Frank Mauseth**

Problem description

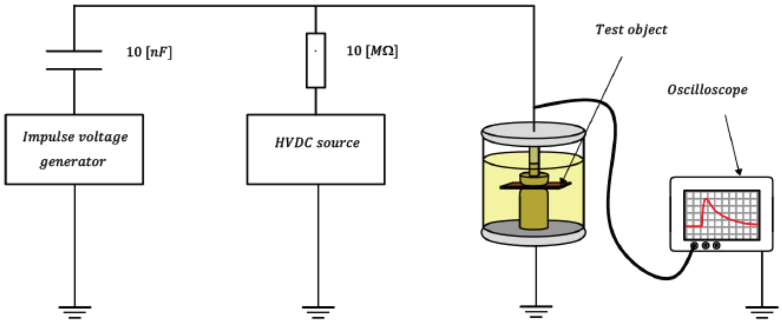
One of the essential checkpoints when performing factory acceptance tests on HVDC cables with oil-impregnated paper insulation is the superimposed lightning impulse voltage test. This test consists of a routine where the insulation is charged with nominal operating DC voltage for a relatively long time before lightning impulses of opposite polarity to the DC are applied. The routine has been indicative for years, but still, there is little published experimental data to verify whether it should be dimensioning.

The task

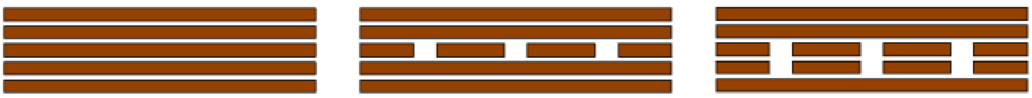
In this master project, the breakdown strength of insulation samples of oil-impregnated paper is tested at DC with superimposed lightning impulse voltage, focusing primarily on the DC pre-stress time and impulse voltage polarity.

Model/ measurements

The tests are performed by exploiting a laboratory setup that allows test objects to be stressed with both DC voltage and lightning impulse voltage at once.



Furthermore, five layers of oil-impregnated paper sheets were placed between two electrodes connected to this setup. These test objects were differentiated into three configurations with spacings/butt gaps that replicate an actual cable in operation, namely; no butt gaps, single butt gaps, and double butt gaps.



Breakdown voltages of these configurations were then found by applying a fixed DC voltage while using the rising voltage test procedure, with steps of increasing lightning impulse voltage. To investigate the influence of DC pre-stress time and impulse voltage polarity, the time parameter and voltage polarity parameter was varied through test sets.

Results

Based on the test results, it was seen that when a superimposed lightning impulse voltage test is performed on oil-impregnated paper insulation, the breakdown voltage is lower when the DC voltage is applied for a long time versus a short time. Moreover, it was seen that a lightning impulse voltage of opposite polarity to the DC voltage provided a lower voltage magnitude at breakdown, compared to that of an impulse voltage of equal polarity to the DC voltage. Furthermore, the critical voltage stress obtained from all of the tests, i.e., the lowest superimposed voltage magnitude to provide a 10% probability of breakdown was measured to 28.6 kV. This occurred for the configuration with a double butt gap when DC pre-stressing lasted for 3 hours before lighting impulses of opposite polarity to the DC were applied. These results are justified by field-theory and simulations of the electric field in the paper and butt gaps, suggesting that the butt gap edge is especially sensitive to superimposed impulse voltages.

Reactive Power Considerations in Reliability Assessment of Power Systems

Students: **Ingvild Grøtterud Birkeland**
Kristian Bjørgve

Supervisor: **Vijay Venu Vadlamudi**

The objective of this thesis is to implement a non-sequential Monte Carlo Simulation method with an AC optimal power flow approach in Python, for assessing the reliability of composite power systems. Further, the work concerns the implementation of a suitable method to account for reactive power considerations in composite system adequacy assessment in power system reliability studies.

Voltage issues in the power system are a growing concern due to, among other reasons, an increase in renewable power sources and heavier loaded systems. Voltage and reactive power are tightly interleaved, and little attention has been paid to the reactive power aspect in the field of power system reliability. Only a few publicly available sources investigate the topic, and even fewer provide a transparent method for replication that can enable further improvements. As such, one of the goals of this thesis work is to synthesise a reproducible method that distinctly differentiates between the curtailment due to active power shortage and the curtailment due to reactive power shortage in power system reliability studies. This includes presenting additional reliability indices based on an analytical method utilising optimal power flow, which takes reactive power considerations into account. A detailed description of the methodological approach with the necessary adaptations and assumptions is presented. In addition, a duplicate contingency state filtering technique is developed to increase the efficiency of the simulations.

Two scripts are developed in Python from the ground up to assess the so-called reactive power considerations (RPC) method. The first one relates to the standard composite system adequacy assessment, applied to the Roy Billinton Test System (RBTS) and the IEEE-Reliability Test System (IEEE RTS). The second one relates to the incorporation of exclusive reactive power considerations in the first one, and is applied to a modified IEEE 30-bus system. The validation is done through investigation of the results as well as a comparison of the obtained reliability indices with the ones available from respective methodological sources in the literature.

In the standard composite system adequacy assessment, the success of the developed Python scripts was verified. In-house composite system adequacy scripts in MATLAB, available at the Department of Electric Power Engineering, were used in the development and verification of the Python code. A difference in the contingency solver routine was observed. However, the overall similarities between the reliability indices provide a proof of reproducibility of the adapted method.

The active power curtailment due to active power shortage was found to be differentiable from the curtailment caused by reactive power shortage.

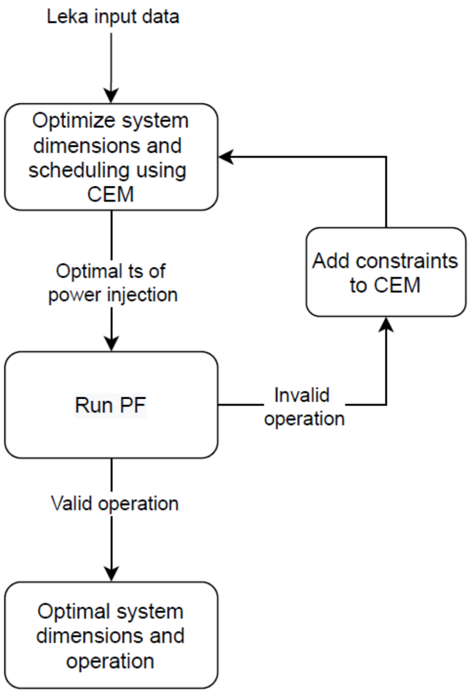
It was also found that the reactive power considerations method could identify optimal locations for additional reactive power sources in the power system, ultimately giving valuable information to system planners and system operators.

The duplicate contingency state filter technique was implemented on all the three test systems, where it was found that it is possible to reduce the number of states considered by the contingency solver. As a consequence, a decrease in computational time was observed.

Analyzing optimal sizing and operaion of renewable hydrogen

Student: **Erik Seeger Bjørnerem**
Supervisor: **Magnus Korpås**

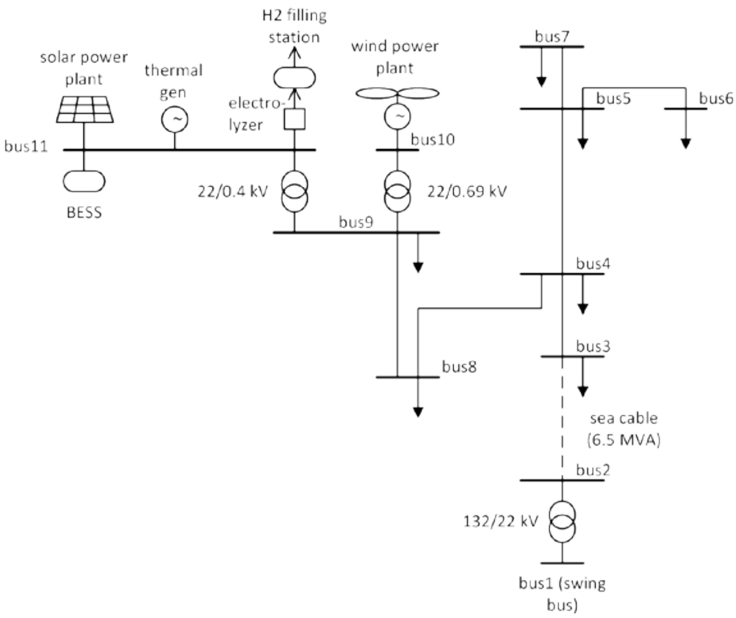
Problem description
In order to reach net-zero carbon emissions by 2050 as agreed upon in the Paris agreement, the installed capacities of variable renewable energy (VRE) production are rapidly increasing. An increasing share of VRE generation leads to lower CO2 emissions, but the inherent uncertainty and variability of renewable energy sources can pose significant operational challenges in today's power systems.



The task
The task of the thesis is to examine how VRE integration affects optimal system sizing and system operation. This task split into two parts. Firstly, the CEM is defined using a least-cost linear program (LP) formulation. This model takes VRE availability, load demand and generation costs as input and outputs the optimal system dimensions and scheduling. Then a PF analysis is performed on the optimal system scheduling to determine the feasibility and efficiency of the optimal system scheduling. The process of setting optimal system dimensions and analyzing system operation is then exemplified through a case study of the Leka power system.

Model/ measurements
The location of each component in the Leka power system is shown to the right. The system features an electric load and hydrogen load for a hydrogen ferry. Different cases are analyzed:

- 1.1 Base case
- 1.2 Base case without transmission
- 1.3 Base case without transmission and thermal generator
- 2.1 Wind power is replaced by solar power
- 2.2 Fully subsidized solar power



Results
Here the optimal system scheduling and bus voltage levels are shown for case 2.1, the only case where the voltage restrictions were violated. For the rest of the results see the full thesis.

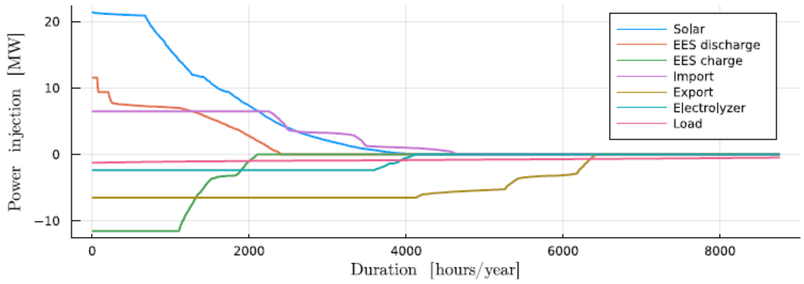


Figure 14: Duration curve of optimal system scheduling for case 2.1.

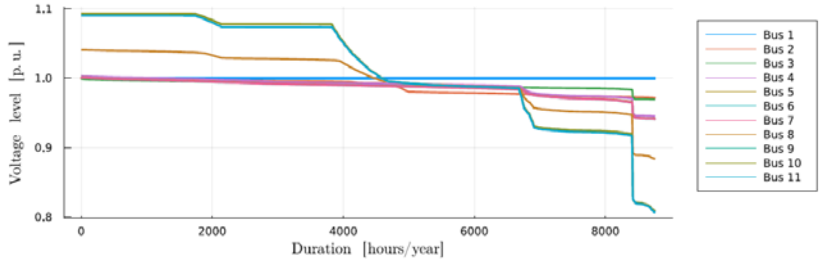


Figure 29: Duration curve of bus voltage for case 2.1.

Conclusion

The results show solid incentives for VRE integration, and the CEM heavily favours wind power investments. In this case, wind power is cost-effective without subsidization, and the levelized cost of energy (LCOE) of wind power was 39.1 $/MWh compared to the average spot price of 47.38 $/MWh. The operation of this system featured maximum voltage deviations of 8% and line losses of 6.9% of total energy production. When wind power is replaced by solar power, the annual cost of operation is increased by five times due to the investment of a large EES. This system featured maximum voltage deviations of 19% and line losses equalling 9.8% of the total power generation. Due to violating voltage restrictions, this case was reoptimized, and the new solution featured similar system dimensions but significantly smoother production scheduling.

Through analysis of defined case studies, it was found that the capacity of the HES varies with the flexibility in the system. For the case with grid transmission, the HES capacity is one day of hydrogen load demand. When the transmission line is removed, the capacity is increased to 3 days as there are periods with low VRE production.

Additionally, when the thermal generator is removed, the capacity is increased to 6 days. The cost of the fuel cell proved too high in order to activate the fuel cell investment. In conclusion, the least-cost optimal systems feature the largest VRE integration when grid transmission is included. This way, surplus VRE production can be exported for revenue, and power import can be utilized in periods with low VRE generation. However, this lead to increased power flows which caused a larger deviation in voltage levels.

Interpretation of Electrical Load Forecasts using Explainable Artificial Intelligence

Student: **Daniel Aunan Bolstad**
Supervisor: **Ümit Cali**

Problem description

Electrical load forecasts are used by a wide number of power system participants in multiple time horizons, ranging from minutes ahead to several years ahead. Forecasts by machine learning models offer very high accuracy, but are so-called black boxes and do not give any reasoning for their decisions. Explainable artificial intelligence (XAI) methods provide a means for peeking inside the black box to understand the model better.

The task

The goal of the thesis was to serve as a first exploratory work in the use of XAI for Norwegian load forecasts. In other words, how can XAI tools be leveraged to interpret and improve load forecasting models?

Model/ measurements

A convolutional neural network for hourly, day-ahead load forecasting was developed for the Norwegian price zone, NO1. Historical load, weather forecasts and calendar information (day of the week, season, month, holiday) were used as input features to the model. A multi-input multi-output forecasting strategy was used, where multiple features are taken as inputs and the output are the twenty-four loads of the next day (shown in figure 1).

The framework of Shapley additive explanations (SHAP) was used during model development for feature selection and debugging purposes. This framework was also used for explanations of selected forecasts made in testing of the final model. Local explanations were made by comparing the forecast in question to other similar days through SHAP background data selection. A forecast can then be explained by the difference from the expected forecast of the background data. E.g., expressed in words: "why is the forecast for this Tuesday any different from the one made for previous Tuesday?".

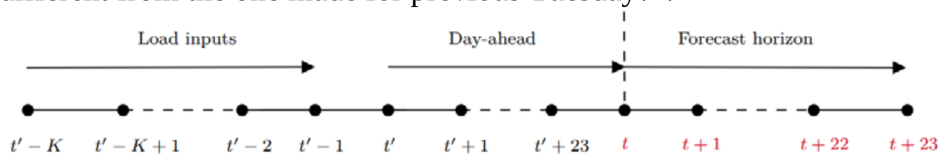


Figure 1: Timeline of the forecasting strategy.

Calculation

The accuracy of the forecasting model were satisfactory, and the model was able to capture the shape of the electrical load cycle, as shown in figure 2.

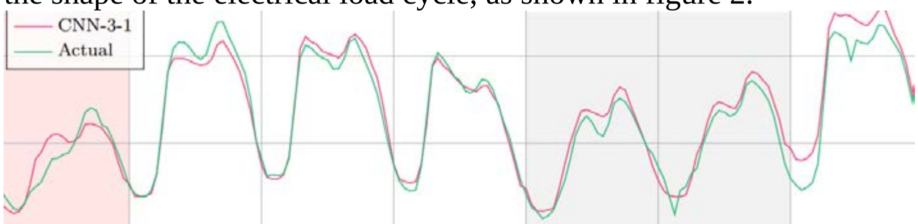
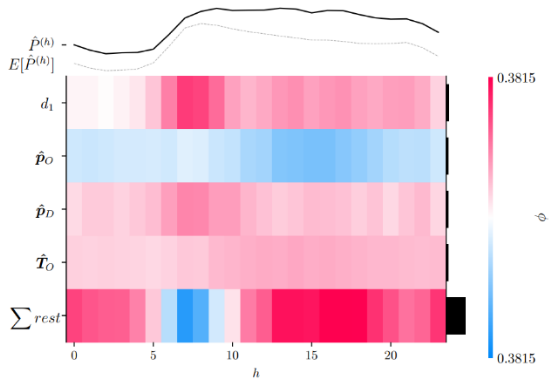


Figure 2: One week of electrical load forecasts. Holidays are red, weekends are grey.

Explaining a forecast by comparing it to a previous forecast, or a set of previous forecasts, implies that the difference in forecast from the expected is made up of the differences in input values of the two. This is shown in figure 3, which shows the curves of the one day of predicted load by hour of the day ($\hat{P}^{(h)}$), and the expected prediction ($E[\hat{P}^{(h)}]$). The difference from expected prediction is made up by the sum of feature contributions ($\hat{P}^{(h)} - E\left[\hat{P}^{(h)}\right] = \sum\phi$), which are shown as a heatmap under the forecasts. The contribution of each feature is based on its importance to the model, and the difference of the input compared to the background inputs, as seen in the table.



	x	$E[x]$
d_1	1	0.2
$\bar{p}_O$	0.09	0.63
$\bar{p}_D$	0.39	0.92
$\bar{T}_O$	-0.37	0.28

Figure 3: Explanation of a forecast by comparing it to the expected forecast.

Conclusion

The findings of the thesis suggest that explainable artificial intelligence methods are well suited for electrical load forecasting models. However, the intuitiveness of the explanations relies on using similar forecasts for comparison. More research is needed on the implications of the choice of background data to make any conclusive statements.

Leveraging residential battery energy storage systems for voltage support in remote distribution grids with high penetration of renewables

Student: **Frida Bratlie**
Supervisor: **Jayaprakash Rajasekharan**
Contact: **Kristian Finborud Hansen**
Collaboration with: **Haugaland Kraft Nett**

Problem description
The high penetration of renewable energy resources in the distribution grid causes new operational challenges for the distribution system operator. Over-voltage is especially an issue that constitutes the major limitation to the increase in RES penetration and integration. One solution to cope with this technical challenge is to utilize the active power support from battery energy storage systems (BESS). Due to today's market structure and regulation, the implementation of BESS in the power system is restricted to network customers.

The task
This master's thesis investigates the potential for utilizing residential BESS for voltage support. To achieve an efficient operation of multiple residential BESSs, a new control strategy was proposed. The control strategy aims to mitigate voltage issues in the distribution grid and, at the same time, allows the customer to operate the BESS on their preferences. The research focused on the operational challenges in the distributed grid caused by the high penetration of renewable energy resources, different voltage regulation techniques, and control strategies for coordinating multiple BESSs for mitigating voltage issues.

Model/ measurements
The proposed control method is based on a distributed control concept consisting of a central controller and local controllers. The local controllers aim to reduce the electricity bill by increasing the customers' self-consumption or taking advantage of the electricity price variations using an optimization-based energy management system. The central controller aims to utilize the active power capability of the BESSs to improve the voltage quality in the grid. Periods with voltage violations are referred to as critical periods. During a critical period, the distribution system operator is given partial control over the active power settings of the battery storage systems, in addition, to a certain percentage of the battery capacity. A voltage sensitivity-based control method was used to determine which BESS should participate in the voltage regulation.

The control method was validated through a simulation case study of the distribution grid at Utsira island. The distribution grid at Utsira was modeled in the simulation software Pandapower.

Calculation
Through a sensitivity study, it was found that an additional 5-8 kWh per BESS was required to completely mitigate voltage issues in all critical periods compared to a battery size that met the customer's need. However, the number could be decreased to 1-3 kWh if two critical periods were disregarded. A combination of different voltage regulation techniques can reduce the require battery capacity, such as reactive power regulation or PV curtailment.

The BESS with the greatest impact on the system performance was selected to participate in the voltage regulation. Since the electrical distance between the BESSs and the critical node in the over-voltage scenario was approximately the same, the method had no significant impact on the total amount of required power. In the under-voltage scenario, the total amount of required power could be reduced from 11.3 kW to 4.2 kW by selecting the BESS with the highest impact on the system.

Conclusion

The control method successfully maintained the voltage within its limits. A decisive factor to completely mitigate voltage issues was the total battery capacity in the network, where the financial incentives the distribution system operator can provide the customer will be crucial in determining the most profitable battery size. Further, as the electric distance between the BESSs and the critical node can vary depending on the distribution grid, it is important to analyze the network and the BESS's impact on the system to utilize the residential BESSs effectively.

A proper business model must be designed to realize the control method, where the models should consider how the provided service generates value and how the created value is shared between the customer and the distribution system operator.

Analysis of fault current contributions from inverter interfaced wind parks

Student: **Andreas Breivik**
Supervisor: **Hans Kristian Høidalen**

Problem description

The European network of transmission system operators for electricity published a report where they predicted that grids with distance protection might struggle in the future. This is because of the increasing share of distributed energy sources using inverters. Inverters have a low current limit, so their short circuit contributions are low. This combined with fault resistance and infeed currents can cause the distance protection systems to under-reach or over-reach.

The task

This thesis is a continuation of a previous master thesis that tried to investigate the same problem. That thesis was limited by the fact that creating a switch-based model was time consuming. It was therefore only able to handle balanced faults while the most common are unbalanced. Since this thesis was a part of the ProDig project, SINTEF was tasked with creating a model to handle unbalanced conditions. This model was an averaged model, so the first part compares the switch-based model and the averaged model. The averaged model is then used to analyse different fault conditions where parameters are adjusted independently to be able discern in what way they affect the distance protection system.

Model/ measurements

The model is set up in PSCAD with a wind turbine/park equivalent on the left, with the grid connections to the right. The protection system is set up in a way to protect line 1-2 which is the lone line connecting the grid and the source. The distance protection algorithm is created by using PSCAD cookbook for protection studies and do not have any advanced features.

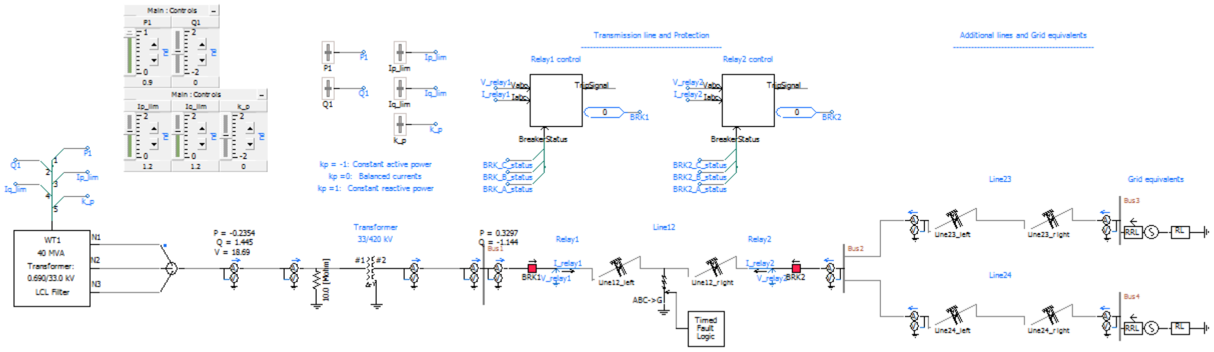


Figure 1: Top level of the system used.

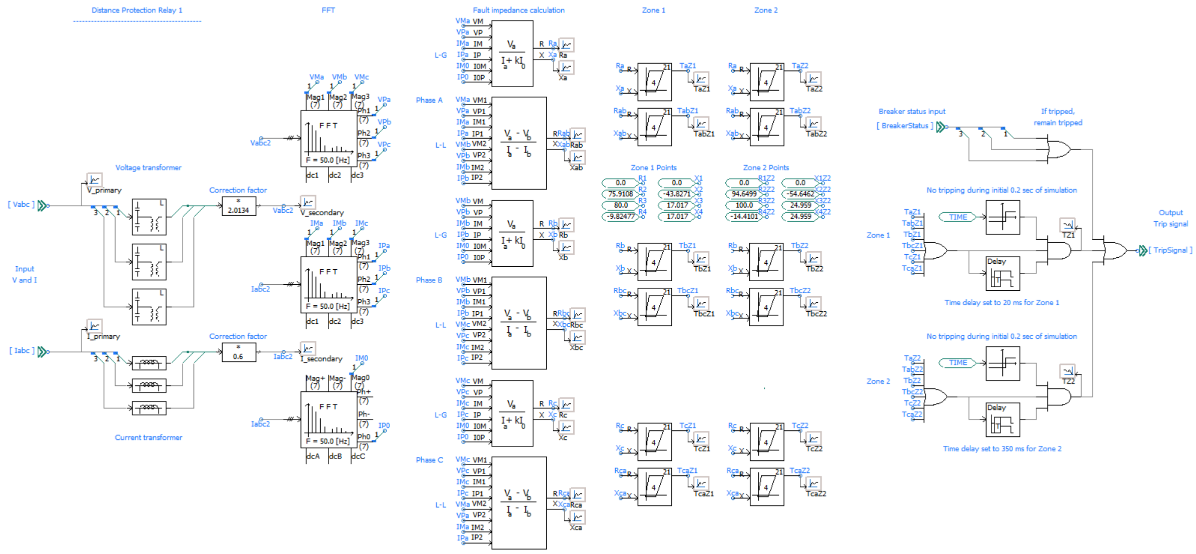


Figure 2: Distance protection utilized during simulations

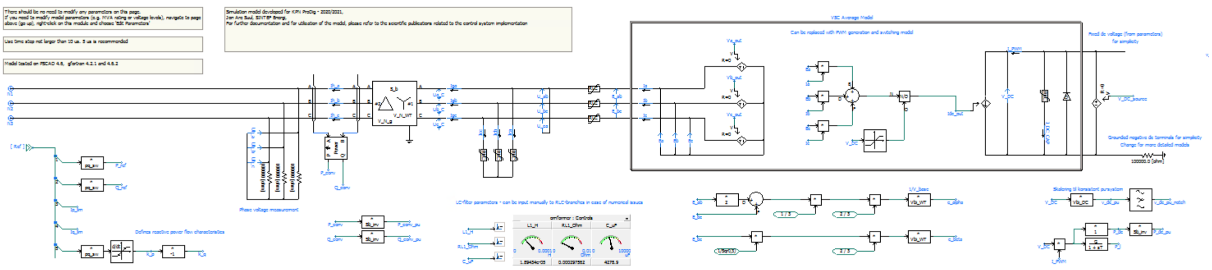


Figure 3: Averaged model created by SINTEF

The distance protection system was then tested over several scenarios where the effect of fault location, fault type, fault resistance and power plant rating were analysed.

Calculation

During the simulations, a fault impedance of 10 ohm caused the system to under-reach and not detect the fault properly with a trend of increasing fault impedance causing worse protection. For the fault location test, the simulations show that increasing distance led to increased measured impedance. In the fault type simulation, none of the tests showed correct fault detection from the distance protection, but for this simulation, the line to ground fault was closest to detection. When it came to the test of different park sizes, an increase in rating lead to more accurate detection, but none of the cases led to the distance protection finding the fault.

Conclusion

With the setup tested, there were clear problems for the wind park side distance protection with detection of faults on its line. Further testing should be performed to find conclusive answers though as the wind park size might be too small. Testing with a synchronous generator attached on the park side to see what difference the share of inverter interfaced generation have would also be useful.

Improving Traceability of Wind Turbine Drive Train Component Failure Rates Through Information Model Mapping and Failure Rate Estimation

Student: **Butcher, Brian Alexander**
Supervisor: **Cali, Umit**
Collaboration with: **DTU**

Abstract

Wind Energy's presence continues to increase as the world puts focus into transitioning to cleaner energy sources. As with any energy generation method, maintaining the lowest LCOE is essential. Operations and Maintenance are a major cost drivers in Wind Energy and understanding the reliability characteristics of Wind Turbines is essential in predicting these costs. Reliability models are only as good as the data put into them, so failure data must be tracked in a consistent and deliberate fashion as the amount of failure data continues to increase with aging turbines. In this paper the information model surrounding Main Drive Train Component failures at Ørsted is mapped and evaluated using the Universal Modeling Language and then proposals are then made to improve it. On the collection and storage side, solutions are presented to automate and improve data collection, processing, and storage. On the application side the Competing Risk Reliability Model is implemented for all main components with sufficient data and its functionality is demonstrated through an analysis of the Siemens 4MW Gearbox. Work is also done relating operating conditions to reliability through linear regression, artificial neural network and random forest tree machine learning models. While the three models implemented have low overall predictive power they all suggest that low temperatures and turbulence intensity negatively affect gearbox reliability. Both the Competing Risk Model and sensitivity analysis are completely reliant on historical turbine data, so it is imperative that the information model surrounding main component failures accept, process, and store the data in a consistent and deliberate fashion. As more data becomes available with aging turbines, the framework outlined in this paper will allow Ørsted to optimally leverage its data in reliability predictions.

Modelling and Stability Analysis of Diode-Bridge Rectifier-Synchronous Generator Systems

Student: **Trude Birgitte Byre**
Supervisor: **Kjetil Uhlen**
Co-supervisor: **Atle Rygg**
Collaboration with: **Siemens Energy**

Problem description

The shipping industry is under social and regulatory pressure to decarbonize its operation and reduce greenhouse gas emissions. Electrification is a fundamental factor in achieving this goal, especially when the amount of renewable power delivered to the transmission grid grows at the same rate as the power consumed. Concerning electrification of the shipping industry, power electronics converters and electric motor drives are being used at an increasingly rapid rate. However, with new technology follows complications regarding system reliability and stability. Synchronous generators in combination with three-phase diode-bridge rectifiers exist in shipboard power systems today. However, not well-understood instabilities are discovered by previous literature in such kind of systems.

The task

The aim of this thesis is to better understand why a synchronous generator connected to a battery through a diode-bridge rectifier, or multiple synchronous generator-rectifier system connected in parallel at the dc side becomes unstable. Previous literature studying this unstable phenomenon exist, but a complete explanation of the physics behind is still not completely known.

The specific objective of this thesis is to develop a simplified model that facilitates studying and aiding the understanding of this unstable phenomenon.

Model/ Measurements

In this thesis, a synchronous generator connected to a battery through a three-phase diode bridge rectifier is under study. A new, simplified model is implemented with the idea of keeping it as simple as possible, only including the system components which are believed to be necessary in order to study the unstable phenomenon. The simplified model contains a fifth-order synchronous machine model, an average-value rectifier model, and a DC circuit. The mechanical part of the machine is neglected. The DC circuit consists of a battery, modelled as an ideal DC voltage source connected in series to an internal battery resistance, which is further connected in parallel with a filter capacitor. The simplified model is validated and compared to a detailed simulation model (reference model) implemented using Simulink/Matlab system blocks and is shown to follow it quite well.

The simplified model is further linearized, and modal analysis techniques are performed. An unstable pair of complex eigenvalues are detected, participation factors are calculated, and sensitivity analysis is conducted. Five different synchronous generator sets are considered during the sensitivity analysis. Moreover, varying combinations of synchronous generators, three-phase diode-bridge rectifiers, and a battery, are studied to explore how the presence of system components affect the presence of the unstable behaviour.

Conclusion

This thesis shows that the unstable phenomenon occurs independently of an AVR and a Governor system. It also shows that instability occurs even though the generator is operated in the absence of a mechanical system. Thus, well-known rotor oscillations are not a part of the underlying problem, and the instability is considered an electromagnetic phenomenon, not an electromechanical phenomenon. Further, based on the fact that the simplified model became unstable, despite that the dynamics associated with diode switching were removed, this indicates that the diode commutation as such is not part of the underlying problem.

The sensitivity analysis conducted indicates x_d' , x_q' and x_q to be the system parameters influencing the real part of the complex pair of unstable eigenvalues the most, followed by T_{qo}'' and x_d'' Furthermore, the sensitivity analysis results show that the system improves stability by moving in a specific direction with respect to the d- and q-axis components, either by increasing the q-axis component and decreasing the corresponding d-axis component, or the opposite. As an example, in order to positively affect the system stability, the system wants to increase x_d' and T_{qo}'' and decrease x_q' and T_{do}'' respectively. Increasing xd´such that xd´ is sufficient close to the value of x_q' solves the challenge concerning low-frequency system oscillations. These observations are in accordance with the stability criteria, $\frac{x_q}{2x_d'} \leq 1$, proposed by previous literature for synchronous generators satisfying
$x_q' = x_q$.

This study has further shown that an unfavourable type of DC load, not contributing with sufficient damping, needs to be present for the unstable phenomenon to occur. This further indicates that the characteristics associated with the DC load, in addition to an unfavourable relationship between the d-axis and q-axis parameters in the generator, are important parts related to the instability.

To conclude, regardless of the underlying reason causing the instability, the unstable phenomenon can be considered a transient electromagnetic phenomenon that primarily depends on the transient reactances and time constants.

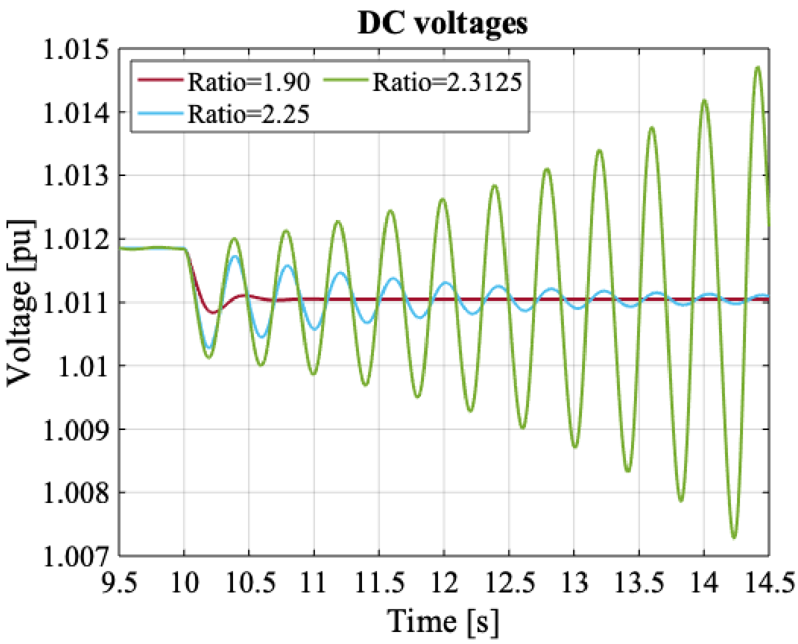


Figure 1: DC voltage responses for varying values of x_d' and thus for the ratio $\frac{x_q}{2x_d'}$, when operating the simplified model developed. The smaller x_d' the larger ratio $\frac{x_q}{2x_d'}$, the more unstable the system becomes.

Intraday bidding optimization for a Nordic hydropower producer using fundamental drivers to forecast the intraday market

Student: **Julien Cabrol**
Supervisor: **Gro Klæboe**
Collaboration with: **TrønderEnergi**

Problem description
This thesis is motivated by the intraday market in NO3 recently seeing increased volumes. This is due to higher penetration of variable production in the system, and coupling to more liquid intraday markets in Europe. For flexible hydropower producers in NO3, this means more opportunities to supply balancing services and take advantage of the different prices in the markets. Recent studies have also found relations between the intraday market development and fundamental drivers, while others have started building tools to predict the intraday prices based on this. The goal of this thesis is to investigate the benefit of participating in the intraday market for a hydropower producer when using forecasting in the decision making.

The task
Develop an optimization and simulation framework that includes intraday bidding in the real order books, forecasting of future trading opportunities, and hydropower scheduling. Evaluate the performance of the framework for a hydropower producer from the bidding zone NO3.

- Find profits of participating in the intraday market with and without forecasting, compared to only participating in the spot market.
- Evaluate the impact of important modelling decisions.

Model
The intraday modelling is based on already decided commitments in the spot market. The modelling framework uses a rolling-horizon approach to go through the intraday market from it opens until it closes. At each hourly time-step, a two-stage stochastic mixed-integer program will accept profitable limit orders from the real order books, considering the production plan, the water value and future trading opportunities. Scenarios of future trading opportunities are generated by forecasting the intraday premium, volume and occurrence of trades for each product. The forecasting is done with random forest regression or neural networks, and uses fundamental drivers as input variables.

Results and conclusion
For a case study with a hydropower producer in NO3, and 256 days in 2020, the benefit of participating in the intraday market converges to around 3 % for the bidding model without forecasting. The bidding model with forecasting does on average outperform the bidding model without forecasting. However, more data and testing is needed to reach a conclusion on the performance of this model. This uncertainty is mostly due to the different performance of the forecasting methods under different market conditions. Testing the bidding model outside of the abnormal year 2020, and development of the forecasting methods is therefore identified as the most important improvements to obtain more reliable results.

Assessing the Feasibility of Developing a High-Speed SynRM by Using a Compound Analytical/FEA-Assisted Design Algorithm

Student: **Tord Traa Carlsen**
Supervisor: **Jonas Kristiansen Nøland**
Co-Supervisor: **Christian Du-Bar**

The synchronous reluctance motor has experienced a surge in interest during the last decade. This increase in interest is driven mainly by low production costs, increased volatility in the price of rare earth materials used in permanent magnets and the potential for very high efficiencies. This paper aims to evaluate the feasibility of designing a high-speed synchronous reluctance motor to power a flywheel, preferably by using a retrofitted PMSM-stator with eight pole pairs.

This was done by conducting a series of parametric sweep across the input parameters of a modified rotor design procedure and a developed compound analytical/FEA-assisted stator design algorithm. The electromagnetic performance of the generated designs was then analysed in Comsol MultiPhysics and the feasibility of the SynRM was assessed based on whether it was possible to accelerate the flywheel from standstill to nominal speed within a given timeframe while at the same time achieving an acceptable saliency.

The PMSM-stator was shown to be inherently unsuited for use in a SynRM, as the relatively high pole-number proved detrimental to the rotor flux barriers which are responsible for creating the anisotropic inductance which the SynRM is based on. Rewiring the stator to reduce the number of poles also proved to be a poor solution as this caused the stator to become extremely saturated.

It was shown that by instead using a stator generated by the developed stator design algorithm it is possible to achieve saliencies which one would expect from a well-designed SynRM, while still being able to accelerate the flywheel to nominal speed within the permitted time. It was therefore concluded that it is feasible to use a synchronous reluctance motor to power the flywheel, given that the stator is properly designed.

Control of Linear Induction Motor Drive for Hyperloop Applications

Student: **Vemund Waterloo Dybvik**
Supervisor: **Roy Nilsen**
Collaboration with: **Shift Hyperloop**

Problem description

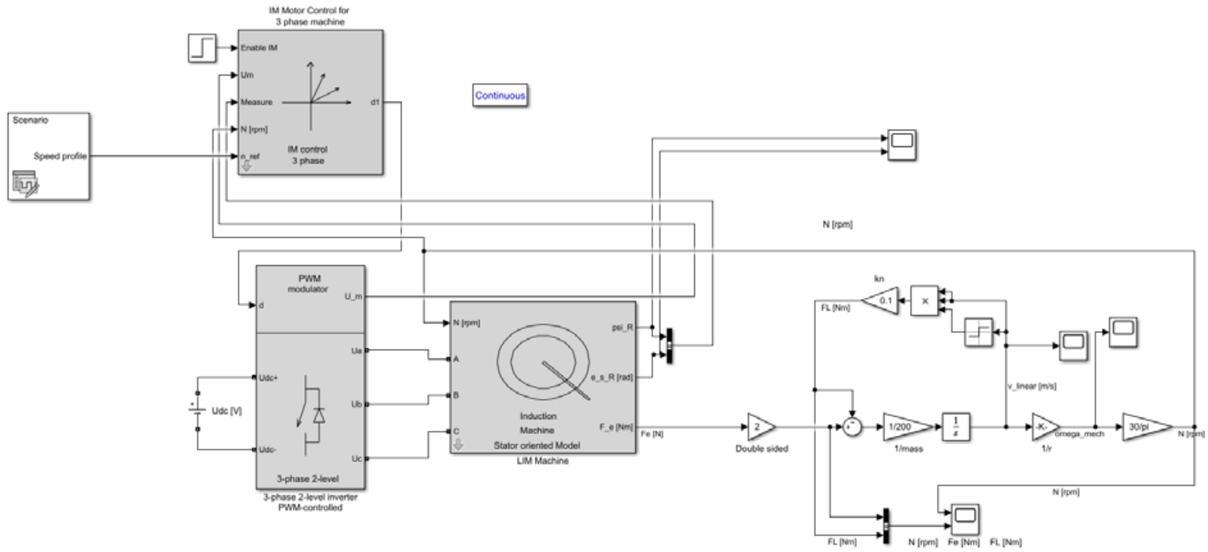
The Hyperloop is a proposed transportation method of the future, that consists of a sealed tube with very low air pressure inside, and a so-called hyperloop pod with magnetic levitation and propulsion systems to drive the pod forward. The pod can theoretically travel at very high speeds, using the advantages of low aerodynamic drag and magnetic systems. At NTNU, a student organization called Shift Hyperloop develops scaled down versions of these pods to compete in the SpaceX competition yearly in California. The goal is to create a magnetic drivetrain so that the pod can travel at many hundreds km/h. A common method for hyperloop propulsion is the Linear Induction Motor. This motor requires three-phase power, supplied by the inverter system on the pod. Due to extreme requirements from the motors, demanding large amounts of power at very high frequencies, the implementation of an efficient inverter control system posed several challenges for the 2020 team. This motivated a better understanding of the system and developing a better control system for the LIM.

The task

The task of this thesis was to implement a control system to control the Double Sided Linear Induction Motor on the pod that Shift is designing. This will be the first control system that Shift have access to and will serve as a base for further development and implementation. Rotor flux-oriented control structure was chosen and implemented in Simulink. The task also included digital implementation of the sensorless induction motor drive and load emulator on NTNUs PESC control platform. Due to the time limit working with the thesis, there was not enough time to do this.

Model/ measurements

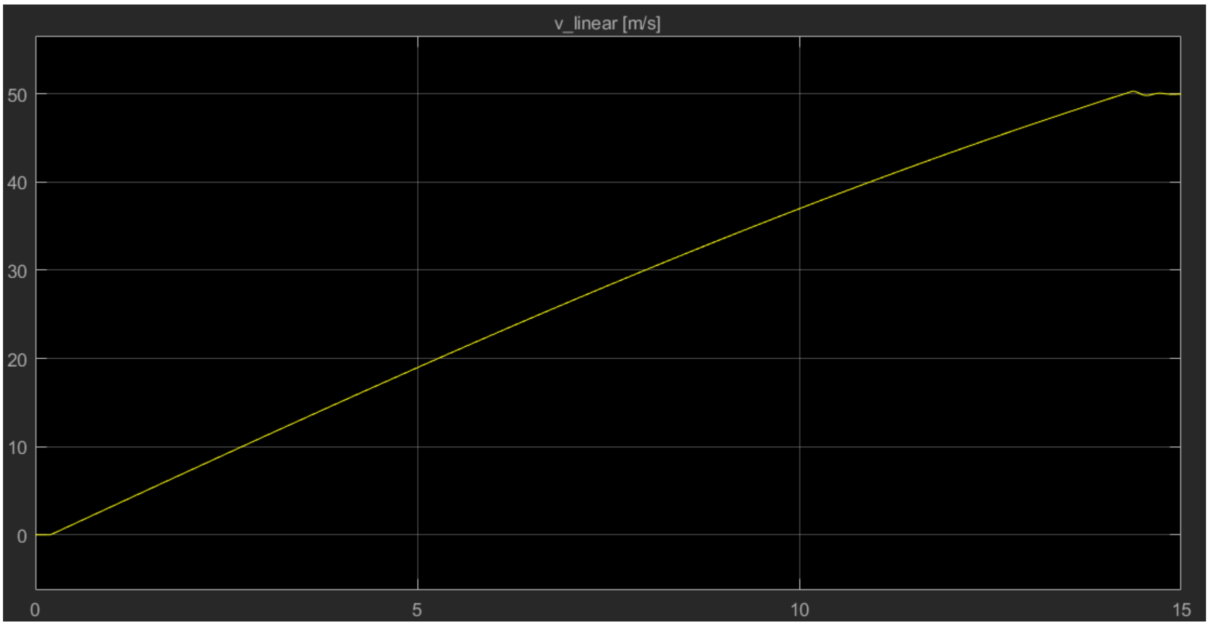
Simulations were performed in Simulink, with the Power System Library. The motor model was developed using a conventional rotating induction motor model as a base and changes were made to represent operation of the Linear Induction Motor.



The rotor flux control system consists of current controllers, speed controller, flux controller and a field weakening function. Decouple equations were also implemented and used for rotor flux estimation.

Calculation

Using estimated motor parameters showed that the pod could reach a speed of 0.5 pu, or 50 m/s in 14.05 seconds.



Conclusion

Parameter estimation of the motor is deficient as the motor design and manufacturing took longer than anticipated. The motor should therefore be tested systematically to characterize the Linear Induction Motor more accurately. The control system will likely fail to perform efficiently until further testing can be done.

The motor is coreless and therefore differs from what other student teams around the world are using to compete. Therefore, simulations were done for different degrees of “corelessness” (leakage coefficients). It was found that the degree of corelessness greatly affects the thrust force the LIM can produce. The Shift team is therefore encouraged to investigate methods of reducing the corelessness of the motor for efficient performance.

Implementation of a field weakening controller or inner induced voltage controller will also improve the flux reference input to the flux controller. The simulations showed that the function for field weakening, is not customized for the different operating scenarios. A field weakening controller may contribute to let the pod reach a higher top speed.

The control system developed will serve as a solid basis for the Shift teams going forward. It performed well and once more is known about the motor performance, appropriate changes can be made.

Contribution of Microgrid to the Reliability of Distribution Systems

Student: **Karoline Boel Johansen and Hilde Enevoldsen**
Supervisor: **Vijay Venu Vadlamudi**

Problem description

As the attention around finding sustainable solutions to meet the future power demand has increased together with the requirement for increased power system reliability, implementing microgrids has shown to be a promising solution. Another key driver for microgrids is related to the liberalisation of today's electricity sector. For increased security of supply, it is becoming more common to include distributed generation and energy storage system at the customer levels. This drives the need to evaluate the contribution of microgrids to system reliability.

The task

The objectives of this thesis are summarised in the following two problem statements:

1. Develop in-house software tools (MATLAB-based) as part of the development of a comprehensive framework for conducting adequacy studies for distribution system using the time-sequential Monte Carlo Simulation method.
2. Evaluate the reliability impact of microgrid operation in distribution systems.

Model

To assess microgrid reliability, the attention has been on incorporating DGs such as WT and PV systems, BESS and a proposed operation strategy. As such, appropriate models of DER have been presented and addressed. MATLAB scripts for time-sequential MCS of distribution system with the presence of microgrid have been created for the purpose of establishing the impact microgrid has on the distribution system, as given in Figure 1. These scripts have been verified with the analytical method by assuming constant generation and load, before DGs of intermittent behaviour and time-varying loads were introduced.

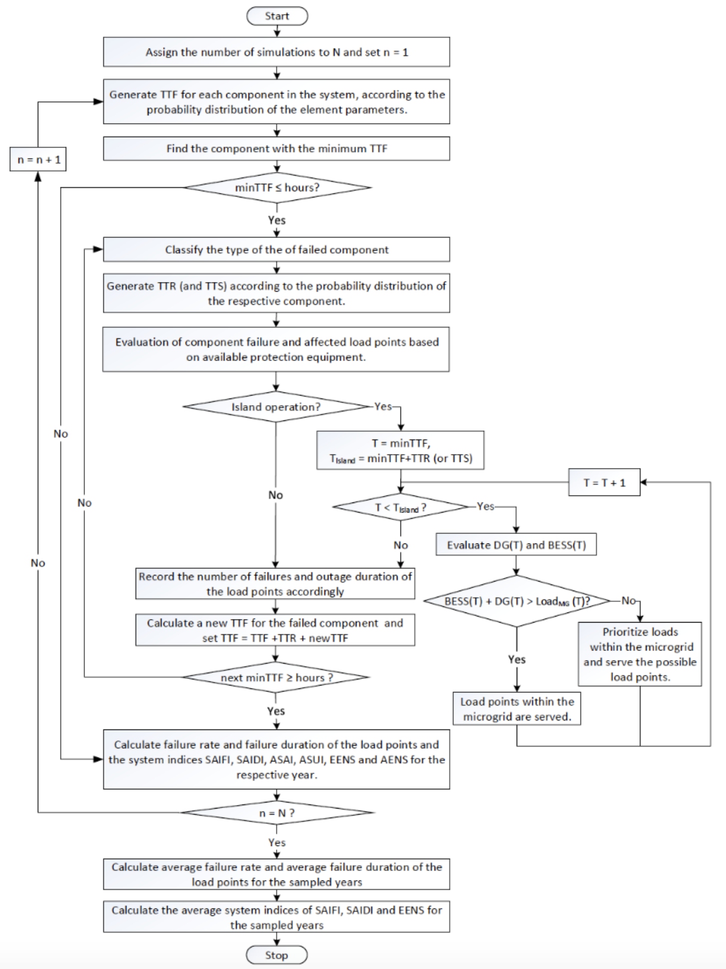


Figure 1: Flow Chart presenting the algorithm used to evaluate the reliability of distribution system with microgrid.

Calculation
Further, four case studies on the modified test system in Figure 2 have been conducted to seek understanding in a transparent manner: two studies to present the impact of implementing microgrid to the reliability assessment, and two incentives to enhance the microgrid operation (i.e., during island mode operation).

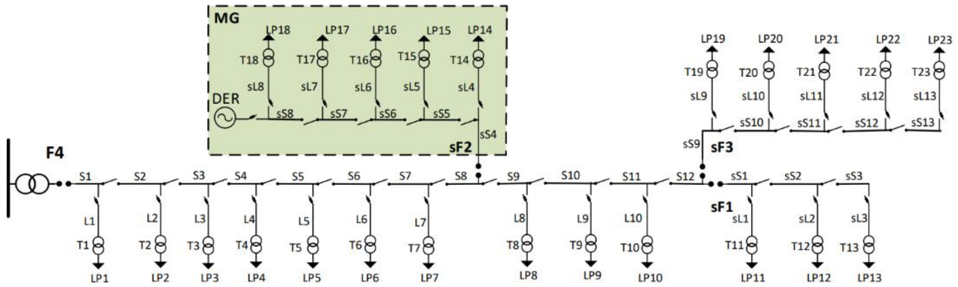


Figure 2: System configuration of modified Feeder 4, Bus 6 RBTS, where sub-feeder 2 is defined as a microgrid.

- Case 1: Passive distribution system (referred to as "Base case").
- Case 2: Active distribution system including a microgrid with DG (PV and WTG).
- Case 3: Active distribution system including a microgrid with DG (PV and WTG) and prioritised loads.
- Case 4: Active distribution system including a microgrid with DG (PV and WTG) and ESS (battery).

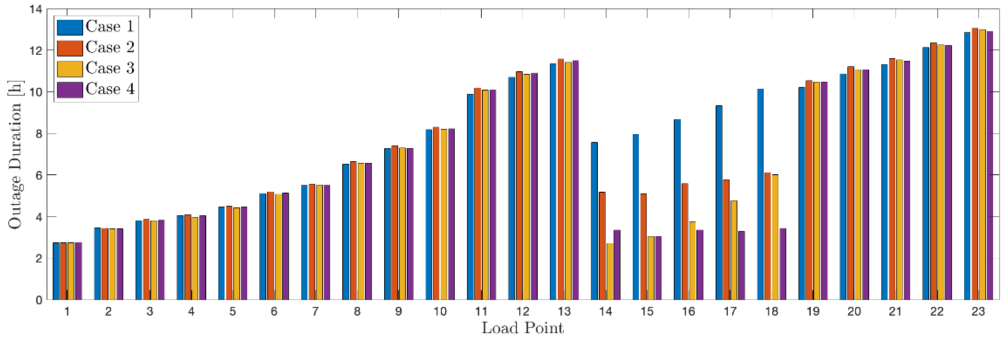


Figure 3: Simulated outage duration of the load points, for the four cases.

Conclusion
The reliability impact of implementing a microgrid in a distribution system is positive but profoundly depends on the size of the microgrid fraction and the proposed microgrid operation strategy. In addition, optimal placement and sizing of the DERs have demonstrated to impact reliability and should accordingly be taken into consideration.

Long term load forecasting for six different building categories, using explainable artificial intelligence (XAI)

Student: **Engstrøm, Audun Aass**
Supervisor: **Karen Byskov Lindberg**

Abstract

The current energy trends indicates that more decentralized energy systems where buildings both produce and consume energy will become more common. This suggests that a more local knowledge of energy consumption in buildings has a value in being able to ensure a suitable and efficient power grid.

In this thesis, we present “Gradient Boosting machine learning models implemented in Python, for long-term prediction of heat consumption per hour per square meter for six different building categories. The models take into account both climatic variables, time variables and the buildings efficiency levels. The models that have been created are “black-box models that are hard to interpret. Therefore, newer methods in explanatory artificial intelligence in the form of SHAP values (a concept inspired by game theory), have been used to explain and diagnose these models. The model's use of solar radiation and the different seasons have been examined in more detail. We saw that the effect of solar flux was almost constant in summer, but with a clearer trend in autumn, winter and summer. The model mainly used lower values of solar flux to give a higher prediction, this unnatural behavior is probably due to the correlation between solar radiation and temperature. The isolated effect of the seasons seems to be greatest on hot days in winter and cold days in summer.

All models has been tested against similar linear regression models created by "SINTEF Byggforsk". All of the models created in this thesis gave a better accuracy than SINTEF's models.

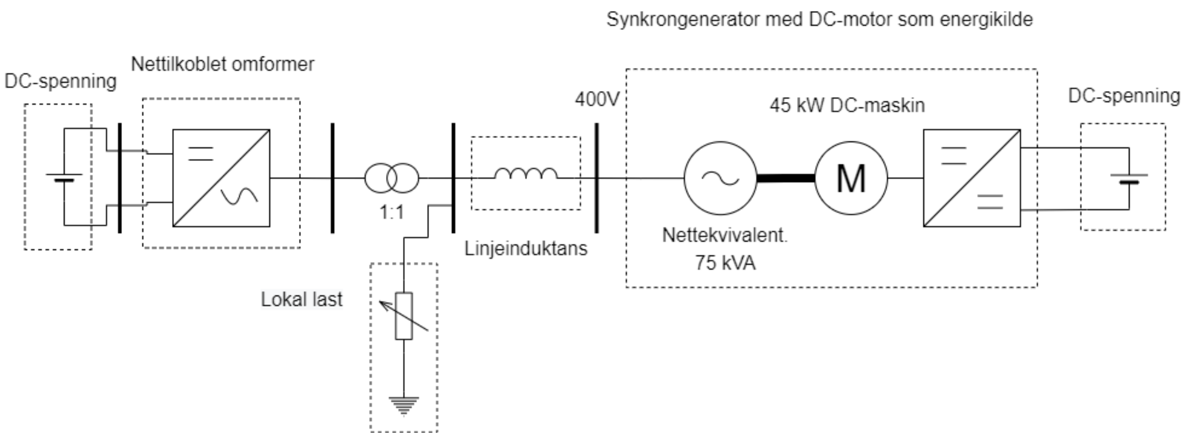
Due to lack of computing power, determination of the model hyperparameters was not done with cross-validation, and there are signs that some of the models probably do not have optimal values for the hyperparameters and thus can the models be further improved.

Laboratory Testing of Virtual Inertia Provided by Converters in Weak Grids

Student: **Kjeld Fjeldberg**
Hovedveileder: **Kjetil Uhlen**
Medveileder: **Trond Leiv Toftevaag**

Økende andel av uregelmessig fornybar energiproduksjon i nettet gir et økt behov for fleksibel energilagring for å sikre frekvensbalansen. Pumpekraftverk er den mest modne teknologien for å dekke dette behovet. Med variabel hastighet blir muligheten for å respondere til raske endringer i nettet forbedret. Når man kobler synkronmaskina fra nettet med kraftelektronikk blir frekvensene frikoblet og man mister det mekaniske treghetsmomentet til maskina. Hovedformålet med denne oppgaven er den økende interessen og behovet for virtuelt treghetsmoment.

Hensikten med denne oppgaven er å teste potensialet for å skape virtuelt treghetsmoment i et pumpekraftverk med variabel hastighet i et laboratoriumsforsøk. Laboratoriumsoppsettet har en 75 kVA synkronmaskin og en 45 kW DC-motor. Synkronmaskina skal representere et svakt nett, mens vannkraftverket er forenklet med en spenningskildeomformer som er forsynt av en DC-kilde. Et konvensjonelt PLL-synkronisert styresystem er valgt for omformeren. I tillegg til dette er det lagt til en supplementær kontrollsløyfe for å skape virtuelt treghetsmoment. Denne sløyfa består av en grein med droopregulering og en grein som gir et pådrag som er omvendt proporsjonalt med den deriverte av frekvensen (df/dt). En forenklet skisse over laboratoriumsoppsettet er vist i Figur 1.



Figur 1: Forenklet oversikt over laboratoriumsoppsettet brukt for testing av virtuelt treghetsmoment.

Forsøket viste at kontrollsløyfa for treghetsemulering effektivt bidro med frekvensstøtte. Med både droop og df/dt regulering aktivert ble frekvensfallet redusert med 50 %, sammenliknet med den konvensjonelle omformerstyringen. For den konvensjonelle reguleringa var frekvensfallet 2,6 Hz, mens for reguleringssystemet med treghetsemulering ble frekvensfallet 1,3 Hz. Det var mulig å øke frekvensstøtten noe mer, men dette på bekostning av stabiliteten til systemet. Stabilitetsgrensene for det gitte systemet ble identifisert.

Et annet formål med denne oppgaven var å identifisere de elektriske standardparameterne for synkronmaskina brukt i forsøkene. Dette for fremtidige simuleringsstudier. Siden maskina var gammel ble det vurdert at den tradisjonelle kortslutningstesten kunne medføre skade på maskina. Det ble derfor utført lastavslagstester for å estimere verdiene. Testene som ble gjennomført var d-akse, q-akse og arbitrær akse lastavslagstest. Metninga av maskina ble ikke tatt hensyn til. Resultatene fra parameterestimeringa er vist i Tabell 1. En simuleringsmodell ble etablert for å kunne vurdere presisjonen for de estimerte parameterne. Det ble anslått at parameterne var innenfor de virkelige verdiene med noen få prosent. Verdi for lekkreaktansen ble ikke estimert, men man kan anta at denne verdien er 10 – 15% av d-aksereaktansen.

Tabell 1: Oppsummering av de estimerte elektriske parameterne for synkronmaskina produsert av Siemens-Schuckert. Impedansbasen er 2,406 Ω.

Parameter	Estimert verdi
R_a	0,0236 pu
x_d	0,7029 pu
x'_d	0,1657 pu
x''_d	0,1051 pu
x_q	0,3542 pu
x''_q	0,1012 pu
T'_d	0,42 s
T'_{do}	1,80 s
T''_d	0,007 s
T''_{do}	0,011 s
T''_q	0,029 s
T''_{qo}	0,10 s

Condition Assessment of Generator Bars by Time Domain Dielectric Response Measurements

Student: **Fjeldstad, Daniel Ekornrud**
Supervisor: **Ildstad, Erling**

Abstract
The majority of Norwegian hydropower generators have been in service for 40 or more years, meaning they are reaching the end of their expected lifetime. New operation conditions introduced in recent years makes condition assessment methods more important in order to understand the limitations and expected life of the equipment. This thesis has therefore explored dielectric response as a condition assessment method and validated a megger as potential test equipment for the method. Several service aged stator bars have been tested on different temperatures and voltages. The megger had significant problems producing credible results on lower temperatures due to the low current. The sensitivity level of the megger was found to be 1 nA. A current level in which results had noise of ±20-30 % current variation per second. Low currents tests also had the occurrence of negative DC currents, breaking with the theory. The megger was able to detect trends in the bars for tests above 90 °C and establish the individual bars DC conductivity and dielectric loss. For these temperatures there were also found some uncertainty in the current measurements from the megger caused by a randomness in current level when measuring. The bars were also subjected to thermal cycling according to IEEE st 1310 and identical tests were repeated. Thermal cycling was found to show no significant impact on the bars. Dielectric response as a method has great potential, but needs significant amount of data handling and data from unaged test objects for comparison. A megger as test equipment does not perform satisfactory on single stator bars but needs further detailed study with repeat testing and other test objects to say for certain.

Analysis of Dynamic Pricing to Utilise Spatial Flexibility in Heavy-Duty Electric Vehicle Charging Demand

Student: **Kyrre Kirkbakk Fjær**
Supervisor: **Magnus Korpås**
Co-supervisor: **Bendik Nybakk Torsæter and Michele Garau**
Collaboration with: **SINTEF Energy Research**

Abstract

The upcoming heavy-duty electric vehicles (HDEVs) are expected to have a charging power between 400 kW and 1600 kW. A transition to HDEVs can cause challenges to the power grid to deliver the charging power needed. Typically, these challenges are coped with by upgrading the components in the power grid, which may be very costly in many areas. Therefore, it is necessary to investigate if there are other solutions to handle the new load demands. A possible solution is utilising demand response and dynamic pricing. By changing the charging price at a high-power charging station dynamically, based on the grid conditions, it is possible to incentivise the drivers to charge at other locations where the grid conditions are better. Thus, available flexibility in the power grid is utilised to increase stability.

This thesis aims to investigate the impact of dynamic pricing to distribute the load from HDEVs in a more favourable manner between two high-power charging stations. A new method for dynamic pricing of high-power charging stations by utilising the nodal prices from optimal power flow calculations is proposed. To investigate the proposed method, an agent-based model used to simulate traffic and charging behaviour is extended to include HDEVs and the new proposed dynamic pricing scheme. The dynamic pricing scheme is then compared to two different pricing schemes, a fixed pricing scheme and a dynamic pricing scheme that consider the voltage levels in the system.

From the case studies, it is evident that the dynamic pricing schemes are able to distribute the HDEVs more favourably and thus move load from a weak bus to a stronger bus. In one topology, the daily minimum voltage magnitudes at the weakest bus have, on average, been raised with 0.005 p.u. and 0.004 p.u. with OPF and voltage based dynamic pricing, respectively. While it in certain time steps have increased with as much as 0.02 p.u. for both pricing schemes. The voltage-based dynamic pricing scheme has decreased the losses from 4.75 % to 4.65 %, while the OPF based pricing scheme has reduced the losses further to 4.55 %. The results have shown a positive impact from both dynamic pricing scheme, where the OPF based tend to outperform the voltage based dynamic pricing scheme.

The two dynamic pricing schemes are strongly dependent on the power system topology and traffic environment. In an additionally investigated power system topology, an unwanted effect is observed from using the two dynamic pricing schemes. At some time steps, the voltage drops have been amplified, thus creating worse gird conditions. This is due to the shortcomings in both dynamic pricing schemes as they are approaches that utilise previously measured load conditions and do not predict the upcoming loads. Thus, the method is poorly adapted to handle significant load changes in the next time steps.

MODELLING THE FUTURE ROLE OF OFFSHORE WIND TO PRODUCE GREEN HYDROGEN

Student: **Flo, Daniel Vetle**
Supervisor: **Hossein Farahmand**
Collaboration with: **DTU**

Abstract

Nowadays the call for more sustainable solutions is ever growing. With an uncertain future it has never been more important for innovations and changes to the world's energy generation. Each country must do its part. In Europe the potential for offshore wind power in the Baltic Sea is substantial. Hydrogen can be key in the energy system transition. An investigation into the role of offshore wind to produce green hydrogen in a future integrated energy system was performed including its interaction with other system elements. The paper is based on research-based data implemented in the energy system modelling tool Balmorel. By performing energy system optimization in a model application of the European energy system and the Baltic Sea connected grid towards 2050. It is found that given the right political framework conditions we find that offshore wind could play a significant role in the future, and that offshore wind energy could form the necessary conditions to produce green hydrogen. Demand and costs were given the upmost priority for this synergy to be favored over other energy sources.

Adaptive Control of HVDC Transmission Systems -- Designing a stability-preserving energy-balancing outer loop

Student: **Gonzalez Gallego, Yeray - Rabanal, Arkaitz**
Supervisor: **Bergna-Díaz, Gilbert**

Abstract

The large-scale introduction of offshore renewable generation will indeed require a multi-terminal HVDC transmission system—based on voltage source (power) converters—in order to efficiently transfer the offshore power to shore over long distances. The conventional power converter control solutions associated to this technology (typically based on standard current control methods) have been designed to satisfactory operate near a single nominal operating point. This makes them inherently unsuitable for guaranteeing uninterrupted operation (stability) of the system in the event of an unexpected large signal-disturbance. Moreover, the offshore HVDC grid architecture complexity is expected to increase as more lines and renewable energy sources are connected to the grid. It then seems desirable to find control alternatives able to operate the system with large-signal stability guarantees, preserved regardless of any topological change or system disturbance size—and therefore avoiding any costly operational interruption of the system.

This manuscript presents the Energy Balance Based Adaptive (EBBA) outer-loop rooted in the Immersion & Invariance methodology, which replaces the traditional outer-loops while preserving the large-signal stability certificate on 2-Level VSCs. This novel controller places particular emphasis on the estimation of the system parameters, crucial for the converter load-flow computation. Additionally, for the development of this Master's Thesis port-Hamiltonian representation, Lyapunov theory and Passivity Based Control strategy are used.

Flexibility Solutions in Distribution Networks. Case study Utsira

Student:	**Anders Grøttås**
	Annvor Teigen Nestås
Supervisor:	**Irina Oleinikova**
Co-supervisor:	**Hanne Sæle**
Contact:	
Collaboration with:	**FME CINELDI and Haugaland Kraft Nett AS**

Problem description

The municipality of Utsira is expecting a sharp rise in power demand due to in-creasing industry activity and electrification, amplifying the already existing voltage issues induced by the island's weak grid and varying wind power generation. Flexibility is in this system therefore of great value in ensuring sufficient quality of grid operation. In this thesis, the potential of and need for various flexibility solutions related to different aspects of the grid is thus investigated.

The task

This thesis investigates how flexibility solutions can contribute to an adequate operation of the distribution network. The main objectives of the work in this thesis are:

- Analyze the potential and need for flexibility in the distribution system on Utsira.
- Develop a model of the distribution network on Utsira to simulate scenarios for how electrification and increased power demand will affect the existing distribution grid.
- Investigate how flexibility resources such as demand side response (DSR) and energy storage can contribute to voltage stability in the distribution grid on Utsira.

Model/ measurements

To investigate the flexibility potential and need, a simulation model of the 22kV grid at Utsira is built. Simulations are done by power flow analysis in PSS®E 34. The model was built using network data exported from NETBAS, provided by the DSO using an export to PSSE function. This served as the fundamentals of the model. The data contained most of the necessary grid parameters, such as all network buses and connections, line impedance data and transformer data, from the viewpoint of the mainland substation directly connected to Utsira through the sea cable. All load connections were also provided, along with their yearly maximum power demand calculated using Velander's formula. However, the load data for Utsira used in the model is gathered from AMS-data collected by the DSO. The AMS-data set consists of measurements from 254 meters, where ten of these are substation meters. Substation meters measures the total load of its radial, on the low voltage side of the transformer. The AMS-data is processed using Python, so that it can be implemented into the simulation model. Additionally, load profiles and voltage profiles are made in Python and used to investigate the loads behavior, identify peak periods and analyze voltage variations for the current situation. The power system on Utsira is not an isolated system, and its network conditions are therefore not only dependent on island activity, but also on the situation on the mainland. A simplified representation of the grid data between the sea cable substation and the regional grid was provided by the DSO to accomplish this.

The model used in this thesis is a one- line representation of the three- phase distribution grid on Utsira as seen from the regional grid connection on the mainland, constructed in PSSE to look into possible, future scenarios of the Utsira power system. It consists of three parts of the real network that have been combined to form a network of 67 buses, where 42 of these are load buses.

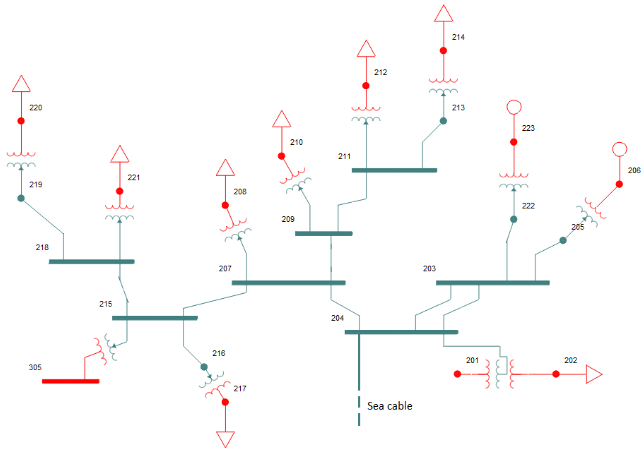


Figure 1: The model of the 22kV grid on Utsira with the associated bus numbers

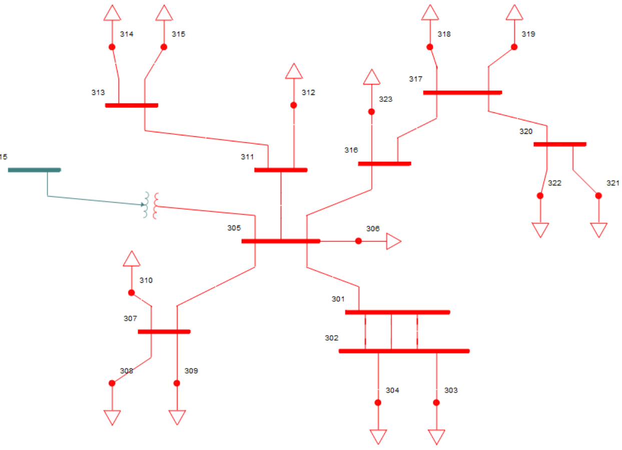


Figure 2: The model of the radial connected to substation 215 (bus 215), with the associated bus numbers.

Calculation

Different scenarios for increased EV charging and charging of a planned electric ferry were developed to identify and analyze the future need and potential for flexibility solutions in the distribution network at Utsira. Figure 3 and Figure 4 presents the main results in form of voltage profiles from these scenario simulations.

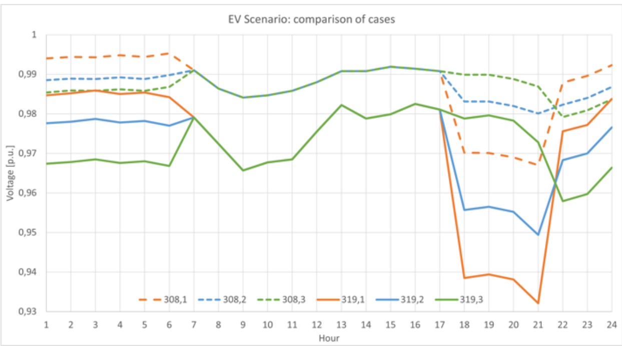


Figure 3: EV charging scenario with 0%(orange line), 67%(blue line) and 100%(green line) DSR participation

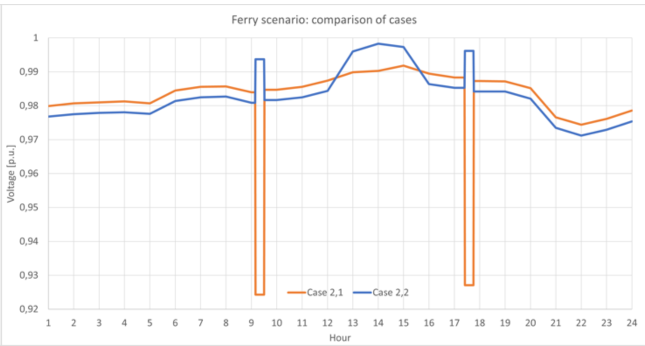


Figure 4: Ferry charging scenario with one (orange) and two (blue) batteries used for charging

Conclusion

The key takeaways from this thesis are:

- Achieving a high DSR participation rate for smart charging of EVs will reduce voltage variations.
- Load shifting by using appropriate BESS for charging the planned electric ferry will reduce voltage variations and reduce needed reinforcements in the distribution grid.
- The increase of load due to electrification of the transport sector at Utsira will demand an increase of power supply from the VRES available on the island.
- There is a potential for flexibility in the thermal loads on Utsira, but that is alone not sufficient to cover the predicted increase in power demand.

The Impact of Hydrogen Production on the Offshore Wind Business Case

Student: **Sander Holt Günther**

Supervisor: **Hossein Farahmand**

Abstract

The European Union recently decided to increase its climate ambition for 2030 and aims to reach climate neutrality by 2050. Achieving a climate neutral economy involves a vast expansion of European offshore wind and will require a large amount of hydrogen, especially in hard-to-abate industrial sectors. Such hydrogen will increasingly be produced on the basis of renewable sources, because only renewable-based hydrogen is fully carbonfree. While being essential in tackling emissions, low-carbon hydrogen can also act as a flexibility provider and help balancing seasonal variations in electricity generation from renewables.

In this thesis, a deterministic optimization model for power system expansion planning (PowerGIM) is formulated and demonstrated on a case study. The case study assesses new and effective ways of realizing the potential of offshore wind in the North Sea, through a transnational and cross-sector approach. The TYNDP 2020 Global Ambition scenario for 2040 is used as the main source of input data and included countries are Germany, Denmark, the Netherlands, Belgium, Great Britain, Norway and France. Primary targets are to investigate the utilization and utilization drivers of new transmission and generation capacity. A main focus is also dedicated to investigate the impact of hydrogen on the offshore wind business case.

Obtained results demonstrate that a high level of integration between countries is essential to unlock the full potential of large-scale offshore wind. Connecting new offshore wind capacity to Germany, Denmark and the Netherlands through hub configurations, compared to a radial configuration, is found to provide a higher utilisation of wind assets. However, new transmission capacity has a low value unless connections are included to the Norwegian and British market. It is also found that green hydrogen can serve as a facilitator for offshore wind integration, providing significant reductions in curtailment and increased revenue in the electricity market. Added load through new electrolyser capacity generally leads to a higher utilisation and capture prices for offshore wind. Conversely, when comparing a fixed and price dependent hydrogen load, it is observed that optimal charging from the grid enables the electrolyser to capture low electricity prices, significantly reducing the power costs of hydrogen production. Given the underlying assumptions it is calculated that the levelized cost of hydrogen could come down to C1.2-2.8/kg H_2, provided a low-cost electricity supply and declining capital costs of electrolysers through 2040.

Evaluating the optimal portfolio of VRE capacity to be integrated into the power system: A case study of Zambia

Student: **Lars Falsen Habostad**
Supervisor: **Hossein Farahmand**
Co-supervisor: **Thomas Haugstenrød**
Collaboration with: **Multiconsult**

Problem description

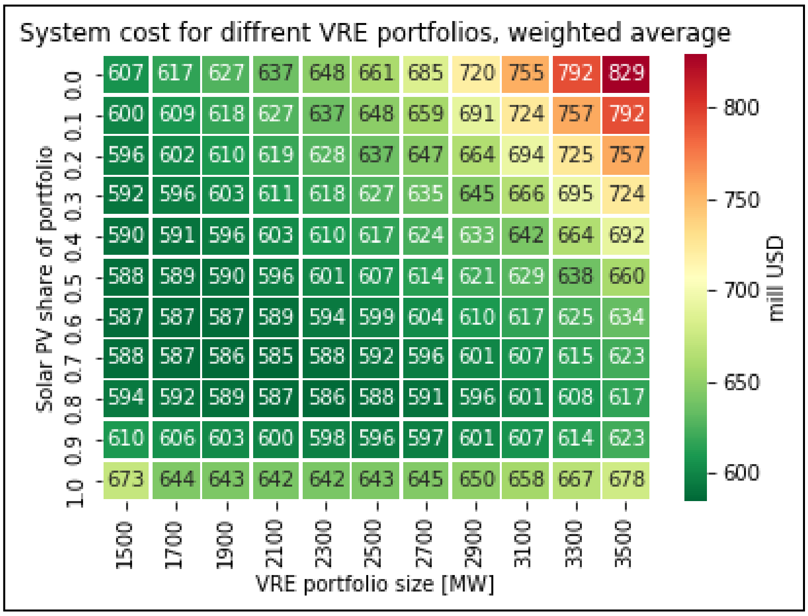
The Republic of Zambia is located in Southern Africa. Like many of its neighboring countries, the electrification rate is low, and less than half the population has access to electricity. Also, the hydropower-dominated Zambian power system has proven vulnerable to changes in rainfall and drought. In recent years, low rainfalls, combined with increasing electricity demand, has led to massive power shortages, resulting in load shedding. Integrating variable renewable energy (VRE) has been proposed as a measure for diversifying the generation portfolio. Renewable energy integration has the potential to increase energy security and lower system operational cost.

The task

This thesis evaluates the optimal portfolio of solar PV and wind power capacity to be integrated into the Zambian power system within 2030. A framework consisting of three steps is developed. First, the expected variations in VRE generation output and precipitation are investigated based on historical data from the Renewables.ninja database. Second, the optimal VRE portfolio is assessed through simulations in a single-node power system model in the open-source software PowerGAMA. System cost is used as the performance metric for evaluating the portfolios, and the optimal portfolio is found as the one resulting in the lowest system cost. Finally, load flows are evaluated with the optimal portfolio of VRE integrated into the electricity grid, to identify potential grid constraints.

Results/conclusion

The optimal VRE portfolio consists of 1470 MW (70%) solar PV and 630 MW (30%) wind power capacity in the base case. This corresponds to a VRE share of 37% of total system generation capacity. When assuming a dynamic valuation of water stored in reservoirs or a lower initial reservoir level, the optimal portfolio size changes to 2700 MW and 3100 MW, respectively. However, the distribution between solar PV and wind power capacity remains at 70/30, suggesting that this could be the optimal distribution of solar PV and wind power capacity. Assuming a lower system load drastically changes the result to a smaller portfolio of 700 MW solar PV, and no wind power capacity.



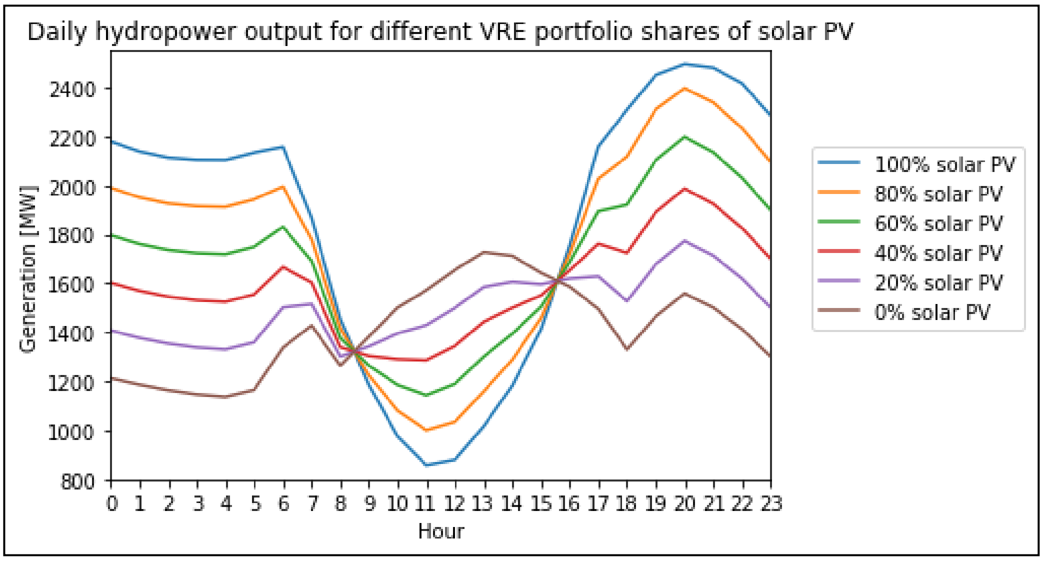
The system costs resulting from 121 different portfolios of new solar PV and wind power capacity integrated into the system in 2030. A solar PV share of 1.0 implies a portfolio consisting of only solar PV capacity, while a solar PV share of 0.0 implies a portfolio consisting of only wind power capacity.

The optimal portfolio of VRE is considered the single most important result in this thesis. Nevertheless, this result should be seen in relation to the other results, which can be summarized as follows:

- The annual electricity output from solar PV and wind power is relatively stable between years, compared to the inflow to hydropower plants. Also, the generation from VRE is negatively correlated with precipitation. This implies that the output from solar PV and wind power plants is higher in dry years. Literature suggests that future climate change could reduce water availability, but that a decrease in solar irradiation and wind speeds is more unlikely. On a monthly basis, the VRE generation output is highest in the dry season. The sum of these findings demonstrates that diversifying the generation portfolio with VRE could increase energy security in Zambia.

- Meeting the expected growth in electricity demand entirely by implementing new VRE capacity, does not seem like an optimal solution. Load shedding occurs for all portfolios included in this thesis, and for the portfolios resulting in the lowest degree of load shedding, substantial curtailment of VRE capacity is seen. Therefore, increasing the dispatchable generation capacity in the system in parallel with the VRE integration could be necessary.

- Integrating wind power capacity could reduce load shedding and decrease the magnitude of hydropower ramping. On average, the wind power output increases in the afternoon, and this corresponds well with the afternoon load peak. Wind power could thus benefit the system from both an economic and a technical perspective, despite having a higher LCOE than solar PV.



The cumulative average daily hydropower dispatch of the three largest hydropower plants with a portfolio of 2100 MW VRE capacity integrated into the system. A high wind power capacity share results in decreased ramping of the hydropower plants. 100% solar PV corresponds to a VRE portfolio consisting of only solar PV capacity, while 0% solar PV corresponds to a VRE portfolio consisting of only wind power capacity.

- The current electricity grid is considered suited for integrating the optimal portfolio of VRE, given the assumed distribution of new power plants in the grid. Therefore, the flexibility of existing hydropower plants is considered the most critical factor when integrating renewable energy into the system, from a technical perspective.

Assessing potential effects of electrolysis and batteries on variable renewable energy in the European power market

Student: **Hagen, Tuva Eikås**
Supervisor: **Korpås, Magnus**

Abstract

The European Green Deal was presented by the European Commission in 2019 and delivered a growth strategy on how to reach zero net emissions of greenhouse gases by 2050. The goal is to reduce global warming to a maximum of 2 degrees compared to pre-industrial times. To reach this goal, fossil fuel needs to be phased out and the transition to RES is essential. When increasing the share of RES, and especially VRE, in the power system the generation will not be as elastic as before. This might result in a high share of curtailment and low prices in times of generation from VRE. If this is the case, investing in VRE might become less financially beneficial which again can slow down the development of VRE.

The EU 2050 target is already ambitious, hence it is important to facilitate the technological transition according to VRE so that the power system enables an economically sustainable transition to a zero-emission society. Batteries and electrolysers is examples of technology that might help the transition. Thus, the focus of the thesis is to assess potential effects of electrolysis and batteries on VRE economics. Firstly, important future trends in the power system that will affect the revenue for RES is located. Secondly, a power system representing 2040 is implemented with an objective to simulate the power prices and the generation dispatch.

The simulation tool used for this thesis is PowerGAMA, which uses DC power flow equations to determine the optimal generation dispatch. The author found that when batteries were not the best option for increasing VRE economics. Adding electrolysers, on the other hand, improved the total revenue and decreased curtailment. It even had a signifcant positive impact on the total CO2 emissions. Further the thesis also contributes with valuable insight in how to easily model batteries and green hydrogen in PowerGAMA so that other master students or stakeholders can benefit from this and build on the work.

Online condition monitoring of synchronous generator using shaft signals

Student: **Gaute Hagen Hallingstad**
Supervisor: **Arne Nysveen**
Co-Supervisor: **Hossein Ehya**

Problem description

Hydropower generators produce almost 100% of Norway's electricity. The primary type of generator is the Salient pole synchronous generators (SPSG). A steady operation of the SPSGs in hydroelectric power plants is essential to avoid unplanned stoppages that can give substantial cost increases in the production. One of the factors that ensures a steady operation of the SPSGs is to avoid faults

The task

The main objective of this thesis has been to investigate whether and how incipient electrical and mechanical faults can be detected by implementing an online shaft voltage monitoring system.

Model/ measurements

- 2D finite element analysis of the generator located at NTNU Smart grid laboratory. The simulations were performed with load and at no-load, in a healthy operating condition, and during faulty conditions including static eccentricity fault and inter-turn short circuit fault in the rotor field winding.

- Generator modifications. The laboratory generator at NTNU was modified with an isolated bearing to accommodate for the simulations. A measurement setup with a brush attached to the shaft was also developed.

- Running of the lab generator. The generator was operated with different loads and faults. During the operation, the shaft voltage was measured.

- The results from the 2D finite element modeling and the measurements from the experimental simulations were analyzed to assess the impact of the generator under the various conditions. And also to find out if it is possible to simulate the shaft voltage of a synchronous generator and to see if load has any impact on the results.

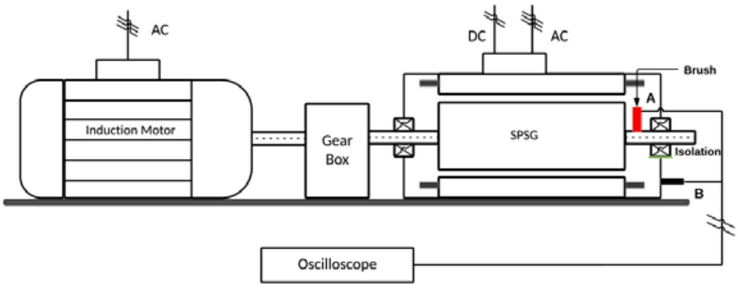


Figure 5.8: Schematic of the lab setup with a brush on the shaft

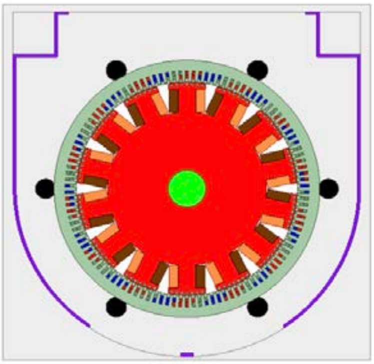


Figure 4.12: Generator model with shaft and housing

Calculation

The most significant results are presented below. Fig 6.19 shows that the magnitude of specific frequencies namely the 814 Hz and overtones of the mechanical frequency increases with number of ITSC. Fig 6.58 show that the 50 Hz component increases with the amount of SC. Fig 6.35 and 6.62 shows how the key frequencies changes when there is a change in loading of the machine.

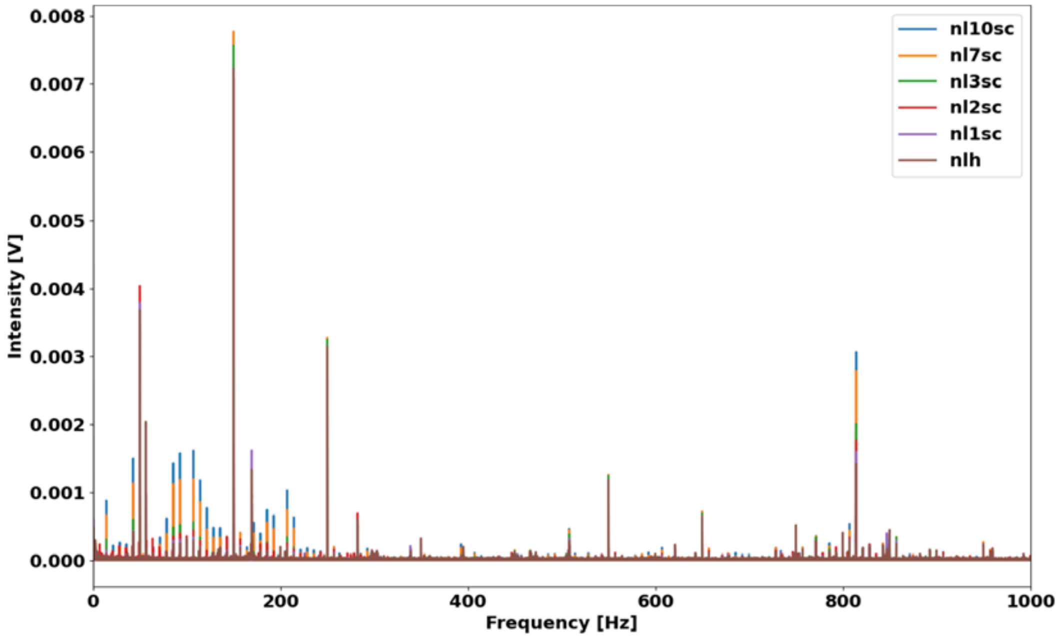


Figure 6.19: Amplitude spectrum that compares the 0, 1, 2, 3, 7, 10 ITSC when running the machine with no load

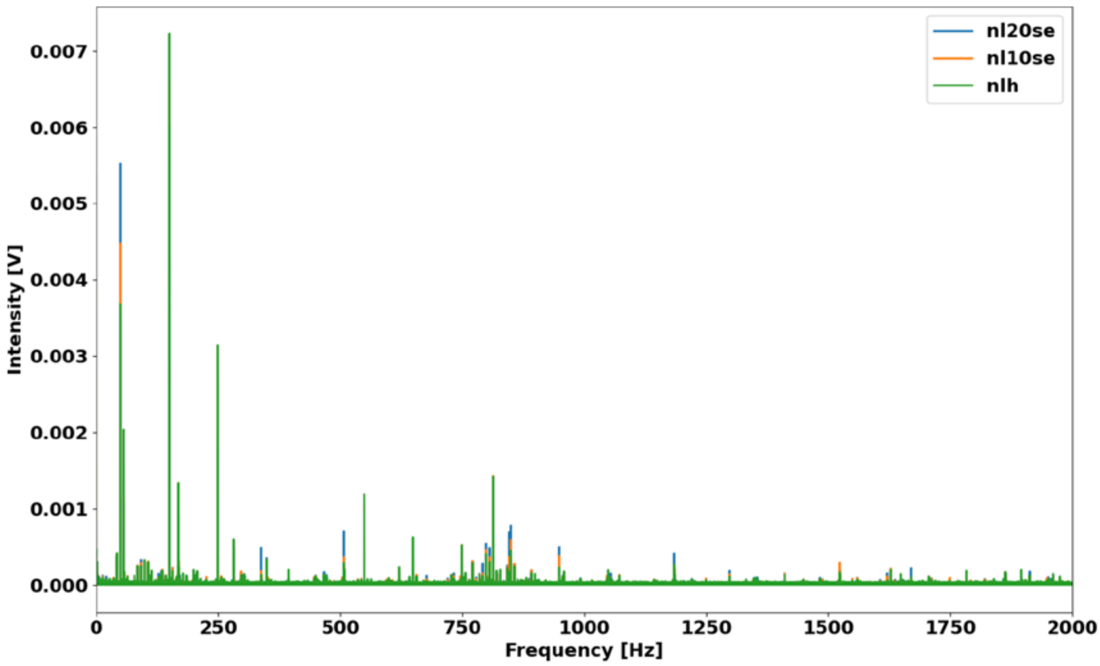


Figure 6.56: Fourier transform of the ITSC shaft signals in the frequency range 0-300 Hz

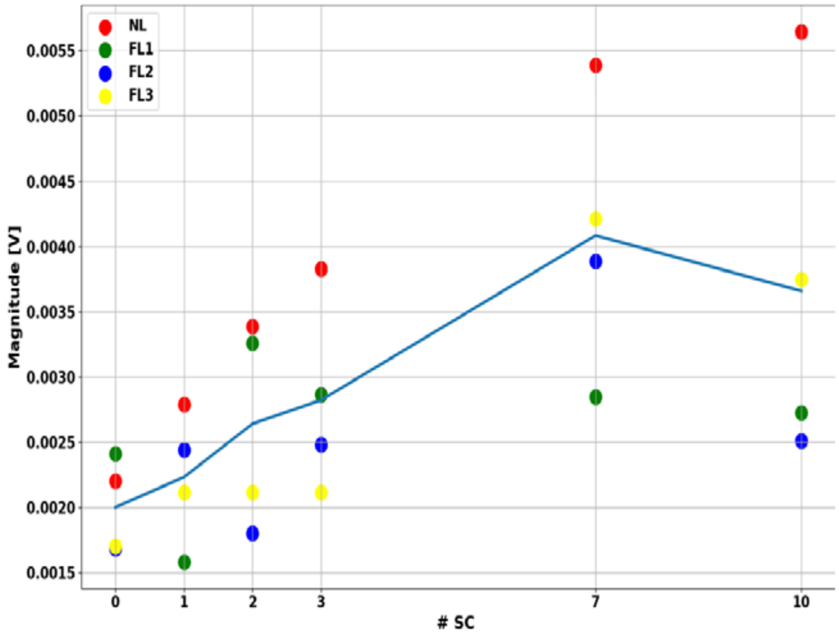


Figure 6.35: The magnitude of 814 Hz plotted as a function of SC and load

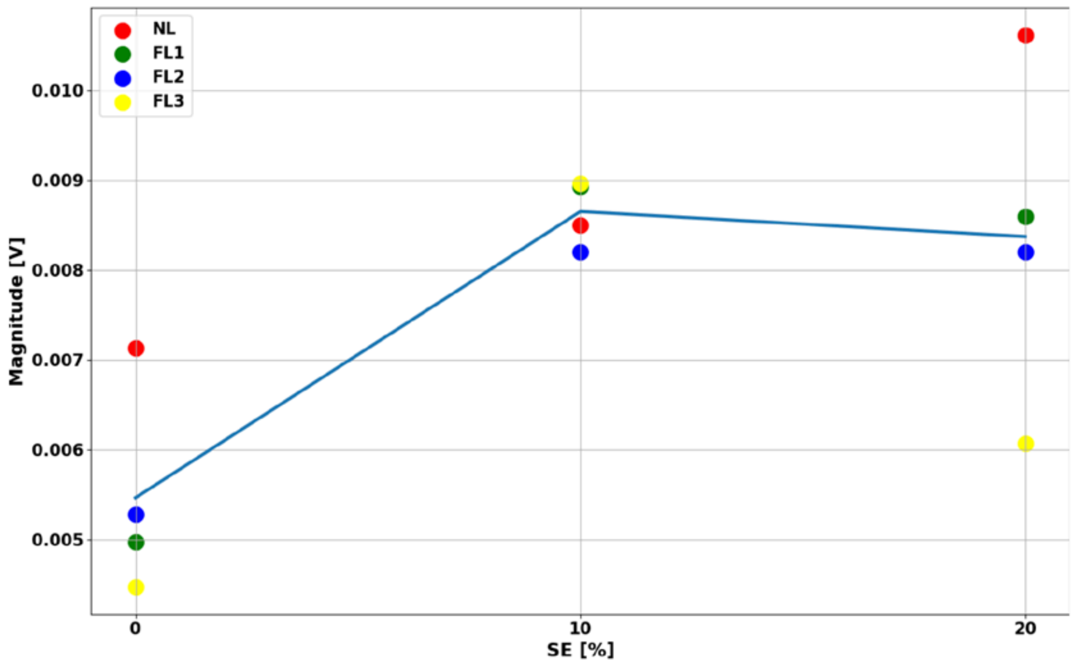


Figure 6.62: The magnitude of 50 Hz plotted as a function of SC and load

Conclusion

Laboratory measurements with different loads on the machine revealed that the load has an impact on the shaft voltage. However, it was more challenging to distinguish between 0 and 2.9% ITSC. In conclusion it is possible to use shaft voltage while running in no-load or use the variability of specific frequency to detect faults in a machine.

Coordinated Multi-objective tuning of PSS and AVR

Student: **Hansen, Vard Nes**
Supervisor: **Nøland, Jonas Kristiansen**

Abstract

In a generator, the Automatic Voltage Regulator (AVR) is responsible for keeping the terminal voltage to the desired level by regulating the field voltage supplied to the field winding. The Power System Stabilizer (PSS) is designed to counteract low-frequency oscillations in the power system by introducing an additional signal to the excitation system. The increasing penetration of some types of renewable energy sources will contribute towards a power system with lower inertia. Thus, the regulation of remaining rotating mass synchronous generators becomes increasingly essential, tightening AVR and PSS tuning requirements.

This thesis deals with the simultaneous tuning of the AVR and the PSS using a heuristic Multi-objective Optimization (MO) approach considering both voltage regulation and oscillation damping. A high-fidelity mathematical model of the \ac{wfsm} connected to an infinite bus is presented and combined with the AVR and PSS equations. The system is linearized, and the combined state-space formulation is suitable for small-signal analysis and implementation in MATLAB R2020b. The \ac{avr} is implemented as an ideal \ac{pi} regulator shown to be equivalent to the recommended IEEE ST7C model of a static exciter.

The \ac{mo} approach, in contrast to single-objective optimization, results in a Pareto front of non-dominated solutions that contains additional information regarding the two conflicting goals of fast voltage regulation and sufficient damping of rotor swings. To an electrical engineer, this information represents an additional degree of freedom when selecting the optimal parameters of the \ac{avr} and \ac{pss}. The two extreme points on the Pareto curve are then compared to another point lying close to the midpoint. Time-domain simulations confirm that the midpoint represents a good compromise between fast voltage regulation and sufficient damping.

The time-domain simulation of the rotor speed deviation and the damping of the dominating oscillatory mode shows that the proposed approach can generate solutions that achieve higher levels of damping for the same level of PSS gain compared to a classical tuning method.

Energy system planning of Zero Emission Neighborhood in Bodø combined with hydrogen ferries

Student: **Marie Hefte**
Supervisor: **Magnus Korpås**

Problem description

The Bodø airport redevelopment project aims to turn today's airport area into a smaller airport and a Zero Emission Neighborhood with a new generation of buildings that are environmentally friendly and energy efficient. 15000 new homes and 20000 working places are planned to be build. This is a pilot project for Zero Emissions Neighborhoods, the goal for the pilot project is to develop an urban and environmentally friendly neighborhood, whit minimized energy demand, and with zero greenhouse gas emissions.

The task

The main contribution of this thesis is an investigation of the power system choice of the new zero emission neighborhood in Bodø in a combination with hydrogen ferries. The neighborhood will have local and nearby power production as wind power and PV power, and a hydrogen storage system will be included.

Model/ measurements

This thesis uses the Matlab model windhydtool to calculate the sizing of the power system for the Zero Emission Neighborhood in Bodø combined with three hydrogen ferries from Bodø, one to Røst, one to Moskenes, and one to Værøy. The ferries run two times a day, and in the summer months June, July, and August the ferries run four times a day, due to all the tourists visiting the area in the summer. These ferry routes are the longest and most difficult in Norway and too long for electricity battery, therefore hydrogen used as the fuel is the right solution.

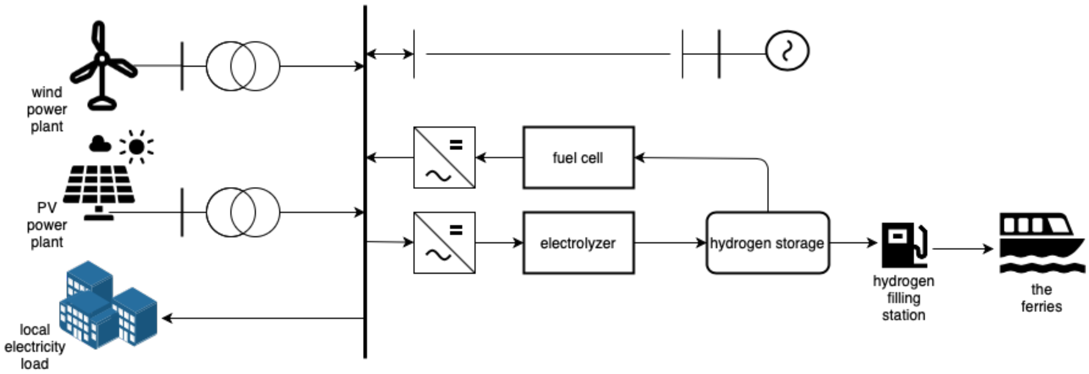


Figure 1: Scematic illustration of the PV, wind, and hydrogen system.

First, an estimate of the building stock and the neighborhood's hourly electricity demand was made. Furthermore, an estimate of the ferries hourly hydrogen demand was made to do the calculations. Three main scenarios were run: one with only electricity load and with use of hydrogen storage and fuel cell, one with both the electricity demand and the hydrogen demand and the hydrogen stored is only used for the ferries, the last one with both the electricity demand and the hydrogen demand and with use of the fuel cell. Further, each of these three main scenarios is run; with only wind power, only PV power, and a combination of 80% wind power and 20% PV power.

Calculation
The results show how the ferries' hydrogen load impacts the power production demand. The hydrogen load each year is 26,5 GWh, and the electricity load is 101,3 GWh. The main goal for the neighborhood is the zero energy goal, and the neighborhood should be as much as possible self supplied with energy. The case where both hydrogen load and electricity load are included and which has the lowest power import from the grid over the year is the case with 43500 kW installed wind power capacity and 10900 kW installed PV power capacity. The power import from the grid for this case is 37 GWh. A combination of wind power and PV power gives an optimized solution, because the wind power plant produces at its maximum during the winter when the wind speed is high and the PV power plant produces at its maximum during summer when the solar irradiance is high. This solution uses the hydrogen fuel cell, so it is beneficial to use the stored hydrogen in the fuel cell and produce electricity to cover a share of the neighborhood's electricity demand.

Conclusion
Renewable energy sources are needed to achieve a low carbon society, and a zero emissions neighborhood is a main part of a low carbon society. A hydrogen storage system can be used to power ferries, and in combination with a fuel cell also produce electricity to supply the neighborhood. This will decarbonize the sea transportation sector, and the building and construction sector. The best solution to supply the neighborhood is a combination of 80% wind power and 20% PV power, and with use of the hydrogen fuel cell.

Control Models for Providing Virtual Inertia to the Electrical Grid of the Offshore Platforms With Large Contribution of Offshore Wind

Student: **Heidari, Mohammad**
Supervisor: **Tedeschi, Elisabetta**

Abstract

Norway as one of the leading countries in the oil and gas and (floating) offshore wind energy sectors, plans to reduce its carbon emission according to the European commission strategy to become carbon-neutral by 2050. One of the considerable contributors to the carbon emission in Norway are oil and gas platforms. Supplying these platforms through offshore wind can accelerate realizing carbon-neutrality.

A well-built grid can withstand a contingency event and have an acceptable rate of change of frequency due to high inertial characteristics. The reduction of the grid inertia is one of the main issues with the paced integration of renewable energy sources into the electricity grid and replacing the conventional generators. To overcome this issue, multiple mathematical methods have been developed to ensure grid stability. These methods are based on an additional energy source to help the system stability throughout the event of a contingency. In this project, a few of the methods to provide virtual inertia for renewable energy sources are reviewed and compared against each other. Based on the ideas inspired by these methods, an algorithm is proposed to assist the inertial response of the grid of oil and gas platforms.

The proposed algorithm is implemented on a voltage source inverter that extracts energy from energy storage and injects it into the grid of the platform alongside gas and wind turbines. The method is validated by a step-change in the load of the platform and the interactions of the grid components are presented. Compared to a scenario in which there is no inertial support provided, the proposed method proves operational in reducing the rate of change of frequency and therefore, stabilizing the grid during the contingency.

Key words: Electrification of oil and gas platforms, Offshore wind turbine, Virtual inertia, vector control of converter, Back to back converter control, DFIG, gas turbine, Energy storage

Aluminium Fuses for Li-ion Battery Systems

Student: **Trym Leivestad Holtet**
Supervisor: **Eilif Hugo Hansen**
Contact: **Magne Runde**
Collaboration with: **SINTEF Energy Research**

Problem description

Copper conductors in the form of sheets and busbars connect the hundreds and thousands of 4-volt cells in series and parallel to form a complete battery system. Integrated into these conductors are fuses that should blow if internal or external short circuits occur.

It is now considered using conductors of aluminium instead of copper as this significantly reduce the material cost and the total weight of the battery system. However, fusible conductors made in aluminium for the voltages and currents of this application is a novel approach that needs to be carefully tested and verified.

The task

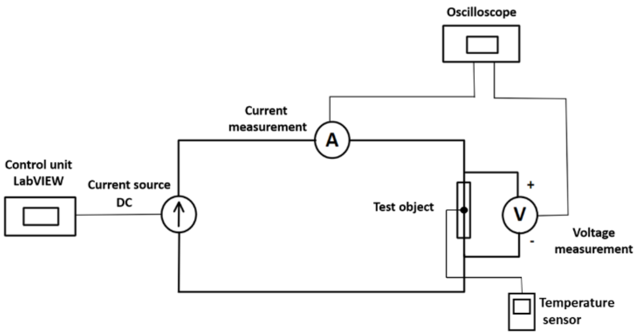
The approach is mainly experimental. The current interrupting capabilities of fusible conductors of aluminium and copper should be investigated and compared.

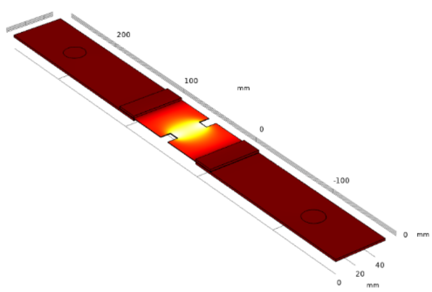
A suitable test setup should be designed and built, and this should be used to carry out systematic parameter studies as:

- Geometries and design
- Alloys
- Current and voltage
- Response time
- Arcing/no arcing
- Interruption/no interruption

Model/ measurements

To test the differences between copper and aluminium, a laboratory setup was made with a current source and a control unit made with LabVIEW. The goal of the setup was to apply different currents through test objects with different geometries and materials. Time-current characteristics was made as well as well as temperature recordings. As the current source could only deliver 1000A, further investigations were done with COMSOL Multiphysics.



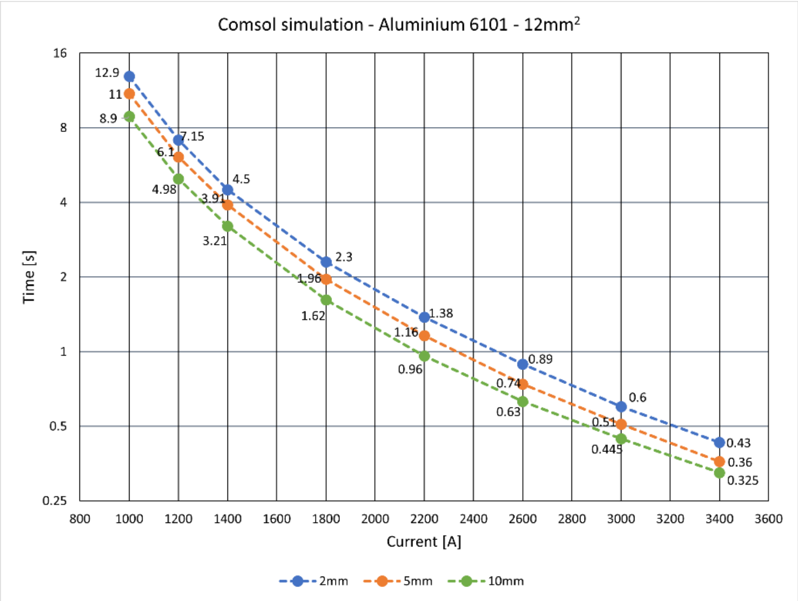


Calculation
The main restriction of designing the fuse is the temperature increase during nominal current of 200A. An equation was developed to estimate this temperature increase with different cross-sectional area and length of the constriction.

$$\Delta T = (2 \cdot L + 48.3)e^{-0.076 \cdot A}$$

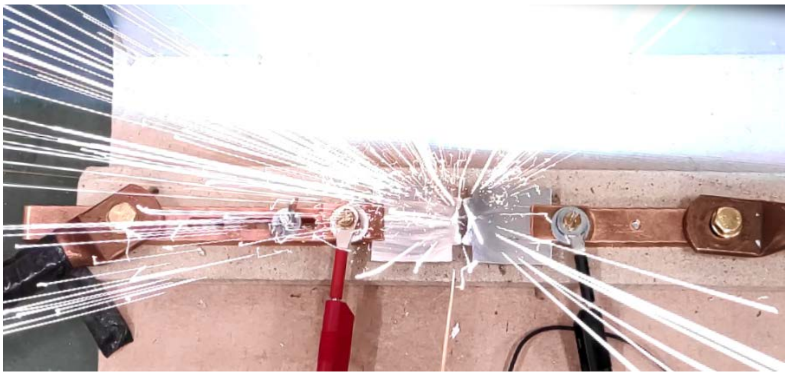
L = Length of constriction [mm]
A = Cross sectional area of constriction [mm^2]

Multiple time-current characteristics were made as the one below



Conclusion
With aluminium and especially with larger cross sections comes significant challenges in regard to spark formation, and with it also larger melted particles that can lead to undesirable after-effects. The fusing time were also undesirable long with the cross section of 20mm^2 which was needed to keep the temperature increase, during nominal current, below 10-12°C.

It is therefore suggested that to use aluminium as a fusible conductor, both a type of encapsulation and utilizing of an “M-effect” material is needed.



Quantifying the Impact of Integrating Wind Power on Composite Power System Reliability

Student: **Joakim Horpestad**
Jo Søbstad Skjævesland
Supervisor: **Vijay Venu Vadlamudi**

Due to global efforts to combat climate change, renewable energy is currently seeing a boom in growth, with wind energy leading the way. Electric power generation from wind energy is different compared to that from conventional sources, due to the intermittent nature of the wind speed. Therefore, the operating characteristics of the wind energy facilities have a different impact on the reliability of the power system compared to that of conventional sources. The rapid development of wind energy installations can lead to increased pressure on electric power utilities. This thesis identifies and develops methods to evaluate and quantify the impact of significant wind power penetration on the reliability of composite power systems through probabilistic Monte Carlo Simulation methods.

Two fundamental Monte Carlo Simulation methods, the Sequential State Transition method, and the Non-sequential State Sampling method, are selected to include wind power penetration in composite system reliability assessment. Two different wind speed models, the auto-regressive moving average (ARMA) wind model and the Weibull distribution-based wind model, are included and compared in the composite system reliability assessment. The wind power modelling considerations are selected through an extensive literature review, which examines the state-of-the-art on the main topic of the thesis. The developed methods are applied to a DC-based contingency solver and an AC-based contingency solver for composite system state evaluation. The developed in-house software tools are tested on standard test systems suited for composite power system reliability evaluation through appropriate probabilistic indices and compared with selected corresponding benchmark results from the literature.

The thesis applies different wind speed regimes to case studies and compares the impact on the reliability of the system delivery points and the overall systems. Wind speed correlation between multiple wind sites is identified as an important parameter in the wind modelling process and is included in the wind speed models. The priority order load curtailment philosophy is used to control the load curtailments at the system delivery points. It is observed that the characteristics of the wind speed regime, transmission network, degree of wind speed correlation, and choice of load curtailment philosophy have a significant impact on the reliability of power systems with significant wind power penetration.

An Optimal Model Predictive Control-Based Energy Management System for Microgrids

Student: **Synnøve Hovden**
Supervisor: **Olimpo Analya-Lara**
Co-Supervisor: **Raymundo Torres-Olguin**

Problem description

The concept of microgrids is considered a promising building block for realizing the modern and future power system much due to its ability to integrate distributed energy resources, energy storage systems, and controllable loads. However, to utilize the full potential of microgrids, they need to be controlled and managed optimally. Therefore, this thesis aims to develop optimal control methods to perform the energy management of a grid-connected microgrid.

Model

Following an extensive literature review on microgrid energy management systems, the first phase of this work developed a microgrid simulation platform in MATLAB/Simulink. This platform utilized a variable-step phasor solving method to simulate a grid-connected microgrid comprising a photovoltaic (PV) system, a variable load, a static load, and a battery, including a degradation model.

In the second phase of this work, two energy management strategies were developed to determine the battery charging and discharging power set-points. As a first step, a simple heuristic method was developed to work as a reference for comparison. Further, an optimization-based scheduling algorithm based on the model predictive control (MPC) approach was proposed. The overall problem was formulated using mixed-integer linear programming (MILP), which can effectively be solved using commercially available solvers resulting in significant improvements in solution quality and computational burden. In this work, the power converter efficiency and battery capacity were considered time-varying by updating the values at each sample time and assuming them constant over the prediction horizon. Consequently, the resulting energy management strategy was cast as a multi-objective MILP problem incorporated in an MPC framework to account for disturbances and to capture some of the nonlinear dynamics of the system.

Simulation results and conclusion

Finally, the proposed control approaches were investigated through an extensive case study over a two-month simulation period using actual PV and load data from Skagerak Energilab and electricity price data from Nordpool. For all cases, the MILP-MPC control algorithm succeeded in reducing the daily cost of the energy drawn from the main grid compared to the heuristic algorithm. Furthermore, depending on the chosen settings, the results showed that the MILP-MPC energy management strategy managed to determine the reference values for the battery power in a way that: (1) minimized the purchased energy during peak times; (2) maximized self-consumption of locally produced PV power; (3) made good use of the battery, keeping it within its limits and reducing its degradation. Thus, the result is a flexible algorithm that can be tuned depending on the overall control objective. Moreover, the two-month simulation was performed within an appropriate execution time using a short sample time of five minutes, which enables real-time operation.

The Nordic Transparency Model for Analysis

Student: **Jacobsen, Oscar**
Supervisor: **Uhlen, Kjetil**

Abstract

The Nordic Electrical Power System, as any other power system, is becoming increasingly more complex. Simultaneously, as complex topology and requirements for safe operations is in focus, its modelling methods and validation of analysis results in open research models are static, often overly simplified representation on both the systems operational responses and topology. As the Nordic power system is dynamic, it's topology and operational data is dynamic and always altering the systems representation and behaviour for analysis. Increased focus on data accuracy in dynamic modelling, maintenance and analysis, allows for real dynamic systems to be accurately modelled.

The goal of this work is to discover, access and implement important dynamic transparent data on the Nordic power systems topology and operations into dynamic system modelling for accurate system representation and analysis. Transparency data was discovered through restrictive research focused on the key market participant within the Nordic, accessed though built applications, and implemented into a Python scientific platform, obtaining dynamic data access and active modelling.

High value, maintained transparent data exist for use in both modelling of the Nordic operational behaviours, but also its present and complex topologies. Through platforms found on Transmission System Operators-, ENTSO-E- and country government sites, somewhat hidden transparent data has been discovered and in this work made accessible. Built applications providing dynamic access in Python to the transparent data sources and the large resulting dataset extracts from discovery and work is made open and available at this projects repository. Utilizing the built applications and high value transparent data, first principles high accuracy modelling and analysis of the Nordic Electrical Power System is made possible.

Position-Sensorless Indirect Torque Control of Permanent Magnet Synchronous Machines

Student: **Isak Nordeng Jensen**
Supervisor: **Roy Nilsen**
Contact: **Alexey Matveev**
Collaboration with: **Alva Industries As**

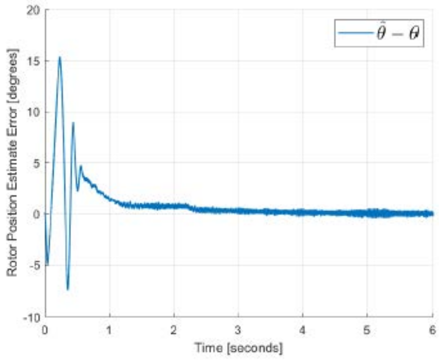
Problem description
Position-sensorless permanent magnet synchronous machine (PMSM) drives are emerging as the state-of-the-art in high-performance safety-critical and weight-sensitive applications due to advantages such as high power and torque density, high efficiency and reliability and reduced hardware complexity, cost and size.

In this thesis, a state-of-the-art system-on-chip (SoC) based embedded controller is used for the development and implementation of C++ software that enables position-sensorless indirect torque control (ITC) of PMSMs.

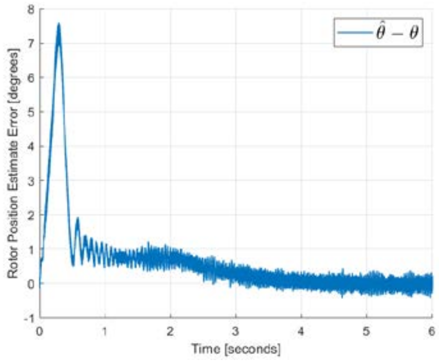
The task
Two fundamental-excitation based methods for sensorless control are developed and programmed on the SoC central processing unit (CPU) and verified using an embedded real-time simulator (ERTS) that is housed by the SoC field-programmable gate array (FPGA). Both methods utilize the active flux concept for rotor position estimation, but the means of which the active flux vector is obtained differs between the two: The first method uses the Niemelä-corrected voltage model, while the second method is based on the voltage-current model.

Model/ measurements
The control software on the SoC processor is intended to drive either a physical PMSM drive in a laboratory setup or the ERTS, and the latter enables the verification of the sensorless control strategies without accessing an actual PMSM drive test bench. This is the approach that is used for software verification in this thesis.

Calculation
The ability of the proposed flux models to estimate the rotor position of the machine using the active flux concept is demonstrated in Figure 1 and Figure 2. Here, the position estimate errors during a scenario that includes start-up and high-speed operation of the sensorless motor drive are plotted. The flux models are seen to enable accurate rotor position estimation.



Figur 1: Rotor position estimate error during start-up and high-speed operation using the Niemelä-corrected voltage model.



Figur 2: Rotor position estimate error during start-up and high-speed operation using the voltage-current model.

Conclusion

The thesis has shown that an inaccurately estimated stator resistance results in a flux estimate that drifts and becomes increasingly inaccurate over time, which makes position-sensorless operation without the implementation of specialized flux models impossible. The proposed flux models both prove to be highly effective for sensorless operation with an erroneous resistance estimate in the medium and high-speed region. Moreover, both models enable crossing of the zero-speed region and persistent operation at very-low speeds below 0.1 per unit. Simulations are initially performed with a speed-dependent, quadratic load function that is valid for the modelling of pumps and fans, but the models are also verified for a scenario where a constant load torque is applied, suggesting that they are applicable for constant-load applications such as cranes and hoists.

An In-Depth Study on Calculation Models for Hydro-Generators: Quantifying the Impact of the Energy Transition

Student: **Yannick Cyiza Karekzi**
Supervisor: Jonas Kristiansen Nøland
Contact: 40511860
Collaboration with the University of Southeast Norway

Problem description

The energy transitions' main impact is the increased prevalence of solar and wind power plants and their influence on exciting electrical grids. In addition to this, there is also a disconnection of fossil power production units. Moreover, the rising demand for fast, reliable, and sufficient power generation, in case of missing solar and wind power generation, creates a need to modernize the current grids. From the hydro generator's point of view, the increased implementation of renewable energy sources creates a bigger variation in loading points, and thus, requires reliable electrical machines with increased operational flexibility. This also creates the need for a hydro generator that can withstand higher thermo-mechanical loads, rapid load ramping, and losses related to variation in production.

The task

This master thesis aims to increase the physical understanding of the phenomena and challenges that occurs when renewable energy sources are connected to the grid. This study focuses on how renewable energy sources affect hydropower plants. The increased incentives for the removal of conventional power plants like coal, gas, and nuclear power in addition to the encouragement of a faster transition to renewable energy sources create entirely new criteria regarding the operation and design of new and existing hydropower plant. The master thesis presents three different operational regimes that are a consequence of the integration of renewables. The thesis also presents two calculation models that quantifies the impact the renewable energy sources has on two existing hydro generators.

Model/ measurements

The methods presented in the report are experimentally validated using measured efficiency and field current at eight different load points from an industry generator in Norway. The load points and key quantities at these load points are presented in a table. The table can be seen in Figure 1. The methods presented in the report was validate qualitatively. This can be seen in Figure 2. The figure shows that the iso-efficiency curves is aligned with its corresponding load point. The saturation modelling is the most sensitive loss component. The calculated field current is therefore quantitatively compared with the measured field current. This is illustrated in a table and can be seen in Figure 3.

Output	#1	#2	#3	#4	#5	#6	#7	#8
S	1.000 pu	0.750 pu	0.500 pu	0.250 pu	1.000 pu	0.750 pu	0.500 pu	0.250 pu
$\cos(\varphi)$	0.900	0.900	0.900	0.900	1.000	1.000	1.000	1.000
P	0.900 pu	0.675 pu	0.450 pu	0.225 pu	1.000 pu	0.750 pu	0.500 pu	0.250 pu
Q	0.436 pu	0.327 pu	0.218 pu	0.109 pu	0.000 pu	0.000 pu	0.000 pu	0.000 pu
I_a	5406.1 A	4054.6 A	2703.0 A	1351.5 A	5406.1 A	4054.6 A	2703.0 A	1351.5 A
I_f	1065.00 A	936.12 A	816.18 A	711.38 A	873.17 A	776.61 A	698.70 A	646.84 A
P_f	173.65 kW	133.66 kW	101.61 kW	77.19 kW	116.29 kW	91.99 kW	74.48 kW	63.81 kW
P_{ex}	15.88 kW	13.02 kW	10.72 kW	8.87 kW	11.65 kW	9.92 kW	8.68 kW	7.92 kW
P_{br}	2.13 kW	1.87 kW	1.63 kW	1.42 kW	1.75 kW	1.55 kW	1.40 kW	1.29 kW
P_a	187.46 kW	105.45 kW	46.86 kW	11.72 kW	187.46 kW	105.45 kW	46.86 kW	11.72 kW
P_s	89.16 kW	50.15 kW	22.30 kW	5.57 kW	89.16 kW	50.15 kW	22.30 kW	5.57 kW
P_c	211.92 kW	211.92 kW	211.92 kW	211.92 kW	211.92 kW	211.92 kW	211.92 kW	211.92 kW
P_{be}	240.90 kW	240.90 kW	240.90 kW	240.90 kW	240.90 kW	240.90 kW	240.90 kW	240.90 kW
P_{wf}	172.92 kW	172.92 kW	172.92 kW	172.92 kW	172.92 kW	172.92 kW	172.92 kW	172.92 kW
P_{loss}	1094.02 kW	921.89 kW	808.85 kW	730.51 kW	1032.05 kW	884.81 kW	779.0 kW	172.92 kW
η	98.834 %	98.680 %	98.250 %	96.944 %	99.008 %	98.868 %	98.509 %	97.294 %

Figure 1:Table of eight load points and key quantities at these load points.

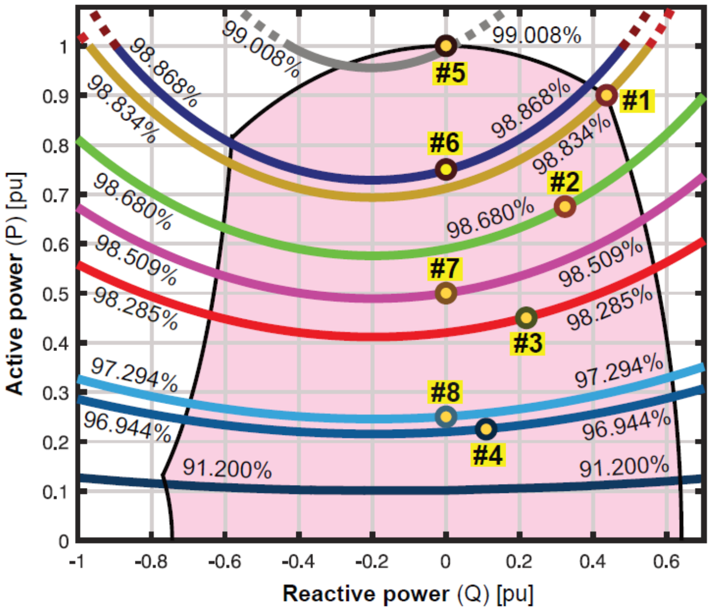


Figure 2: Experimentally validation of the iso-efficiency curves with eight load points

Output	#1	#2	#3	#4	#5	#6	#7	#8
Measured I_f	1065.00 A	936.12 A	816.18 A	711.38 A	873.17 A	776.61 A	698.70 A	646.84 A
Calculated I_{fu}	907.99 A	794.05 A	689.23 A	597.70 A	747.18 A	657.57 A	586.96 A	541.21 A
Calculated I_f	1064.88 A	934.23 A	815.01 A	711.11 A	857.50 A	764.76 A	691.88 A	644.67 A
Deviation I_f	−0.01 %	−0.20 %	−0.14 %	−0.03 %	−1.79 %	−1.52 %	−0.97 %	−0.34 %

Figure 1: Validation of the saturation modelling

Calculation

In the results section, a case study is made, where the efficiency and field current are calculated analytically using the methods presented in this report. The calculated values are compared with the measured efficiency and field current from an actual industry generator. The methods are experimentally validated using the measured efficiency and field current at eight different loading points. The industry generator under study is a Norwegian hydro-generator called Åbjøra (G2). The calculation models accumulated average efficiency (AAE) and weighted average efficiency (WAE) are also compared for different load distributions. This is done to observe how the calculation models perform for different operational regimes. The characteristic behaviour of the calculation models is also studied. This is done to see how the calculation models behave for different active power levels and an increasing number of discrete loading points.

Conclusion

It is shown that the proposed AAE is more effective and adaptable than the alternative WAE for all the different load distributions that were investigated. The AAE is therefore, a possible tool to quantify a generator's overall efficiency accurately in future operating regimes. To legitimize the results, the efficiency and loss map has been validated by eight handpicked load-point measurements. Once the method was validated the AAE and the WAE were compared. The following findings comparing the AAE and the WAE have been identified.

A load distribution dominated by synchronous condenser generation yields a difference as high as 33.18 % while an even distribution deviates by 1.43 % in their respective efficiencies.

A concentrated load distribution found from a full year of measurements on the studied generator revealed a discrepancy of 0.67 %, which could be a significant deviation considering what the operating regime would mean in terms of economic implications.

It is perceived that there are technical and economic implications of the significant reduction in the WAE against the AAE, as it is much more heavily influenced by the weight coefficients and by intervals of lower active power.

Digital tvilling for storskala demonstrasjonsprosjekt vedrørende intelligente distribusjonsnett – med vekt på modellering av automatisk trinnkobler- og batteristyring i svake distribusjonsnett

Student: **Sofia Jøssang Kerchaoui**

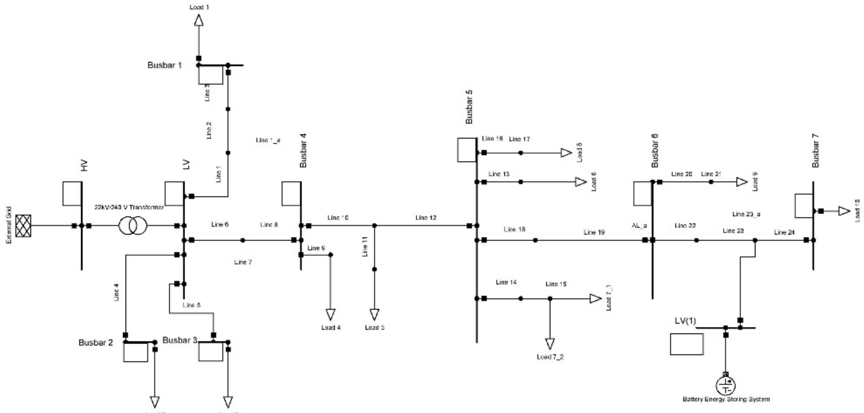
Veileder: **Kjell Sand**

Utføres i samarbeid med: **Elvia**

Problemstilling
Formålet med prosjektet er å undersøke hvordan nettbatterier og spenningsregulering av fordelingstransformatorer, sammen og hver for seg, kan bidra som spenningsstøtte i krevende driftssituasjoner. En reell radial i Elvias nettområde er undersøkt. Det er av interesse å avdekke om det kan være hensiktsmessig å benytte de to teknologiene i samme nettsystem.

Oppgaven
Oppgaven handler om å undersøke hvordan nettbatterier og trinnkoblere kan bidra til å løse spenningsutfordringer i et lavspent distribusjonsnett med stort spenningsfall og lav kortslutningsytelse. For å identifisere nytten av nettbatteri og trinnkobler i det aktuelle nettområdet, er tre ulike caser studert: Det første caset fokuserer på å finne frem til optimale målinger/reguleringsinnstillinger for styring av tilkoblet nettbatteri ved bruk av kvasi-dynamiske lastflytanalyser. I det andre caset blir også optimale målinger/innstillinger for styring av trinnkobleren etablert, samt uttesting av trinnkoblers innvirkning på nettspenningen simulert over ett døgn. I det siste caset er det testet ut en kombinasjon av trinnkobler og nettbatteri i det aktuelle nettområdet.

Modell/målinger
Modellen av nettområdet er bygget i DIgSILENT PowerFactory, og inneholder et nettbatteri og en trinnkobler med automatisk spenningsregulering. Batteriet er lokalisert ved kunden lengst ute på radialen for å kunne bistå som spenningsstøtte.



Beregninger

Resultatene viser at automatisk spenningsregulering med trinnkobler er det beste alternativet for det spesifikke nettområdet, for å oppnå tilfredsstillende spenningskvalitet. Med målepunkt ute på radialen, er laveste spenning i nettet den gjeldende dagen simulert til 0.92 p.u., som tilsvarer 211.6 V. Nettbatteriet bidrar også til god spenningsstøtte i tidsrommet det er behov for det, men som et resultat av batteriets opplading, er laveste spenning i symmetriske simuleringer estimert til 207 V klokken 15:00. Siden høy usymmetri i nettet har blitt identifisert for det gjeldende nettområdet i prosjektoppgaven, er 207 V, som er innenfor FoL, ikke vurdert til å være tilstrekkelig siden det i simuleringen ikke er tatt hensyn til usymmetri. Tilførsel av effekt i nettet fra nettbatteriet er imidlertid vist til å være en bidragsyter for å redusere belastning på linjer i nett som er utsatt for stort spenningsfall og lav kortslutningsytelse. Kombinasjonen av trinnkobler og nettbatteri i samme nettområde, fører til at trinnkobleren utfører færre omkoblinger i løpet av døgnet, samtidig som at batteriet bruker mindre av sin kapasitet. På denne måten er det vist at de to teknologiene kombinert, kan dra nytte av hverandre i form av reduksjon av iverksettingshyppighet for trinnkobleren og begrensning i batteriets bruk av kapasitet.

Konklusjon

Resultatene viser at målepunktet for å bestemme når nettbatteriet skal mate inn, eller trekke effekt fra nettet, bør være lokalisert i nærheten av fordelingstransformatoren.

Tilknytning av nettbatteri sammen med aktiv trinnkobler, medfører at trinnkobleren foretar færre omkoblinger i løpet av dagen. Effektbidraget fra batteriet øker spenningen ved regulatorens målepunkt, og det blir derfor ikke nødvendig å foreta like mange trinnoperasjoner for å holde nettspenningen innenfor dødbåndet. I nett hvor kortslutningsytelsen I_{kmin} blir svært mye mindre utover radialen, bør målepunktet til regulatoren lokaliseres ute i nettet. Dette kommer av at spenningen opptrer som stiv desto nærmere fordelingstransformatoren man kommer. Den automatiske trinnkobleren vil dermed ikke oppleve lav spenning dersom referansepunktet er nær transformator. Dersom nettets ytterste punkt settes som referansepunkt, vil derimot spenningen bli alt for høy ved fordelingstransformatoren. Det blir derfor ansett som nødvendig å sette referansepunktet midt på radialen.

Det er blitt dokumentert at både nettbatterier og trinnkoblere kan være effektive virkemidler for å oppnå tilfredsstillende spenningsnivå hos nettkunder som har behov for spenningsstøtte. Fra resultatene kan det konkluderes med at hurtige trinnkoblere kan være godt egnet i det aktuelle nettsystemet. Når trinnkobler og nettbatteri er installert i samme nettsystem, vil teknologiene dra nytte av hverandre i form av færre trinnoperasjoner og redusert bruk av batterikapasiteten.

Magnetic Modelling of Saturated IPMSMs, for Improved Torque Estimation and Accurate MTPA Control

Student: **Øyvind Sommer Klyve**
Supervisor: **Robert Nilssen, Roy Nilsen, Aravinda Perera**
Contact: **Robert Nilssen**

Problem description

Based on the competence built in COMSOL Multiphysics, the student will study an Interior Permanent Magnet Synchronous Machine (IPMSM) in COMSOL. The machine model in COMSOL will be used to categorize motor parameters used to define linear differential equations describing the IPMSM in the electrical drive. In addition, saturation and cross-coupling phenomena in the IPMSM will be studied with the goal of developing non-linear differential equations in the electrical drive software corresponding to these phenomena.

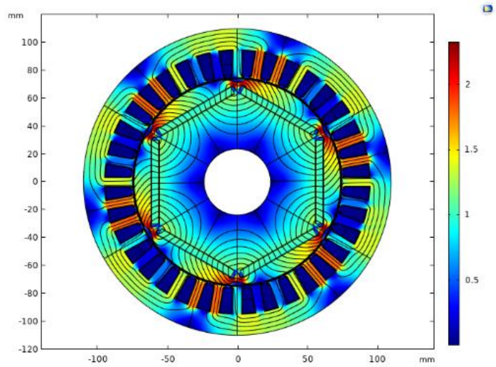


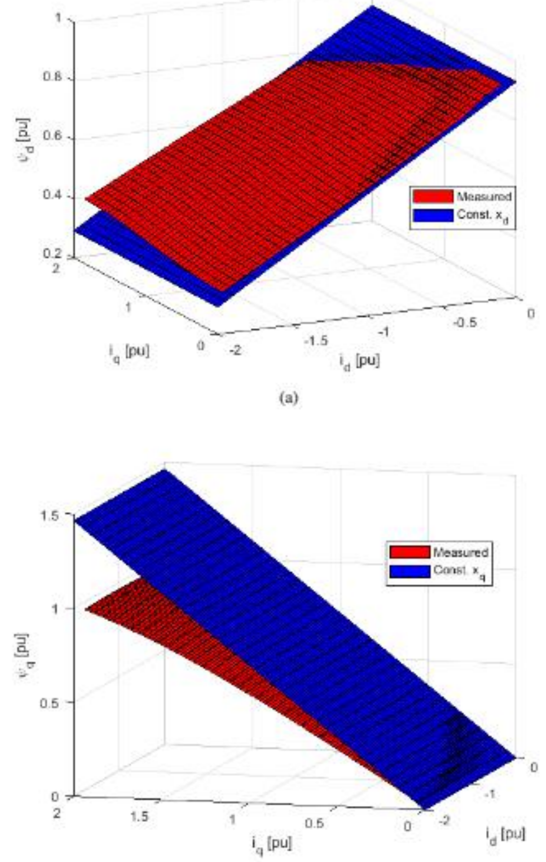
Fig. 1: Magnetic flux density in the FE model of the IPMSM at full load and pure q-axis current.

Abstract

A challenge when aiming for optimal control of interior permanent magnet synchronous motors, is to develop accurate models describing the relation between the applied currents and the resulting flux linkages in the machine, meaning the machine's magnetic model. It is commonly assumed a linear relation between the currents and flux linkages, but there are magnetic saturation and cross-coupling phenomena present, making the motor magnetics non-linear. In this thesis, in order to model the non-linear magnetic phenomena, several formulas differing in complexity and form are proposed and compared. The formulas are developed by coefficients curve fitted to measured data from a FE model of a commercial motor developed in this thesis. At full load and when operating with maximum torque per ampere, the deviations from the FE measured q-axis flux linkage to the modelled one was 17.85%, when assuming linear magnetics. However, the deviation between the measured and modelled q-axis flux linkage was only 0.88% for the same operating point, when curve fitting one of the polynomial formulas to a wide range of FE measured operating points. When curve fitting the same polynomial formula to only 9 FE measurement points, the deviation only increased to 3.00% for the same operating point, proving the possibility of rapid development of accurate magnetic models for new undescribed motors during start-up.

Using one of the developed polynomial magnetic models when calculating the current references to achieve maximum torque per ampere, the torque obtained at full load only increased by 0.04% compared to when using the linear magnetics model. However, for higher stator currents, the relative increase in torque got larger compared to the linear model. In addition, the deviation from the analytically calculated torque to the FE measured torque was assessed. At full load the deviation was 6.35% when assuming linear magnetics, but reduced to 2.89% when using a polynomial magnetic model. Finally, it was argued that the accuracy of the analytical torque equation could be improved by being extended to take into account the spatial harmonics of the magnetic flux density in the air gap.

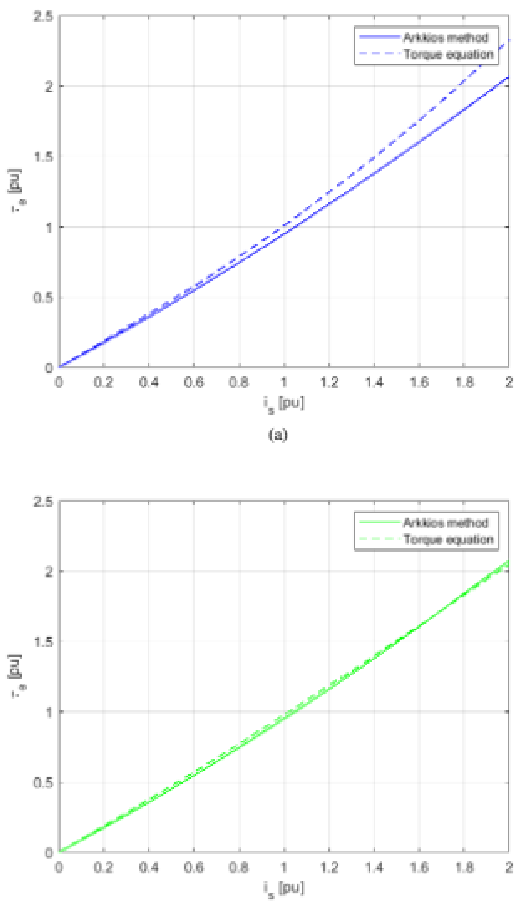
The magnetic models presented and the related torque evaluations were to be verified at the lab during this thesis. However, the commissioning of the IPMSM is still ongoing by the research group, such that the conclusions made from this thesis would have to be verified experimentally at a later stage.



(a)

(b)

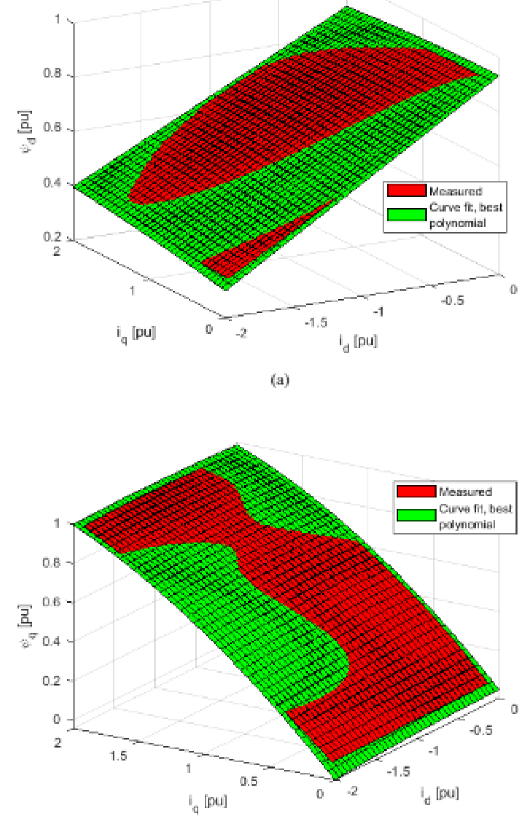
Fig. 15: The measured (a) ψ_d and (b) ψ_q by COMSOL, plotted with the calculated ψ_d and ψ_q when using the linear model, meaning assuming constant x_d, x_q.



(a)

(b)

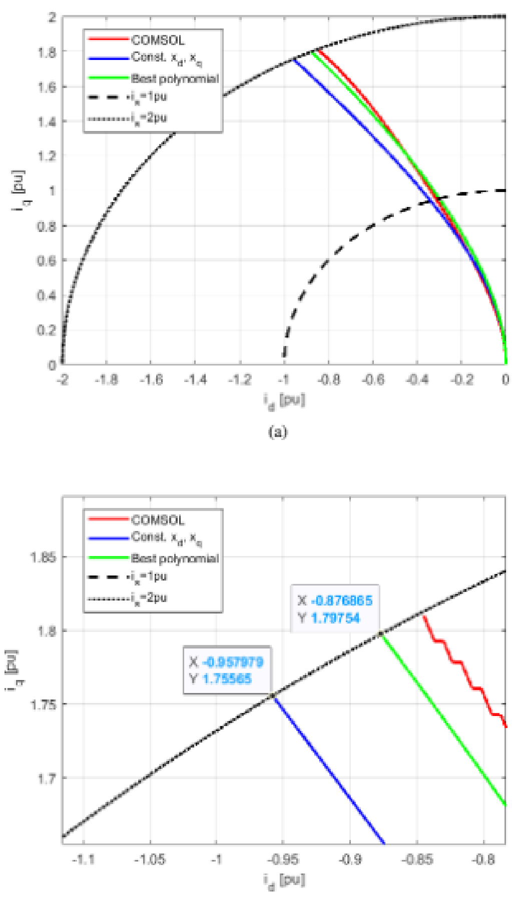
Fig. 36: Torque achieved by Arkkio's method in COMSOL compared to the torque calculated by the analytical torque equation, when using (a) the linear model and (b) the best polynomial model. The same current references were used in COMSOL and the analytical torque equations.



(a)

(b)

Fig. 19: The measured (a) ψ_d and (b) ψ_q in COMSOL, plotted with the calculated ψ_d and ψ_q when using the best polynomial model with coefficients curve fitted for 26244 measurement points in $i_d \in [-2, 0]$ and $i_q \in [0, 2]$.



(a)

(b)

Fig. 25: (a) The proposed MTPA trajectories either found numerically by COMSOL or analytically by calculating the flux linkages by either constant x_d, x_q or by the best polynomial formula. (b) The proposed operating points to obtain MTPA at a stator current of 2pu, by either calculating the flux linkages by constant x_d, x_q or by the best polynomial formula.

Dynamic current rating of Power Transformers

The effect of maximum temperature and thermal ageing

Student: **Trond Ivar Kopperud**
Supervisor: **Erling Ildstad**

Abstract

Due to expected increase in power demand and use of renewable energy sources in the future, there is a pressure to investigate methods to increase the efficiency of existing grid infrastructure. Smart grid concepts such as dynamic thermal ratings represent an opportunity to utilize the true capacity of the transmission network. Traditional static ratings are based on the worst weather conditions of power equipment. Dynamic ratings use measured load and environmental parameters to determine the actual loading capability in real-time.

In this thesis, dynamic current rating of power transformers is investigated. The critical parameters to assess the dynamic rating is the winding hot-spot temperature, and the paper insulation loss-of-life. A simulation methodology is developed in Matlab Simulink to conduct dynamic thermal rating calculations. The methodology simulates expected transient temperatures and thermal ageing in the transformer. A 300 MVA power transformer is examined in various case studies with different overload currents and ambient weather conditions.

Results show that the examined transformer can be overloaded continuously with up to110% increased current, depending on the ambient temperature. The transformer can be operated safely under 140°C. Higher temperatures can lead to gas bubble formation in the transformer oil. Overloading with 50% and more increased current exceeds recommendations for current loading of large power transformers by present day industrial standards. As dynamic rating systems of transformers become more prevalent in the future, it is pro-posed that the current loading recommendations should be revised.

Thermal ageing studies suggest overloading with 50% increased current at 0°C ambient temperature and above reduces the life expectancy of the transformer. Therefore, a time limit must be introduced if the transformer capacity is to be preserved. Optimizing the paper insulation life is the main challenge in implementing dynamic transformer ratings. There is great potential for increasing capacity usage of transformers in cold weather regions like Norway.

Dual Active Bridge Converter

Student: **Dalina Krasniqi**
Supervisor: **Dimosthenis Peftitsis**
Co-supervisor: **Gard Lyng Rødal, Yoganandam Vivekanandham Pushpalatha**
Collaboration with: **Norske Tog**

Problem description

The increasing demand in renewable energy sources has led to the need of optimizing these energy production systems where power electronics plays a major role. Renewable energy sources are known for their unstable energy production due to their dependency on natural factors. Different conditions in various time periods result in variation of the output voltage of these systems, due to the dependency these energy production systems have with nature, which as a result requires regulation. This regulation is provided by DC-DC Converters where converters that will allow for bidirectional power flow are necessary to allow for the power to flow in two directions. This bidirectional power flow capability is mainly necessary since renewable energy sources require energy storage system due to their variation in energy production throughout the day. The most prominent topology among the IBDC Converter is the Dual Active Bridge converter which due to the increasing demand in renewable energy production, is also required to be further developed and optimized.

The task

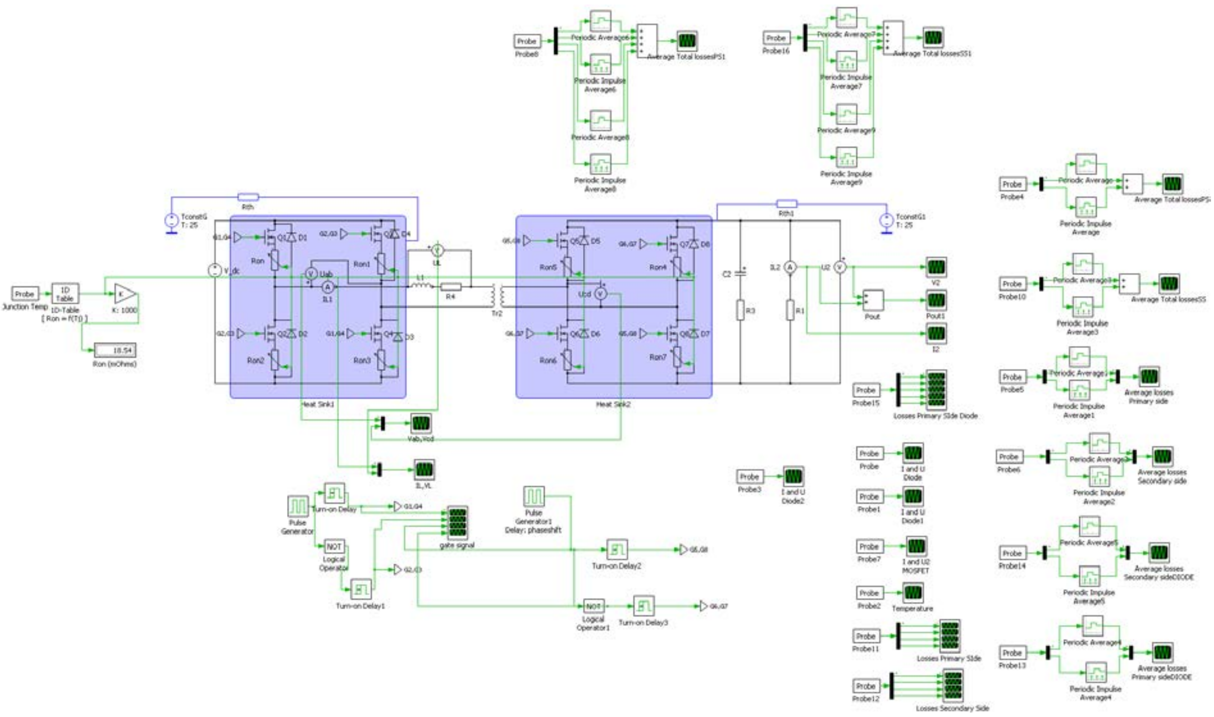
One of the properties of the Dual Active Bridge Converter that directly affects the operation of this converter are the losses that this converter generates. Therefore, this thesis estimates these losses, the conduction and switching losses, and observes these losses in terms of the phase shift value variation where the SPS Modulation scheme is applied in this DAB mode. The estimation of these losses is conducted both analytical and simulation based where the DAB converter model is built in the PLECS window. The results of these two approaches are compared and different observations are made in the two approaches.
The ZVS capability of the converter directly affects the switching losses of the converter and therefore this property of the DAB Converter is further studied in terms of its realization. The ZVS boundary is generated and analysed in terms of realizing ZVS for varying phase shift angle.

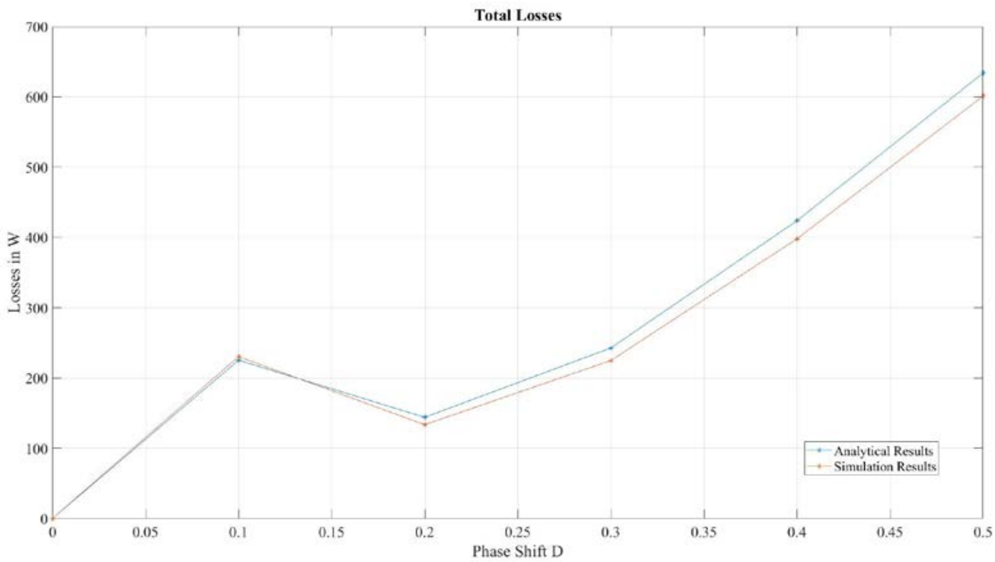
Model/ measurements

The DAB Model used in this thesis is built in PLECS window where each component is assigned the designed parameter. The focus of this thesis is on the losses generated by the switching devices therefore, the datasheet of the MOSFETs and diodes chosen is implemented in this model by the Thermal Library that will allow for more accurate estimation of the Losses.

Results and Finding

The results of the two approaches where visualised by MATLAB plots and a difference between results generated by these two methods is observed where the losses obtained from the simulation approach are the lowest. This difference is observed to be mainly due to assumptions made in the analytical approach and the method PLECS estimates losses by. The switching losses were observed to be particularly low for D=0.19 which corresponded to the ZVS Boundary operation. The secondary Bridge was able to realize ZVS during turn on and ZCS during turn off of the switches. This phase shift value and other were later observed and analysed in terms of ZVS operation of the Switches alongside with the conditions that will provide this. It was observed that for a low phase shift region ZVS was not achieved for the DAB converter operating in buck mode, whereas for conventional ration k=1 ZVS was obtained independent of any other factor.





Conclusion

The total losses generated by the DAB converter model used in this thesis, from both approaches, were proven to be low compared to the total transferred power highlighting so the low losses property of the DAB converter. The approaches were proven to be accurate to a certain extent where the simulation-based approach allowed for better results and for more space for observations. The ZVS capability of the converter directly affected the switching losses and therefore the DAB model should be designed to operate at the required conditions to provide ZVS of the switches which would allow for lower losses and as a result more optimal operation of the converter.

Assessing local flexibility services in a Zero Emission Neighbourhood with focus on space heat demand and battery storage

Student: **Malin Valbø Kaaløy**
Supervisor: **Karen Byskov Lindberg**

Problem description

Utilising energy flexibility in buildings can enable qualities such as reduced energy consumption, reduced peak loads, increased self-consumption, or provide flexibility services to the distribution grid. This thesis investigates the energy flexibility potential of a neighbourhood consisting of a school, a nursing home and a kindergarten. The neighbourhood, Oksenøya, is currently being built at Fornebu and is owned by the municipality of Bærum. Oksenøya is part of an energy system consisting of a district heating grid and an electricity grid.

The task

The aim of the thesis is to obtain an operating strategy that reduces the energy costs for the neighbourhood by minimising the peak load on both energy grids. The thesis also studies how the neighbourhood can be utilised to provide flexibility services to the distribution grid.

Model/ measurements

Oksenøya is a ZEN pilot project. Therefore, it is studied both as three individual buildings and as a group of buildings to evaluate any advantages of operating with individual or common energy metering. The two energy systems have been investigated separately, enabling flexibility by using space heating flexibility for district heating and a stationary battery for electricity. The method used is "what-if" analyzes of a rule-based modeling approach. To establish the baseline, energy simulations are performed in the Building Performance Simulation (BPS) tool IDA ICE. The space heating flexibility schedules are then found by trial and error in IDA ICE, while the battery flexibility is modeled in Excel.

Calculation

The study uses a conventional control strategy and manages to reduce energy costs by implementing energy flexibility measures. The recommended operational strategy from the results obtained is common energy metering, for both electricity and district heating, and control of flexible loads with the objective of reducing the total peak load. This results in a peak load reduction of 44.7% and 33.0% for district heating and electricity respectively, giving a total cost reduction of 16.1%. The study is limited to scenario modeling, which means that the real cost saving potential might be higher.
Furthermore, the study found that it is possible to shift a neighbourhoods peak load to the off-peak hours of the distribution grid. Oksenøya is a relatively small neighbourhood, and is therefore not sufficient to remove Fornebu's peak load. However, if flexibility measures are aggregated to a district level, it can have an actual impact on the distribution peak load.

Conclusion

The results of this work have demonstrated that energy flexibility measures can be implemented with a rule-based control strategy that reduces energy costs and can help avoid grid expansion.

Synthetic Inertia Provision from Variable Speed Turbines and HVDC in the Nordic Power System

Student: **Georg Lande**
Supervisor: **Kjetil Uhlen**

Problem description

With a growing demand for low emission energy sources, renewable power sources are likely to make up a larger share of the total power supply in the future power system.
The increasing amount of renewable power introduces new challenges for the transmission system operators. By connecting power sources like wind and solar to the grid using converters, they do not contribute to the inertia of the system, as they are decoupled from the electric frequency of the grid. At the same time the amount of high-voltage direct current (HVDC) links connecting the Nordic power system to other grids is increasing. When importing power, this also contributes to a lower system inertia. By operating turbines at variable speed, the power output can be controlled faster, and they are able to provide synthetic inertia by responding to the rate of change of frequency with a change in power output.

The task

In this thesis the influence on power system stability when operating turbines at variable speed and providing synthetic inertia is studied. The ability of variable speed wind turbines (VSWT), variable speed hydro power (VSHP) and HVDC to provide synthetic inertia is also compared and analysed.

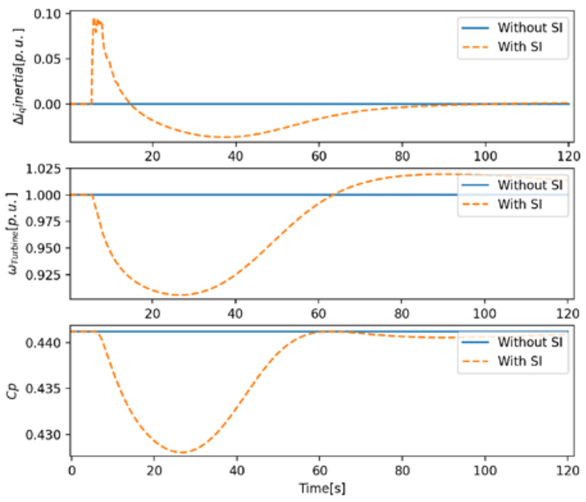
Model/ measurements

The system used in the study is the Nordic 44 test system, which is an aggregated model of the Nordic power system. In order to study the effects of the different power sources providing synthetic inertia, existing power plants and HVDC links in the Nordic power system are modelled to emulate inertia, following the outage of a HVDC link importing power to the system. The variable speed hydro plant is Kvilldal power plant in southern Norway, the wind farm is Fosen Vind located in central Norway, and the HVDC link is the North Sea Link in southern Norway. All simulations are performed in a dynamic power system simulation tool in Python, and models of the variable speed turbines and synthetic inertia controller are built using the differential equations describing them.

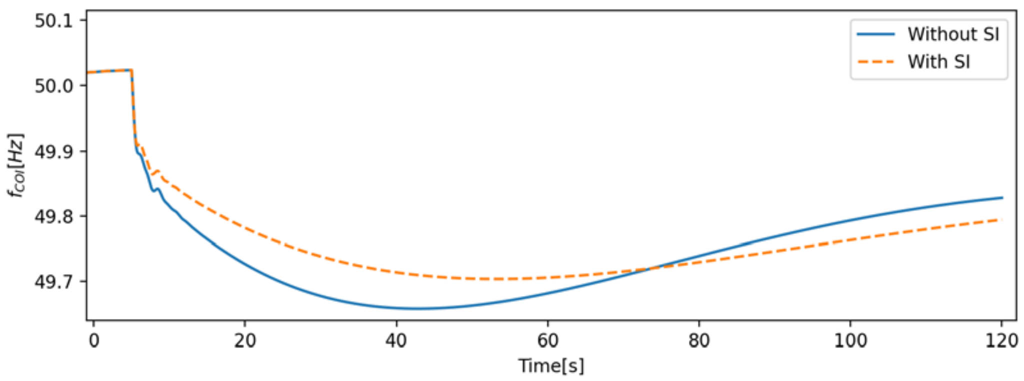
Calculation

The synthetic inertia provision from the different power sources is studied in three different scenarios; high system load, low system load, and finally low system load with a decreased system inertia to simulate a predicted future scenario.

An example of the simulation results is presented below:



Figur 1: Turbinrespons for vindturbin ved syntetisk svingmassebidrag



Figur 2: Systemfrekvens med og uten syntetisk svingmasse fra vannturbin

Conclusion

By operating the turbines at variable speed, they are able to provide synthetic inertia. The wind turbine is however not as suited as the hydro turbine, as the wind turbines do not have governors to increase the mechanical power input, and the risk of stalling the wind turbines limits the synthetic inertia contribution.

Compared to the turbines, the VSC based HVDC is very well suited to provide synthetic inertia, as the required converters are already in place. By providing synthetic inertia, the nadir of the system frequency is improved.

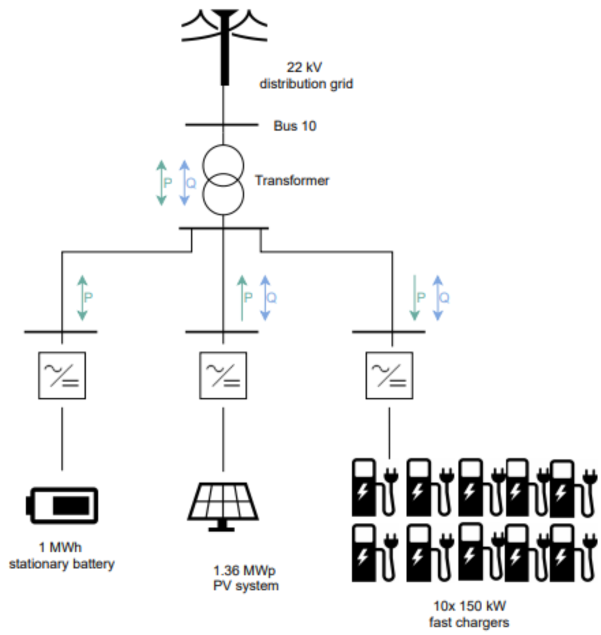
Voltage Support with Reactive Power from Fast Charging Stations with Local Energy Storage and Production

Student: **Ida Langseth**
Supervisor: **Jayaprakash Rajasekharan**
Contact: **Bendik Nybakk Torsæter**
Collaboration with: **SINTEF Energi AS**

Problem description
Norway is a world leader in electric mobility, and the Norwegian government has stated that all new passenger cars, light vans, and city buses should be zero-emission vehicles by 2025. Even though low power home charging is the most prevalent charging option today, the rapid increase in electric vehicles will also increase the need for fast charging stations that can compete with conventional fuelling stops. The associated high power of fast charging loads can lead to voltage issues, which is undesirable for the distribution grid operators.

The task
In this master's thesis, a methodology for voltage support from a fast charging station has been developed. Three control strategies namely, a rule-based, optimization-based, and a Model Predictive Control (MPC) based battery control have been developed, together with a reactive power control based on voltage sensitivity calculations. The purpose is to mitigate the voltage issues caused by high power charging, and simultaneously minimize energy costs for the charging station operator.

Model/ measurements
To verify the proposed approach, simulations were carried out on a system consisting of a fast charging station equipped with 10 charging outlets of 150 kW rating each, a 1 MWh stationary battery, and a 1.38 MWp PV system. The control strategies are evaluated in a comparative analysis, and a sensitivity analysis is conducted. The system:



Calculations
The results demonstrate the benefits of a control strategy for reactive power and local storage- and production. The battery successfully minimizes energy costs for the charging station operator when an optimization-based control is used. Simultaneously, the voltage is corrected by reactive power injection. In a low production scenario, the rule-based control strategy does not utilize the full potential of the battery. With an optimization or MPC-based control, the battery recharges when the prices are low, which leads to new voltage drops. However, combined with reactive power, the voltage drop is mitigated. The reactive power is therefore the main contributor to the improved voltage profile. In a high production scenario, the results verify that the system can sustain an acceptable voltage profile. The battery and PV production are the main contributors to keeping the voltage close to the limit, and the main is that the optimal battery control can reduce costs to a larger extent than the rule-based control.

The sensitivity analysis demonstrates that an upper limit on the grid imported power or on the charging power, are possible solutions to the new voltage drops due to battery recharging. If the proposed battery controllers were to be implemented in practice, they should either account for grid tariffs or have an upper limit on charging power or grid imported power. It is also found that the proposed control system gives better voltage mitigation results with a 45\% higher load, compared to the voltage without battery and PV and original load. The developed control strategy, therefore, allows higher charging powers for the charging station operators without causing significant grid impact. The results also illustrate that the utilization of reactive power can provide adequate voltage support even when the battery has a sub-optimal performance due to prediction errors for load and production and could therefore allow less computationally expensive prediction algorithms.

Conclusion
The optimal battery control strategy for the FCS operator is an optimization-based control. However, if the proposed battery controllers were to be implemented in practice, they should either account for grid tariffs or have an upper limit on charging power or grid imported power. A good strategy for voltage support with reactive power is by utilizing both the FCS converter and PV inverter, but there is a need for some secondary voltage support when the reactive power capacity is not sufficient. It is concluded that the voltage at the critical bus can be improved considerably by using reactive power. By combining this with a stationary battery and local production, it can also increase benefit for the charging operator.

Optimal Resource Allocation andPricing for Distributed Demand-Side Flexibility Services

Student: **Stine Larsen og Amanda Njøten**
Supervisor: **Jayaprakash Rajasekharan**

Abstract

The increasing share of renewable energy will significantly challenge the stability and reliability of power systems as balancing generation and consumption becomes more difficult. As a result, there is a growing interest in exploiting the demand-side flexibility to mitigate imbalances in the grid, and in particular, the use of residential flexibility services procured through an aggregator. Since participating in a flexibility program can cause inconvenience for the end-users, the aggregator needs to provide financial incentives to encourage them to participate. It is therefore necessary to establish an allocation algorithm that ensures preferences and technical constraints, as well as a pricing mechanism that is considered fair to both the aggregator and end-users for residential flexibility to be realized. This thesis investigates the allocation feasibility and economic viability of residential flexibility from the perspective of an aggregator, assuming that the buyer of flexibility is a Balance Responsible Party (BRP).

A method is proposed for the optimal allocation of residential flexibility sources from a portfolio of batteries, curtailable, regulatable, and shiftable loads in response to a flexibility request, which takes into account user preferences and technical constraints. Then, a novel pricing mechanism with three different pricing strategies is developed to find a price range within defined bounds that ensures a profit for both the aggregator and the end-users. The strategies are used to test and analyze the profitability for an aggregator and end-users. Strategy 1 assumes uniform prices bounded by existing power market prices in each quarter of the day. The same is assumed for Strategy 2, but with individual prices for each source. Strategy 3 assumes uniform prices for all sources bounded by heuristically determined fixed bounds of 0 NOK/kWh and 100 NOK/kWh in each quarter of the day.

An optimal schedule is determined for each day of the week, and the results show that shiftable sources and batteries provide the most flexibility but benefit the least. This suggests that it is fairer to differentiate flexibility prices for each source type. A feasible price range is found to exist only for three days of the simulated week with Strategies 1 and 2 but found to exist for all seven days with Strategy 3. The results show that the aggregator’s profit increases when individual prices are allowed compared to uniform prices, and it increases further when prices are constrained by fixed values independent of existing power market prices. In conclusion, this thesis shows that bounding the flexibility prices based on the existing power market prices is profitable for both the aggregator and end-users. However, future research on the pricing of residential flexibility services should incorporate measures of fairness and explore how prices can be set based on additional parameters, taking into account social and behavioural aspects.

Investigating thermal management solutions in a modular high voltage machine for offshore wind applications

Student: **Kristian Husmo Lyngved**
Supervisor: **Pål Keim Olsen**

Problem description
For all high voltage machines with high power density, cooling becomes important for a fully functional machine with high efficiency. In addition, the insulation around the stator in the ModHVDC machine contributes to a large thermal barrier. A question that has arisen is therefore whether the concept is possible to realize or not, due to thermal management of the machine.

The task
The task for this thesis is therefore to make a thermal model of the ModHVDC machine, that can be used to investigate different cooling solutions. In doing so, answering the question" Is the ModHVDC concept possible to realize, with regard to thermal management?". Further, come up with a recommendation for development of a complete thermal management system for the ModHVDC machine.

Model/ measurements
In this Master's thesis, simulation have been the main approach for solving the thermal models made. Two types of thermal models are made in this thesis. One analytical thermal equivalent circuit model and one numerical FEM model. The analytically made thermal equivalent circuit, is made using MATLAB and Simulink. Where the complete circuit is simulated using Simulink. The numerical FEM model is made in the software COMSOL Multiphysics. The models only include a section of the ModHVDC machine.

Calculation
The most efficient cooling solution, was a combination of forced air through air gap and forced air through a concentric duct between the stator surface and the frame. Resulting in a maximum temperature of 125°C in the windings. Figure 4.6.2 illustrates the temperatures for the modelled section of the ModHVDC machine with this cooling solution implemented.

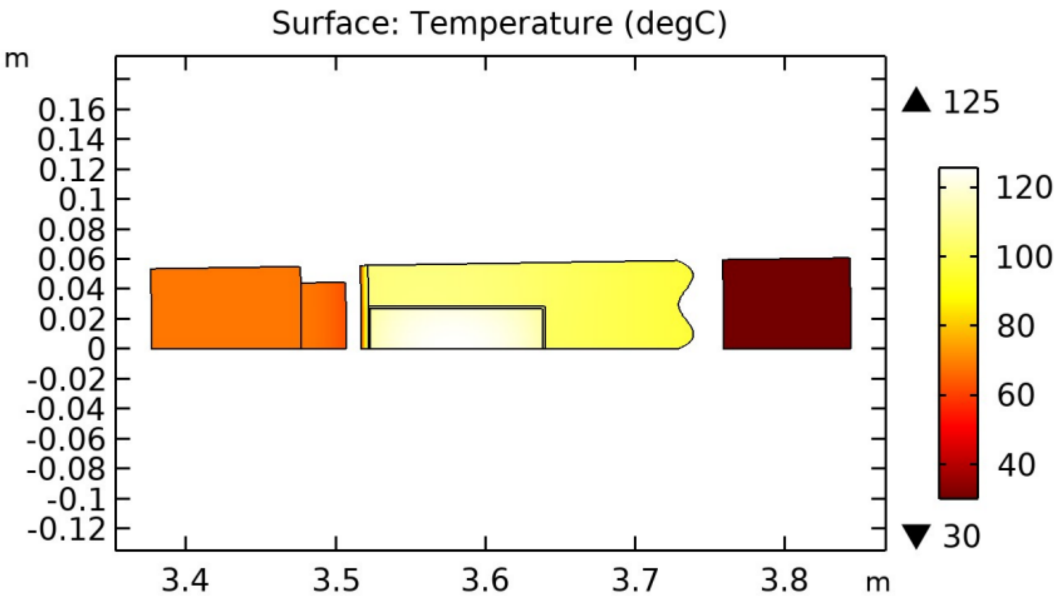


Figure 4.6.2: *Temperature distribution for the combined cooling method of air cooled air gap and concentric duct on a waved stator surface.*

Conclusion
The main goal for this Master's thesis, has been to investigate different cooling solutions for the ModHVDC machine by making a thermal model of the machine. In doing so, answering the question ”Is the ModHVDC concept possible to realize, with regard to thermal management?”. This question has been answered by making two base thermal models. One analytical thermal equivalent circuit and one numerical FEM model. Then, different cooling solutions have been implemented and tested one at a time.

From the results, it was found that no single cooling method investigated yielded sufficient thermal management to the ModHVDC machine. However, by combining two cooling methods into a combined cooling solution, several different cooling solutions yielded acceptable temperatures. Acceptable temperatures meaning below the maximum temperature of 80◦C in the magnet and 150◦C in the windings. The cooling solutions have been implemented with conservative convection coefficients and have not yet been optimized, yielding conservative results. Because of this, the results show that the ModHVDC concept is indeed possible to realize, with regards to the thermal management aspect.

By comparing the analytical thermal equivalent circuit and the numerical FEM model, it was seen great coherence throughout the thesis. For the base model and for all the cooling solutions implemented, a maximum difference between the two methods of only 2.58◦C was found. Verifying that the methods used are appropriate.

Seamless Operation Mode Change of the Inverter-based Microgrid with Robust Synchronization Loop

Student: **Rafael Marentes Ortiz**
Supervisor: **Mohammad Amin, NTNU**

Problem description

Micrograms can operate connected to the grid or independent from it, known as islanded mode. The ability of the microgrid to work independently represents a huge advantage, but also a challenge. When the microgrid operates islanded, despite its voltage and frequency controls, the electric parameters drift away from the main grid ones, resulting in unwanted transitory currents that destabilize the system if reconnected. Therefore, a process must be carried out to effectively achieve the reconnection to the grid.

There have been several proposals to address the obstacles encountered when microgrids change operation modes. They vary widely from attenuation methods that reduce overcurrents and oscillations, to resynchronization techniques that ensure a match of the electric parameters at the point of common coupling (PCC), these parameters are frequency, phase, and voltage magnitude. The process by which this is achieved is known as synchronization.

The task

In this thesis a method to seamlessly change the mode of operation of microgrids connected to the grid is presented. A detailed analysis of a control block known as Robust Synchronization Loop (RSL) is presented as an alternative to traditional Phased-Locked Loop (PLL) devices, and as the key enabler of the reconnection procedure proposed.

Model/ measurements

A microgrid model was developed in Matlab/Simulink with solar energy as a source, battery storage and an inverter interface to the grid with an LCL filter to ensure compliance with harmonic distortion requirements. A local load was considered to test its operation during islanded mode.

The inverter was controlled with the vector control method with two control loops, inner for the current and outer for the power or voltage. A stateflow chart controls the operation mode of the inverter and an islanding protection is added.

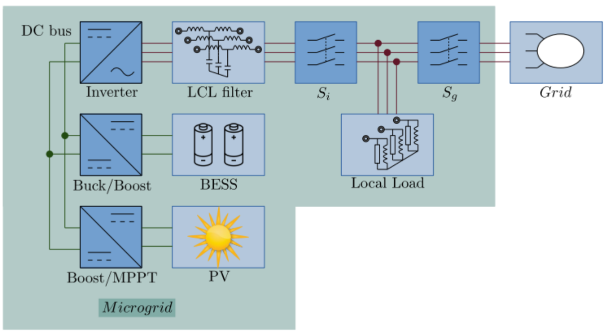


Figure 1: Microgrid Model

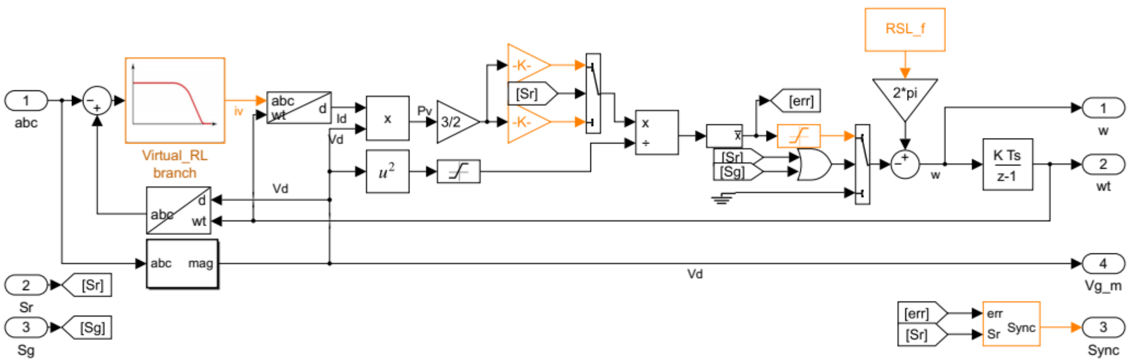


Figure 2: Robust-Synchronization-Loop Model

Calculation

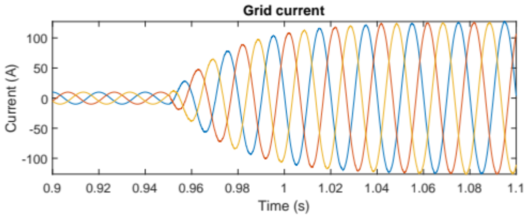


Figure 3: Turn-on to grid-connected

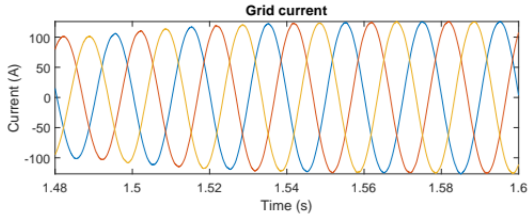


Figure 4: Operation mode change

The control proposed can start the operation of the inverter to both islanded and grid-connected modes and transition from controlling voltage components to controlling active and reactive power seamlessly.

In the thesis some grid error conditions are also considered and it is observed that the control is able to correctly address unintentional islanding scenarios.

Conclusion

The desired objective of reconnecting a microgrid to the grid seamlessly was achieved with satisfactory results; small renewable power plants can benefit from being part of a microgrid when they are located near the shore. The two processes needed for it, i.e. the synchronization, and the reconnection, both happen without noticeable effect on the grid, other than a controlled frequency variation and a possible small step change in the voltage reference.

The synchronization period is relatively short limiting the frequency variation to 2 hertz above or below the nominal value. It is in the same order as the resynchronization time of the Universal Droop Control with the virtual-current-based synchronization block. It could be said that the use of the RSL leads to the equivalent in the vector control of the virtual current resynchronization used in the droop control.

Analysis of Losses and Radial Vibration in a PM Synchronous Machine with Physical Modularity

Student: **Runar Mellerud**
Supervisor: **Pål Keim Olsen**

Problem description

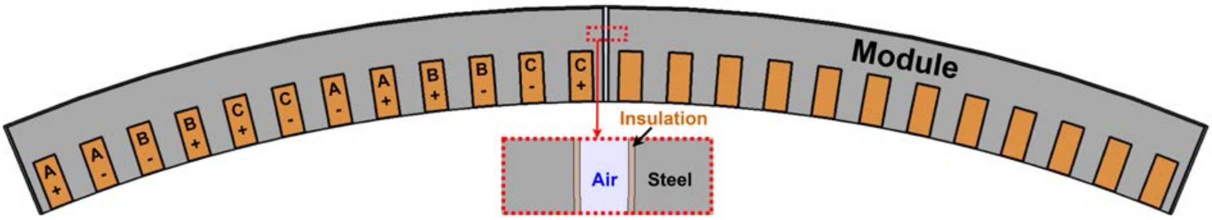
The ModHVDC generator is very lucrative for offshore wind power as it reduces the need of several grid components while also improving availability. This solution uses physical modularity, where air gaps divide the stator into separate modules. This could present challenges concerning altered magnetic performance and loss of rigidity in the structure.

The task

The goal of this thesis was to identify losses and radial vibration in a previously designed ModHVDC machine and compare it to its non-modular equivalent. Magnet segmentation was also applied to reduce magnet losses. Radial vibration was divided into an investigation of force harmonics and mechanical properties, as it stems from their interaction.

Model/ measurements

All results were found through finite element modelling in COMSOL Multiphysics 5.6. There, a direct driven permanent magnet synchronous machine with 192 slots, 160 magnets and 16 stator modules was modelled. An illustration of the implementation of modularity and phase layout is given below.



The modelling was divided into three separate analyses concerning: losses, harmonics and mechanical eigenfrequencies of modules. For the losses and harmonics, the rotating magnetic machinery physics were used, while the solid mechanics physics were used to find the module eigenfrequencies and their shapes.

Results

Losses at full load are summarized in the table below.

Loss type	Modular [W]	Non-modular [W]	Difference [%]
P_{Steel}	24 976	20 464	22.0
P_{magnet}	10 040	10 081	-0.4
P_{copper}	224 740	224 740	0
Total	**259 756**	**255 285**	**1.8**

The average force density in the air gap was 177 kN/m^2 at full load, while the lowest force subharmonic was the 32nd, which had an amplitude of 87.6 kN/m^2 at full load. This had a temporal frequency of 26.67 Hz, which was far from the lowest module eigenfrequency of 322 Hz.

Conclusion

At full load, total losses in the modular machine were estimated to 259.8 kW, which comprises 3% of the mechanical power. Radial vibration was considered unlikely, and modularity was found to mainly influence steel losses and mechanical properties.

Detection and Protection strategy for a modular HVDC generator

Student: **Thomas Mickelborg**
Supervisor: **Pål Keim Olsen**
Co-Supervisor: **Bruce Mork**

Problem description

This thesis considers a new concept based on a modular HVDC (ModHVDC) generator that proposes a transformer-less concept with one single conversion step to achieve 100~kV HVDC on the output. This technology aim to be a solution to one of the main innovation gaps in regards to offshore wind power, which is to drive down costs and lower risk related to transmission and distribution of electricity.

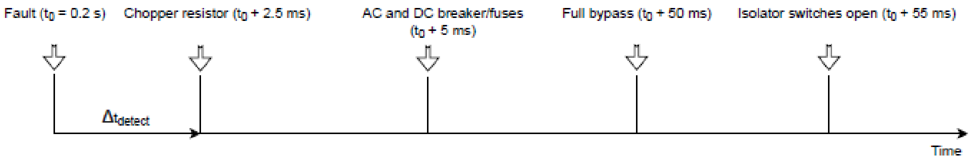
This thesis specifically aim to fill some of the knowledge gaps within the field of faults and protection regarding this new concept. The segmented machine introduces some new failure modes that needs to be investigated before a commercial product can be achieved. There is little to no known literature on this topic and thus three predefined research objectives was chosen as a starting point. A simulation model is made in the Simulink environment that models the modHVDC generator with multiple stator segments and corresponding converter modules. Based on the model and circuit analysis, a fault analysis of module-to-module and module-to-ground faults are conducted to investigate the severity of these faults. An overview of the different faults that can occur for this machine and an initial protection strategy is presented. As a part of the protection strategy a bypass solution is proposed for isolating faulty modules and achieve redundant operation.

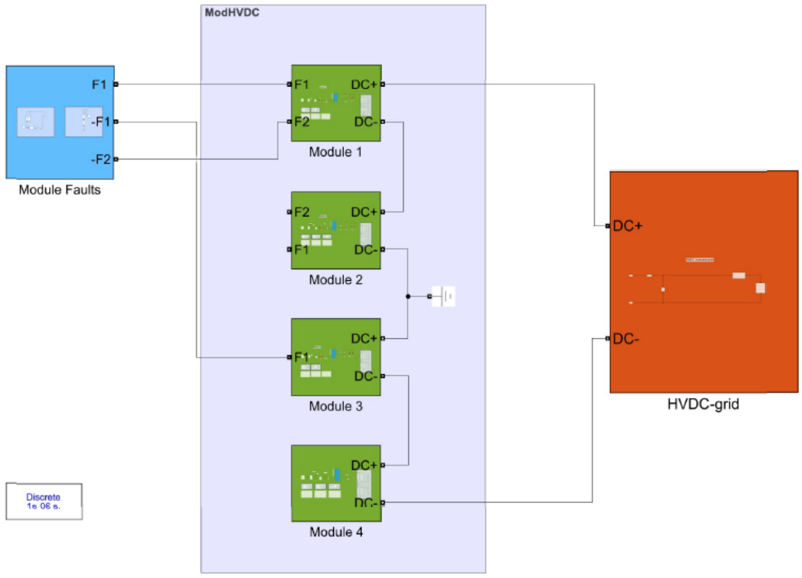
The task

- Develop a simulation model in Simulink environment that models the modHVDC generator with multiple stator segments and power electronic modules.
- Conduct fault analysis for module-to-module faults and module-to-ground faults to investigate the severity of the corresponding fault currents and voltages that will occur.
- Identify possible faults and propose protection strategy for the modHVDC concept in regards to these, which should inhabit detection, mitigation and handling.

Model/ measurements

A Simulink model based on a system with four individual stator segments was created and used as a basis for the fault analysis. Two failure modes were investigated, namely module-to-module and module-to-ground faults, in regards to fault handling and specifically investigate the feasibility of a proposed bypass solution in order to achieve redundant operation. One of the proposed protection sequences and the Simulink model are illustrated below.





Conclusion
The first objective was to develop a simulation model in the Simulink environment which describes the modHVDC machine with multiple stator segments and corresponding converter modules. Although there is little basis of comparison, the model has been discussed with several professors and considering the stated limitations used, the model is regarded as sufficient for these initial investigations.

The second research objective was to conduct fault analysis for module-to-module and module-to-ground faults. The implications of these fault situations have been highlighted regarding corresponding over currents and voltages. The results suggests that the natural fault impedance seen by these faults are low, leading to high over currents with high di/dt that can cause severe damage to the generator. Also, the module-to-ground fault is found to be the most severe of the two, depending on fault location.

The third and last research objective was to identify possible faults and propose a protection strategy for the modHVDC concept. A preliminary proposal consisting of detection and breaker components is presented. The protection strategy is implemented in the simulation model and different breaker sequences and fault mitigating components are tested and presented. The main goal was to achieve redundant operation by implementing a bypass solution which isolates the faulty modules while achieving continuous operation of the remaining modules. This was successfully achieved.

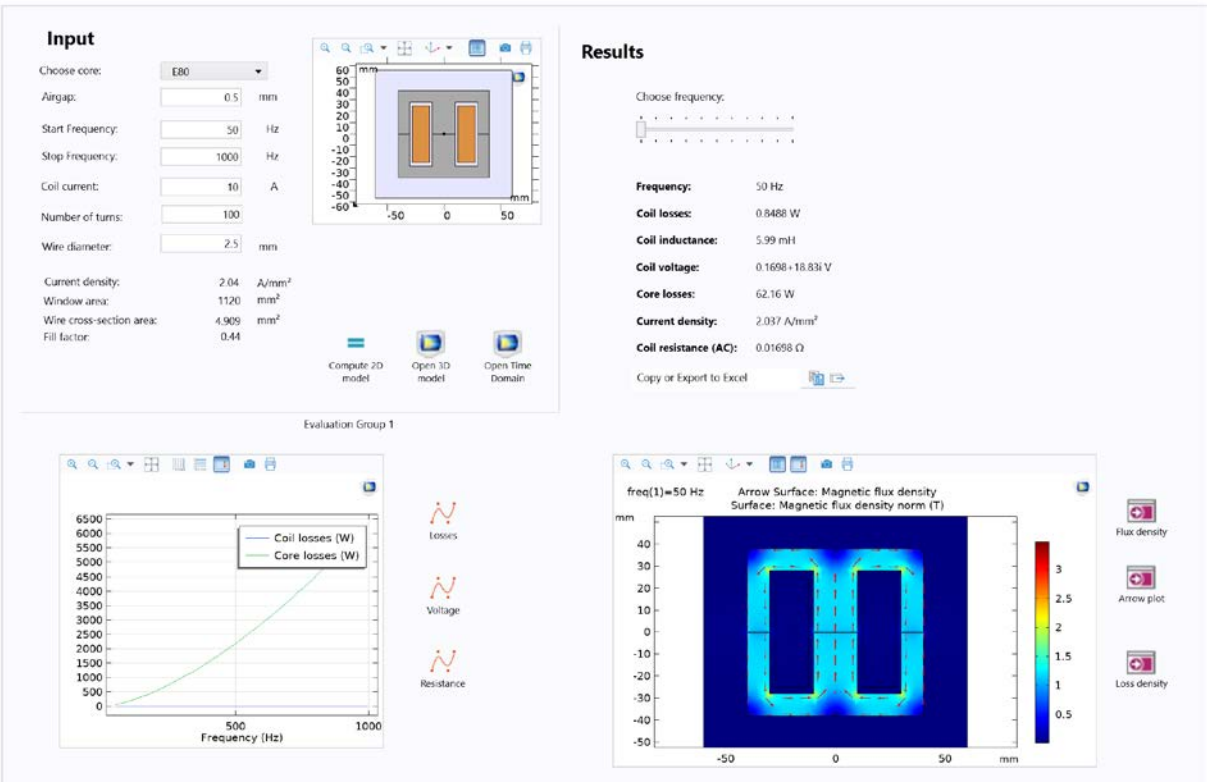
The proposed protection strategy provides an initial solution based on the investigated failure modes. As there are additional failure modes that needs investigation, the proposal must be seen as a suggestion for further work. However, the results illustrate the need for a current limiting reactor to limit fault current for the applied RLC parameters. Although at the expense of faster voltage rise time on the affected DC-links. This supports the suggestion of applying a fast-acting solid-state switch in the bypass in order to mitigate the heat dissipation. The results also support the proposed use of fuses or breakers on the floating DC voltage connections, as this has a considerable and positive impact on bypass heat dissipation.

Inductor application for teaching purposes

Student: **Siri Schüller Minothi**
Supervisor: **Robert Nilssen**

To enable students to learn about inductors through a trial and error method, a simplified user interface for COMSOL Multiphysics has been made called Inductor Analysis Application (IAA). Without deep knowl- edge about finite elements method simulation tools, the student can simulate inductors and make changes to them, and see how different parameters affects the behavior of the inductor.

In this thesis, the IAA results have been compared with paper calculations and laboratory testing. IAA provides accurate inductance calculations and can give students good insight to how voltage, resistance and losses changes when different input parameters are used. All the values from IAA are not exact and further work is needed to correct the loss and resistance calculations. For the resistance, this includes adjusting the calculations in the 2D model to capture the shape of the coil. To correct the losses, Steinmetz coefficients for the inductor must be found.



Picture on how the application looks.

Optimization of Zero-Emission Power Devices for an Electric Aircraft

Student: **Arne Filip Nygaard**
Supervisor: **Roy Nilsen**
Co-Supervisor: **Kristen Wagelid Jomås**
Collaboration with: **Rolls-Royce Electrical Norway AS**

Problem description

To reach global climate targets, proton exchange membrane fuel cells (PEMFCs) appear as one of the most promising alternatives to conventional aircraft propulsion systems. The optimization of such hydrogen-based energy systems is essential to achieve technical and economic competitiveness. The main objectives of this work were to:

- Find the optimal hybridization and sizing of PEMFCs and batteries for an electric aircraft based on technical and economic considerations.
- Investigate and test the power balancing and switching conditions of the optimal energy system.

The task

Numerical power balance modelling and qualitative considerations on transient requirements, fast dynamics and switching conditions were used to suggest the optimal power devices' sizes in a hybrid fuel cell/battery aircraft propulsion system. The quantitative calculations are based on mass, investment costs and fuel costs. The reference aircraft is a 50-56 passenger regional turboprop aircraft requiring an approximate peak power of 4 MW from the power devices. The energy requirement is in the range of a few MWh.

Model/ measurements

By using flight mechanics theory and open-source logging data, power profiles and environmental conditions have been estimated for real flight carried out by the regional reference aircraft. Similarly, the power devices have been modelled based on existing, high-performance devices to achieve good compliance with state-of-the-art products. MATLAB has been used to implement numerical models for the various components of the system. The models have been used to optimize and evaluate the power devices on key performance indicators, such as mass, lifetime and costs. The optimal power balancing between the fuel cell and the battery has been investigated for different hybridization factors by dynamically calculating the power devices' operation in each case. From the models, relevant limits and profiles are obtained to estimate the optimal fuel cell size, the battery cell count requirement, the hydrogen consumption, the fuel cell lifetime and the corresponding power requirement from key balance-of-plant components. The estimates are used to investigate which hybridization factor and fuel cell size that give the best overall performance in terms of total energy system mass, investment costs and fuel costs. A connection between mass and costs has been allowed by calculating the cost per available seat kilometer (CASK), which implicitly depends on the available payload capacity of the aircraft. The optimality was primarily investigated for three different mission profiles of 526 km, 1093 km and 187 km. A schematic overview of the optimization approach is shown in Fig. 1. To supplement the calculations, a literature review was performed to investigate the impact of high and low frequency current ripple on the fuel cell lifetime and performance.

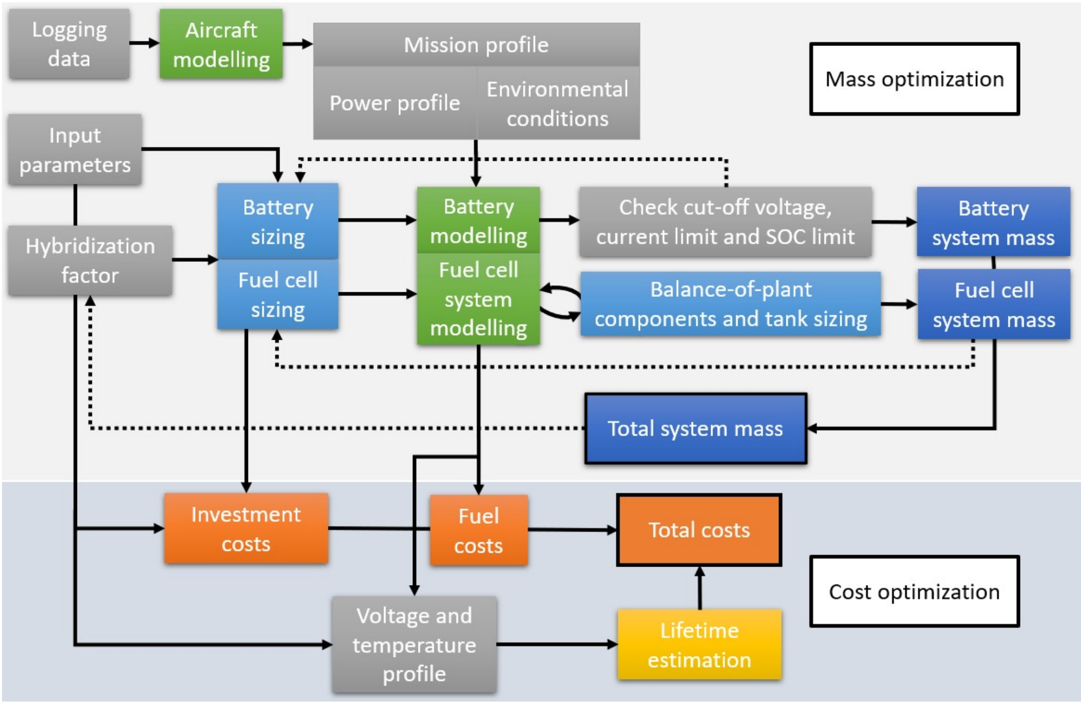


Figure 1: Schematic overview of the mass- and cost-optimizations.

Calculation

The optimization slightly favoured fuel cell only-propulsion, with no battery support, for the short- and the medium-range missions. Fuel cell oversizings of 45% and 40% were optimal for these two cases, respectively. For the longest flight, a hybridization factor of 0.8 (i.e., 80% fuel cell power) and a fuel cell oversizing of 56.3% was found optimal to supply the 3.2 MW power share. In all cases, fuel cell only and hybridization cases with small power boosting batteries showed little differences in CASKs. Lower hybridization factors with bulk energy batteries yielded poor results due to the low energy density of batteries.
Based on the literature and obtained knowledge on fuel cell characteristics, a battery introduction was suggested to be beneficial in the energy system. This claim is substantiated by the superior response time of batteries, allowing the fuel cell system to operate at lower air excess ratios and, thus, enabling a more efficient overall operation. In addition, faster-responding devices, such as batteries, may help relieving the fuel cell from low-frequency load variations. Such variations were found to be far more damaging to the fuel cell than high-frequency current ripple caused by power electronic converters.

Conclusion

Due to the sensitivity of key parameters for the reference devices, one should be careful to make definite suggestions on the optimality in the general case. With the given mission profiles and power devices, the combined results and investigations point in the direction of including batteries for power boosting as the best overall option. A hybridization factor of 0.8 with a FC sizing around 5.0 MW gives good results for all the evaluated mission profiles, and particularly the longest flight.
The power balancing is incorporated quantitatively in the numerical optimization and is also implemented and performed by graphic simulations. Contrarily, the impact of switching conditions is solely based on quantitative considerations. This is mainly due to the lack of available data, complicating the effort to address the topic from a quantitative perspective. Thus, a further evaluation and quantification of the impact of power converter switching, and other fast dynamics, remain as important subjects of investigation.

Testing and Verification of SiC Voltage Source Inverter

Student: **Jan Ottar Seljebu Olsen**
Supervisor: **Roy Nilsen**
Co-supervisor: **Kjell Ljøkelsøu**
Collaboration with: **Revolve NTNU**

Problem description

This master's thesis is written in collaboration with Revolve NTNU. Revolve NTNU is one of the technical organizations at NTNU and builds electric racecars and competes in the worlds larges competition for engineering students, Formula Student.

The purpose of this thesis is to minimum viable product test and assess the newly designed silicon carbide (SiC) voltage source inverter (VSI) which Revolve NTNU has planned to use on the four motor drive system for the 2021 season.

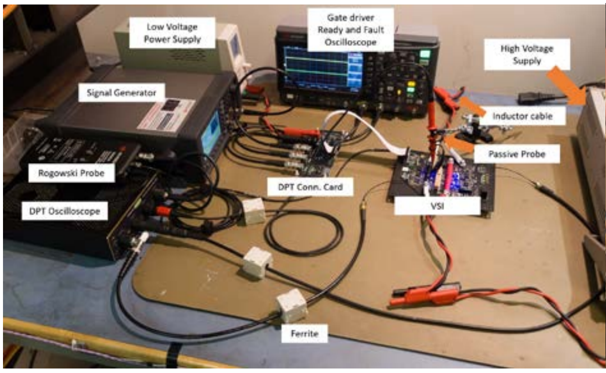
The task

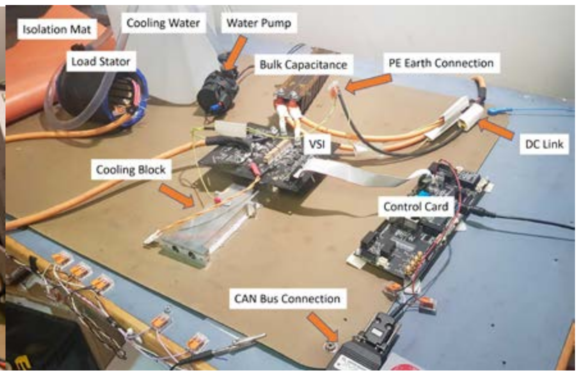
- Double pulse test the new design and finalize tuning of the gate driver circuit
- Establish losses in the VSI and investigate heat development and dissipation
- Compare losses and heat dissipation with the previous generation VSI using discrete TO-247-3 SiC MOSFETs in parallel
- Finalize the design of the entire inverter system in cooperation with another member of Revolve NTNU
- Assess the entire system with regards to the points mentioned above

Model/ measurements

An overview of the equipment used for double pulse testing can be seen in the picture to the left below (DPT inductor and high voltage supply not pictured) and the essential considerations for the setup have also been specified in the thesis. The oscilloscope used has isolated inputs which allowed for coaxial cables being used for gate voltage measurements and multiple measurements at different voltage levels could be done at the same time without the use of isolated differential probes.

For high current testing of the VSI can the equipment used be seen in the picture to the right below (high voltage power supply and additional safety systems not pictured) and the essential considerations for the setup have also been specified in the thesis. Here wasn't external measurement equipment used, but rather the sensors already implemented in the VSI and the data was collected by the Control Card of the VSI before being relayed to a computer through a CAN bus connection.



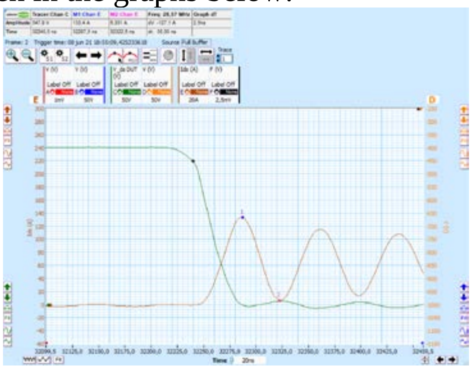


Calculation
Losses of the VSI was calculated through DPT of the VSI and datasheet values from the SiC module of the VSI. Instantaneous losses during turn-on and turn-off of the device under test (DUT) and freewheeling diode was found from the turn-on and turn-off waveforms and integrated to find the turn-on and turn-off losses for the DUT was found and turn-off losses of the freewheeling diode was found. The total losses of the inverter was found as switching losses, conduction losses, gate losses, and capacitor losses, where the remaining losses was found from datasheets.

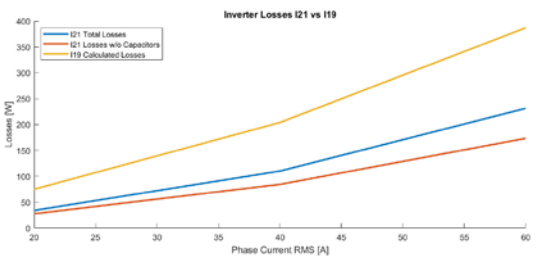
From the total losses was junction temperature of the MOSFETs estimated through steady state calculations of different load cases and compared with the previous generation SiC VSI of Revolve NTNU

Conclusion
The most important results from DPT can be seen in the table below where the results was compared to the prototype tested during the specialization thesis in addition to the previous generation SiC VSI used by Revolve NTNU. Waveforms for drain-source voltage (green) and current (brown) for the DUT during turn-on can be seen in the graphs below.

DPT Results			
	I19	**I21 Prototype**	**I21 Final**
Turn-on	$10.9V/ns$	$6.7V/ns$	$13.4V/ns$
Turn-off	$16.1V/ns$	$12.6V/ns$	$12.8V/ns$
Peak V_{DS}	$600V$	$624V$	$638V$
V_{GS} Diode Max	$< 2V$	$0.5V$	$1.2V$
V_{GS} Diode Min	-	$-4.2V$	$-4.2V$
Miller Plateaue	$4V$	$6.1V$	$5.5V$



The total losses calculated for different phase currents at 600V DC link voltage and 20 kHz frequency can be seen below. The maximum theoretical efficiency of the VSI during 60A phase current output was found to be 99.4%. The From the DPT was the turn-on losses deemed underestimated due to current waveform measurements not measuring current discharged and charged from the ceramic capacitor inside the module. This results in the actual efficiency being lower than calculated but since the switching losses are not substantial in the total losses was it deemed as a sufficient approximation.



The final design of the four motor drive converter system was completed and deemed as a better solution than the previous SiC VSI system Revolve NTNU used.

Model Development for DSO-TSO Coordination in a Local Flexibility Market

Student: **Ole Kjærland Olsen, Damian Sieraszewski**
Supervisor: **Irina Oleinikova, Hossein Farahmand**
Contact: **Irina Oleinikova**
Collaboration with: **NTNU-HONOR**

Problem description

Future requirements of the power system give rise to the need for better usage of the present flexibility in the distribution grid. For this purpose, necessary tools and coordination needs to be developed in order to secure its proper application. These measures include the development of an optimal power flow model and a scheme for market participants' coordination. Such a development will give the possibility to securely take advantage of the flexible resources for enhancing grid's operation.

The task

The task of this thesis is to give an insight into the execution of operation planning in an local flexibility market, with both market strategy description and procurement of flexibility. This aim will explore two objectives within the planning phase, which are to:

- Propose a market strategy for flexibility planning to solve grid problems through DSO-TSO coordination in this market platform. The proposed market strategy will include a short explanation of roles and responsibilities for each market participant and a potential coordination scheme between them. It will also look into a planning strategy for finding and deciding optimal flexibility dispatch in a distribution grid based on the rolling-horizon technique and the two-stage stochastic optimization approach.
- Develop a tool for optimal power flow analysis in the form of a multi-period hybrid AC/DC-OPF model. This model will generate grid scenarios that obtain optimal flexibility dispatch for the local flexibility market to solve potential grid problems. After developing the model, verification of the model's applicability will be achieved through different test cases designed as proof of concept.

Model/ measurements

The developed optimal power flow model was written in the programming language Python with the use of module Pyomo. For solving the optimization problem formulated in the program, Gurobi was used as the solver. The developed model was also amended with a description of the mathematical formulation.

Calculation

The result presented several test cases designed as a proof of concept. Each case attempted to describe the flexibility's potential in providing ancillary services for both the transmission and distribution grid. For each test cases the model has found an optimal flexibility dispatch which has benefited the operation of both the transmission and the distribution system.

Conclusion
The presented local flexibility market strategy in this thesis suggests a potential framework for how the cooperation between market participants can be conducted. The two-stage stochastic optimization combined with the rolling horizon has shown to be possible methods for how flexibility activation can be planned. It also presents the opportunity for more accurate scheduling of the operation due to the updated grid measurements.

With regards to the multi-period hybrid AC/DC-OPF model, this thesis has presented a potential prototype for planning flexibility. For this model, two optimal power flow methods have been implemented in a single program. The model applied the SOC-ACOPF for the distribution grid and DC-OPF method for the transmission grid. The combination of these two methods was accomplished by mathematically formulating the AC-to-DC connection constraint. This constraint connected these two methods resulting in an action being performed in one of the optimal power flow methods affecting the other.

Consideration of Arc Flash Development in a Switchboard Installed in Hazardous Area

Student: **Isabela Prates Cardoso**
Supervisor: **Kaveh Niayesh**

Problem description

The focus is to contribute to a safer switchboard design by identifying factors that can minimize the incident energy released by an arc flash inside an enclosure.
The incident energy is the parameter used to evaluate the safety aspect related to arc flash exposure, calculated at a specific working distance to select the suitable protective equipment (PPE) against human burn. However, calculation based in this distance is not suitable for investigating if the arc produces heat enough to auto-ignite a flammable gas if presented in surrounding air in sufficient concentration.
The absolute maximum energy and consequent temperature rise are the relevant parameters to verify if an arc could cause fire or an explosion for the hazardous area consideration.

The task

The scope is to present the factors that impact on energy released level by an electrical arc flash in a switchboard. In addition to evaluate if this incident energy could be an ignition source leading to fire or an explosion if enclosure is installed in hazardous area.

Model/ measurements

The case study is based on a model representing a simplified version of an offshore power system with one turbine generator supplying a 6.6 kV switchboard and a 690 V switchboard via a stepdown transformer as illustrated in Figure 1. The switchboard and loads are installed in areas where the flammable gas, H_2S, is likely to occur.
The simulation was performed in the ETAP software version 20.0.2, the thermal incident energy results were generated by the Arc flash module using calculation method from IEEE 1584 2018.

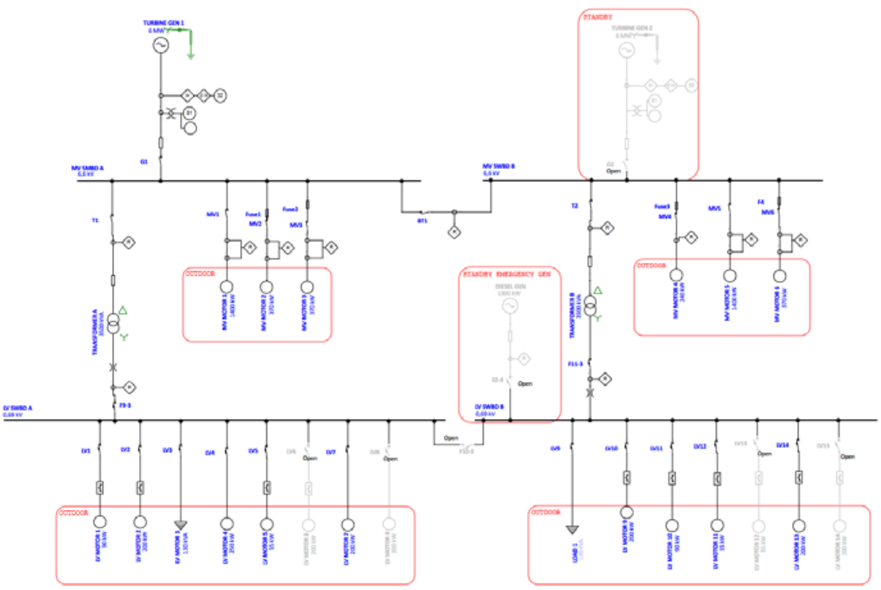


Figure 1: Model study case

Nine scenarios were simulated as described in Table 1, covering three electrode configurations: Vertical Electrodes Metal Box Enclosure (VCB), Vertical Electrodes terminated in insulation barrier, Metal Box Enclosure (VCCB) and Horizontal Electrodes Metal Box Enclosure (HCB), besides reduced enclosure dimensions, shorter conductor gap and various fault clearance times (FCT).

	Electrode Configuration	Conductor Gap LL (mm)	Enclosure (mm)	Final FCT
Case 1	VCB	Typical*	Typical*	Typical*
Case 2	VCB	Reduced	Reduced	Typical*
Case 3	VCB	Typical*	Typical*	Reduced and Increased
Case 4	HCB	Typical*	Typical*	Typical*
Case 5	HCB	Reduced	Reduced	Typical*
Case 6	HCB	Typical*	Typical*	Reduced and Increased
Case 7	VCCB	Typical*	Typical*	Typical*
Case 8	VCCB	Reduced	Reduced	Typical*
Case 9	VCCB	Typical*	Typical	Reduced and Increased

Table 1: Studies case summary

Calculation

The results have shown that the maximum temperature at closest to the arc source reached above the H_2S auto-ignition temperature of 260 °C. Therefore, the temperature rise cause by arc flash could lead to a fire or an explosion if H_2S was presented in sufficient concentration in the air.

	Temperature (°C)			
	LV SWBD A	LV SWBD B	MV SMBD A	MV SWBD B
Case 1	4157.0	3897.0	11049.6	11049.6
Case 2	4157.0	3328.9	14209.6	13318.5
Case 3	3128.1	9683.0	9064.4	15923.0
Case 4	28081.5	26316.3	36917.8	36917.8
Case 5	28081.5	21058.5	41700.0	38807.4
Case 6	21071.1	65731.1	30267.4	53240.7
Case 7	10761.5	10014.8	27492.6	27492.6
Case 8	10761.5	8566.7	33600.7	30237.0
Case 9	8080.7	24976.3	22542.2	39644.4

Table 2 – Temperature at 2.54 centimeters from arc source.

Nevertheless, results were within acceptable values when incident energy was calculated at working distance, not considering flammable gas being presented.

Conclusion

The VCB would be the preferred alternative for this case study since it resulted in the lowest incident energy, while HCB reached the highest. Moreover, the time taken for a fault to be cleared had linear impact on the incident energy, so the longer an arc lasts, more the incident energy increases. In addition to the linear relation to distance, as far from the arc source, lower incident energy results.

Furthermore, an explosion proof certified enclosure and internal components would be required considering that the switchboard is installed in hazardous area, besides a T3 rating to ensure that no equipment surface temperature exceeds 200°C and IIB that is suitable for H_2S exposure.

Harmonic filter design for large offshore wind power plants

Student: **Stian Rasmussen**
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Contact: **mohammad.amin@ntnu.no**
Collaboration with: **DTU and Vattenfall**

Problem description
Defining a methodology for designing harmonic filters for large offshore wind power plants.

The task
The objective of the thesis was simulating, analysing, and identifying the main factors influencing the harmonic distortions in HVAC connected offshore wind powerplants and, with this information, discuss methods for harmonic filter design and its location.

Model/ measurements
A DIgSILENT PowerFactory model of an offshore wind power plant from one of Vattenfall's projects was used for the simulations. Industry provided models (wind farm and grid connection model from Vattenfall and vendor-data based wind turbine model) were used for the modeling of the system, and background emissions, limits, and external grid harmonic impedance were provided by the TSO. The IEC limits were also used in the analysis. The types of simulations conducted were mainly harmonic load flows and frequency sweeps. This was done in two parts: A parametric sensitivity analysis part, and a filter design part. The parametric sensitivity analysis was cases covered changes in external grid modeling, changes in various components impedance, varying cable lengths, landfall cable voltage level, as well as TSO filter type, size, location, and component tolerances. The results were sorted into three broad categories based on the harmonic distortions: Low, medium, and high impact.

The filter design part consisted of designing a filter for three different voltage levels, and the goal was to evaluate the location of the filter.

Calculation

Case	Impact	Description
1.1.1–1.1.2	Low	$V_N \in \{-5, +10\}\%$
1.4.1	High	Grid loci points
1.4.2.1–1.4.2.2	High	SC power and R/X ratio
2.1.1–2.1.2	Medium	Landfall impedance $Z = \pm 10\%$
2.2.2.1–2.2.2.4	Low	Changing TSO filters and reactors size and type
2.2.2.5–2.2.2.6	High	Changing TSO filters resonance frequency
2.2.3.1.1–2.2.3.1.2	Low	Changing TSO filters and reactors tolerances
2.2.3.2.1–2.2.3.2.2	Medium	Changing TSO filters and reactors tolerances
2.2.3.3.1	Low	Changing TSO filters and reactors tolerances
2.2.4.1–2.2.4.8	Medium	Changing TSO filters and reactors location
3.1.1–3.1.3	High	Landfall cable length $l \in \{+100, +50, -50\}\%$
3.2.1–3.2.2	High	Landfall cable voltage $V \in \{110, 380\}$kV
3.2.3–3.2.4	Medium	Landfall cable voltage $V \in \{150, 275\}$kV
3.3.1–3.3.2	Medium	Landfall cable impedance $Z = \pm 10\%$
4.1.1–4.1.2	Low	Offshore transformer impedance $Z = \pm 10\%$
5.1	Low	Wind turbine operating points
5.2	High	$(N-1)$ contingency on PoC1
5.5.1–5.5.3	Medium	Collector cable length changes

The calculation results for the sensitivity analysis is presented in the table above.

Conclusion

Some of the results are thought to be model and case dependent.

Some key takeaways from the analyses performed are that the way the external grid is modeled, and the level of detailed knowledge of its emissions and impedance profile, will heavily influence the magnitudes of the distortion in the various buses in the system. It was also found that the landfall cable length, cable type, and voltage level have a high impact on the harmonic distortions. These considerations are thought to be true for any installation.

It was found that a filter did not adequately attenuate the harmonics when located south of one of the onshore transformers. This was thought to be caused by a combination of the external grid and onshore transformer impedance, although more testing would be needed to make any firm conclusions on this.

An Artificial Neural Network-Based Power Management in Hybrid Microgrid

Student: **Katrine Hansen Reisænen**
Supervisor: **Mohammad Amin**

Problem description

More and more renewable resources are integrated to the power system. The renewable resources, such as wind power, is unpredictable and the generated power can change rapidly. To avoid keep a satisfying energy balance, a sufficient power management strategy has to be implemented.

This thesis focuses on using an artificial neural network as a centralized controller for power management in a hybrid microgrid. The goal is to secure that loads have a stable and sufficient energy supply. Simulations are done in Simulink/MATLAB to see how the ANN works as a power management strategy. The power from and to all the units are examined and compared to an OPF algorithm. The simulations are done with one base case scenario, one scenario with abnormal change in load, one scenario with abnormal change in solar irradiance, and one with fully discharged batteries.

The task

This thesis presents a hybrid microgrid, an optimal power flow algorithm and an artificial neural network. The hybrid microgrid is modelled in MATLAB/Simulink and includes two loads, one EV, one BESS and one solar PV. Simulations are performed with the optimal power flow as a centralized controller and with an artificial neural network as a centralized controller, respectively. The centralized controllers outputs is the grid switch reference, current reference for the EV current controller and active power reference to the self-synchronized universal droop controller for the voltage source converter. The inputs are measurements from the microgrid, for example solar irradiance. The artificial neural network is trained based on inputs and targets from the optimal power flow algorithm.

Model/ measurements

The artificial neural network is a network with six inputs, two hidden layers with ten neurons each and three outputs. The microgrid model is given in fig.1.

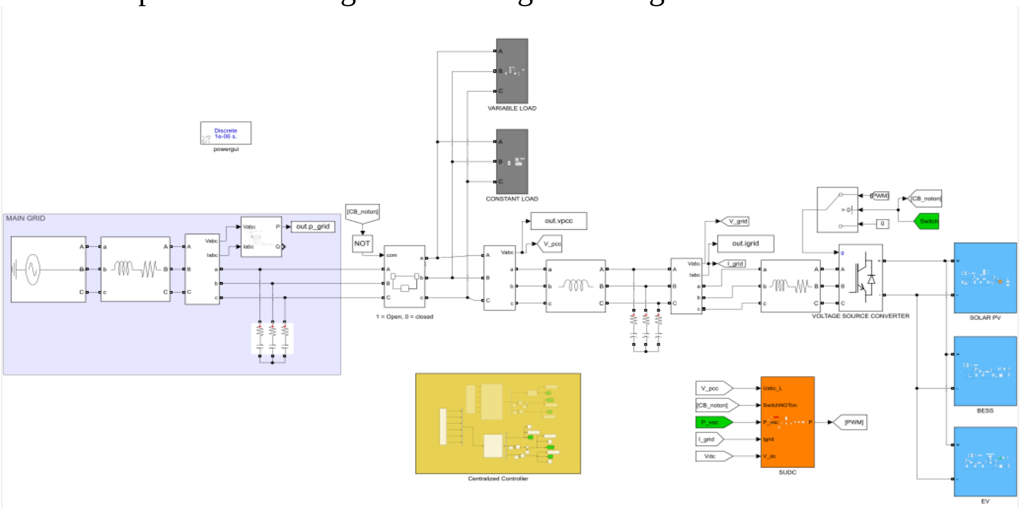


Figure 1: Microgrid model in Simulink.

Results

The results of the power to the loads are given in fig.2.

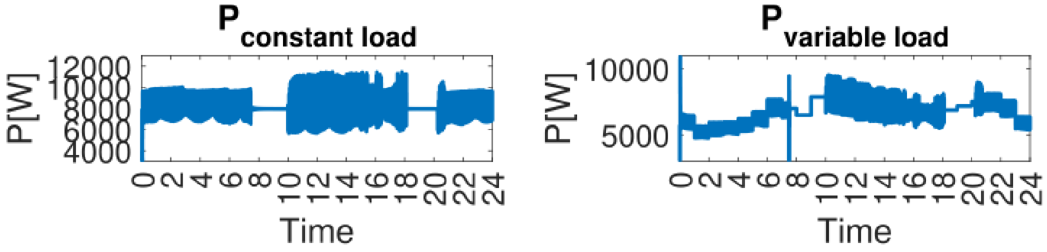


Figure 2: Power delivered to the loads with an artificial neural network centralized controller.

The outputs from the artificial neural network compared to the output from the optimal power flow is given in fig.3.

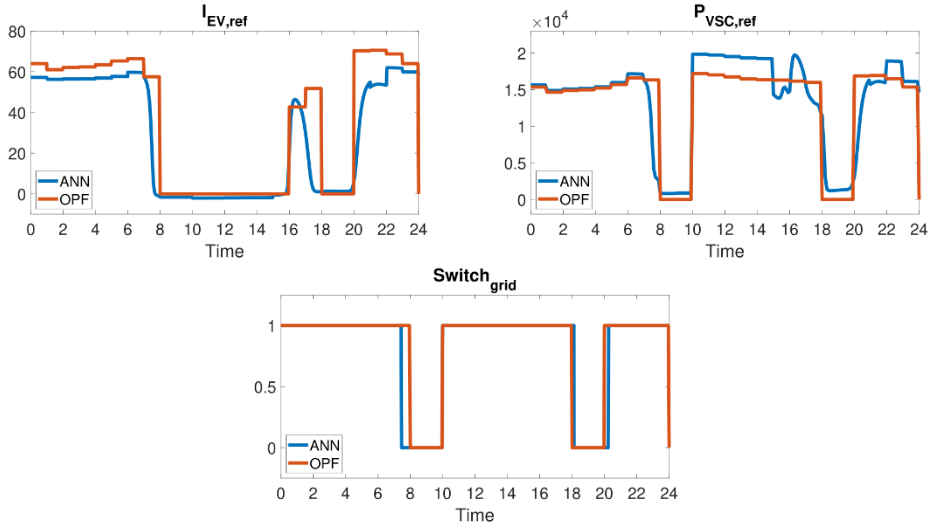


Figure 3: Outputs from the artificial neural network and optimal power flow algorithm.

Conclusion

The artificial managed to keep an efficient load sharing between the units in the microgrid and supply power to the loads. However, the power quality was poor, and the system experienced transients, and power limits were exceeded. Because the poor power quality was present during all of the simulation time when the microgrid was islanded, it is most likely that the low-level control and converters need improvements.

The artificial neural network manages to follow the same trends as the optimal power flow. In some places, the error between the two methods becomes large, and improvements are suggested. For example, changing the network architecture, implement a new training method or new training sets.

The findings in this thesis indicates that with improvements, the ANN can be used for optimization and power management of a hybrid microgrid.

Impact of Shared Battery Energy Storage System on Total System Costs and Utilisation of Locally Produced Energy in Commercial buildings

Student: **Mette Rostad and Ida Emilie Uglem Skoglund**
Supervisor: **Gro Klæboe**
Co-supervisor: **Kasper Emil Thorvaldsen**
Collaboration with: **TrønderEnergi AS**

Problem description

The demand for electrical power and the share of distributed renewable energy production is increasing. These changes are straining the grid by causing a demand for higher grid capacities, which in turn requires costly grid investments. As a response to this issue, the interest in local energy communities with shared battery energy storage systems is increasing. With shared storage, the community power peak can be reduced, relieving the stress on the external grid. However, the realisation of local energy communities is facing a variety of regulatory barriers.

The task

The aim of this master thesis is to provide further insight into how a shared energy storage system solution for commercial buildings in an urban area can improve total system cost and energy efficiency through increased utilisation of locally produced energy and peak shaving. This will be done by creating a stochastic linear optimisation program that minimises the total system costs including grid tariff and energy prices. The model will be applied to a case study based on existing buildings at Brattøra in Trondheim. With existing regulations and future possible regimes in mind, different solutions for joint battery operation will be investigated.

Model/ measurements

The optimal scheduling of the battery is solved with a two-stage stochastic linear programme implemented with a receding horizon optimisation approach that considers monthly measured peak tariffs. Time series analysis and forecasting is utilised to model the uncertain parameters in order to generate scenarios. The generated scenarios are reduced to a reasonable amount using SCENRED and implemented in the second-stage problem. A flowchart illustrating the receding horizon approach is shown in Figure 1.

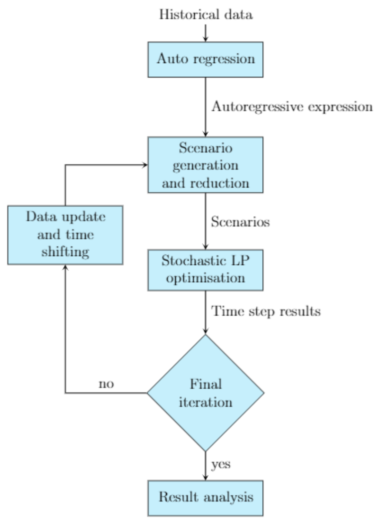


Figure 1.

The optimisation model is applied to a Norwegian case study with six different configurations for battery allocation within a local energy community. The case study includes configurations with both joint and individual metering. The model is tested for three different months; January, March and June.

Calculation

As it is the only configuration with direct incentives for community peak reduction, the shared battery energy storage system with joint metering outperforms all other configurations. The community power peak was reduced by 7-11% and the total system costs by 10-20%, depending on the season. Shared storage within a local energy market where the participants are metered individually is revealed to perform almost equally well. The community power peak was reduced by 2-8%, and total costs were reduced by 6-17%. The self-consumption was increased by an additional 45-46% in June for all configurations that included a shared battery energy storage system.

Conclusion

The main results show that there is a significant community benefit for shared battery energy storage systems considering peak shaving, self-consumption and monetary savings. Although shared storage with joint metering faces regulatory limitations, shared storage within local energy communities with individual metering proves to be a good alternative. It is therefore concluded that adaptation of current regulations to local energy communities with shared battery energy storage systems should be considered.

Dielectric Characterization of Semi Conducting Field Grading Varnish for Hydro Generator

Student: **Olav Henry Sagøy**
Supervisor: **Frank Mauseth**
Contact: **Jorunn Hølto, Espen Eberg**
Collaboration with: **SINTEF**

Abstract

The main purpose of this work was to characterize a field grading varnish that was used in hydro generators. The varnish tested is used in the end-windings of generators. It is made to even out field concentrations in the transition between slot and air in the end-windings.

This work mainly focuses on the characterization and the behavior of the varnish. It is also introducing the use, purpose and design around field controlling materials. This project includes several measuring methods, calculations and approximations to end up with acceptable results.

The first characterization method used was the insulation diagnostic analyzer, IDA 200. This is a measuring device that can apply a high voltage and a wide range of frequencies. The inconvenience with this apparatus is that it can only deliver a certain amount of current. With great losses from the varnish, this was not the optimal solution.

The IDAX 206 was used to apply a higher frequency. It was equipped with a thermal cabinet, that made it possible to test the temperature dependency at the same time as the field and frequency dependency.

With a Megohmmeter, there was performed polarization and depolarization measurements to obtain values for calculation. The values were used to produce graphs that represented the relationship between the applied electric field and the conductivity of the varnish.

Finally, it was done a potential measurement on the surface of the varnish on several different test samples. These measurements were done to see how the varnish influenced the already existing electrical field present without varnish.

The results of these methods show different graphs and values. The most interesting measured values are the loss factor ($tan \; \delta$), conductivity and the surface potential. The results show different dependencies when it comes to the losses of the varnish. Temperature, frequency and the electric field are parameters considered in this work. The varnish has much higher losses compared to a dielectric material and the conductivity of the material plays a major role here.

Conclusion

The desired outcome of this thesis was to increase the knowledge around the behavior of the field grading varnish. The dependency of the temperature, frequency and electric field was considered in this work. The different measuring methods performed through this work gave several different types of results. All the dependencies were confirmed present during the testing.

From the IDA 200 measurements, the graphs presented, clearly shows the dependency of the frequencies. At higher frequencies, the loss factor decreases. The same goes for the imaginary part of the capacitance. The results also showed that the higher fields gave higher losses. The carefully measured current confirmed the influence of the field, by showing a more distorted current with higher fields.

With the fairly similar IDAX, the fields obtained were too weak to show any interesting results. The outcome that gave interesting values from this measuring method, was the different graphs with the different temperatures. It was possible to see that the higher temperatures gave higher losses. In addition, the dependency of the frequency was confirmed with the results from this analyzer. If the frequency increased, the loss factor decreased. With little consistency, these dependencies were hard to pinpoint exactly.

By comparing the results from the two analyzers, a more complete overview of the dependencies was found. The complete figure showed graphs from 0.0025 to 0.5 kV/mm with frequencies from 0.1 Hz to 100 Hz. The transition between the IDAX and IDA measurements is not as desired, these should complete each other.

Two graphs were made out of the results from the megger. The stable values of the stationary current and resistance were used to produce the graphs. The modeled graphs represent the dependency of the conductivity on the electric field. The only disadvantage is that these are fitted graphs and not as precise as a totally measured curve. Because of the varying graphs from the measurements, the modeled graphs needed to be adapted. The graphs showed that the dependency of the electric field started around 0.01 kV/mm. The nonlinear section was found between 0.05 and 0.25 kV/mm.

The measurements done with the electrostatic voltmeter confirmed the given effect of the varnish from the manufacturer. The curves of the potential distribution were found in the data sheet. The graphs that showed the measured potential on the surface of the varnish resemble the ones in the data sheet.

Oppgradering og optimalisering av synkrongenerator ved Lutufallet kraftverk

Student: **Nils Andreas Sande**
Faglærer: **Arne Nysveen**
Veileder: **Arne Nysveen & Tormod Kleppa**
Utføres i samarbeid med: **Hafslund Eco**

Problemstilling

Lutufallet kraftverk er et elvekraftverk sør i Trysilelva helt på riksgrensen mot Sverige med et aggregat installert på 18 MVA med en midlere årsproduksjon på 71 GWh. Kraftverket ble satt i drift i 1964. Det er ikke utført større rehabilitering på generatoren siden den ble satt i drift og dermed er tiden inne for å utføre tiltak på generatoren. Det er derfor ønskelig å undersøke om det er mulig å oppgradere og optimalisere generatoren med ulike alternativer.

Oppgaven

For å kunne ha kunnskap om å vurdere og diskutere ulike generatordesign var det nødvendig å ha en betydelig del med teori for å øke forståelse av virkemåten til en generator. Videre var det nødvendig å validere GenProg opp mot de reelle verdiene på generatoren ved Lutufallet kraftverk som kommer fra underlag, kontrakt og prøveprotokoll. Prøveprotokollen fra 1965 innehold varme- og tapsprøver, men disse ble gjort ved lav vannføring. Dermed ble maskinen kjørt kraftig overmagnetisert. Det ble derfor nødvendig å kjøre maskinen med samme magnetiseringsstrøm i GenProg for å kunne sammenligne verdiene. Resultatet fra GenProg og verdiene fra prøveprotokollen stemte godt overens og det ble konkludert med at GenProg gir tilfredsstillende verdier.

Videre ble de undersøkt 4 alternativer til oppgradering og optimalisering av generatoren. Første alternativet var å optimalisere det eksisterende designet uten å bytte ut komponenter. Det var lite som kunne utføres for å optimalisere det eksisterende designet, kun øke effektfaktoren fra 0,8 til 0,86 som resulterte i mindre magnetiseringstap.

Andre alternativet var å bytte ut statorviklingen. Dette er det mest vanlige tiltaket å utføre på en generator. Her ble gammel vikling byttet ut med ny vikling med moderne isolasjon som har bedre egenskaper. Isolasjonen i moderne vikling er tynnere og dermed økte kobberarealet i statorsporet som senket strømtettheten i statorviklingen og ga en lavere belastet stator. Det ble undersøkt å sette inn både en flervindingsspole og en røbelvikling. Ved å sette inn en røbelvikling var det nødvendig å øke spenningen i maskinen. Spenningsnivået ble optimalisert ved røbelvikling og dette ble benyttet i både alternativ 3 og alternativ 4.

Tredje alternativet var å bytte ut statorviklingen og statorblikket. De samme fordelene med ny vikling fra alternativ 2 foreligger i dette alternativet. Nytt statorblikk har bedre egenskaper og dermed mindre relative tap som resulterer i mindre jerntap i statorkjernen. Dimensjonene på blikkpakkene og ventilasjonskanalene ble justert slik at blikkpakken ble større og flukstettheten i statoren ble redusert uten at temperaturøkningen i maskinen økte ut over akseptabel verdi.

Fjerde alternativet var å se på en ny stator med optimalisert sportall, ny dimensjon på sporet, blikkpakkene og ventilasjonskanlene og ny statorvikling. I dette alternativet var det flere parametre å endre på slik at optimaliseringsprosessen ble mer utfordrende ved dette alternativet. Det viktigste i design av en ny stator er å vurdere antall spor til det optimale. Antall spor per pol per fase er viktig å velge til en gunstig tall for å undertrykke subharmoniske komponenter i maskinen for å unngå vibrasjoner og deformasjoner av statoren. I dette alternativet ble ytelsen til maskinen også økt til en verdi som ga akseptable verdier. Det er vanlig at det er feltviklingen og polen som begrenser en økning i ytelsen.

Beregninger

For å utføre ulike alternativer til oppgradering av generatoren var det nødvendig å benytte et beregningsverktøy. GenProg er et beregningsprogram i Matlab som benytter en excel-fil til input og skriver ut resultatene til en excel-fil. GenProg er laget for å kunne beregne på synkrongeneratorer mellom 10 – 50 MVA.

Konklusjon

Målet med oppgaven var å optimalisere generatoren ved å oppnå en høyere virkningsgrad. Ved å øke spenningen i generatoren slik at det var mulig å benytte en røbelvikling ga dette den høyeste virkningsgraden i kombinasjon med å bytte ut blikket i statoren. Men ved å øke spenningen er det også nødvendig å bytte ut generatortransformatoren og andre komponenter i kraftverket. Derfor er det lite trolig at kraftverkseier realiserer dette alternativet.

Alternativet som er mest trolig at kraftverkseier iverksetter er med eksisterende spenningsnivå og utskiftning av statorblikk og statorvikling. Dette kan en økning i virkningsgraden fra 97,52 % til 97.89 % og dette tilsvarer en reduksjon i tap på 33,5 kW.

Tabellen nedenfor viser virkningsgradene ved de ulike alternativene.

Virkningsgrader

Opprinnelig	97,52 %
Alt 1	97,73 %
Alt 2.1	97,79 %
Alt 2.2	97,88 %
Alt 3.1	97,89 %
Alt 3.2	97,98 %
Alt 4.1	97,75 %
Alt 4.2	97,92 %

Alt 1: Optimalisering av eksisterende design
Alt 2.1: Ny flervindingsspole
Alt 2.2: Ny røbelvikling
Alt 3.1: Nytt statorblikk og ny flervindingsspole
Alt 3.2: Nytt statorblikk og ny røbelvikling
Alt 4.1: Ny stator med nytt sportall, økt ytelse og flervindingsspole
Alt 4.2: Ny stator med nytt sportall, økt ytelse og flervindingsspole

Assessing the impact of synthetic inertia controls in DFIG wind turbines on small-signal stability

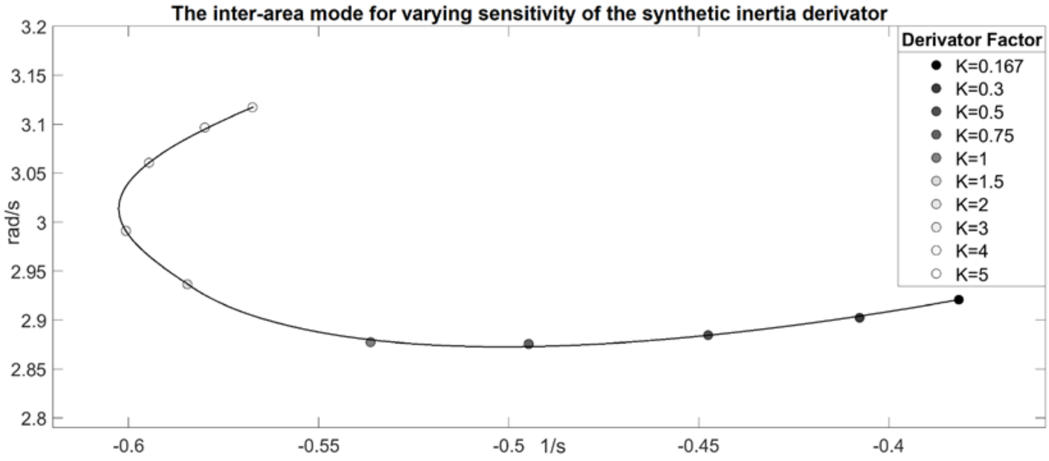
Student: **Johannes Silde**
Supervisor: **Olimpo Anaya-Lara**

Problem description
The presence of renewable energy sources, in particular wind power, is rapidly increasing in the power system. The rotational speed of large wind turbines is regulated to obtain maximum power extraction from the wind. This speed regulation causes a decoupling between the mechanical rotation of the wind turbine and the electrical frequency of the power system. Because of this decoupling, implementing wind power to the power system reduce the system inertia and impairs the frequency stability. A popular solution to the inertia decrease is the synthetic inertia controller. This is a power reference manipulation technique in the wind turbine controls, causing fast and potentially significant power changes. It is expected that these synthetic inertia controllers will gain presence in the power system in the near future. Fast, reference-based power electronic converters will impact the power system stability.

The task
This thesis provides insight into how synthetic inertia controllers in doubly-fed induction generator wind turbines affect the small-signal stability of the synchronous-based power systems.

Model/ measurements
Kundur's two-area system is used for the analysis, where one of the synchronous generators is replaced with an aggregated wind turbine model. A test system is developed in DIgSILENT PowerFactory, where the wind turbine model is developed from the DFIG wind turbine template in the DIgSILENT library. Complete frequency service controls are designed, including a generic synthetic inertia controller. Comprehensive model verification is performed by reconstructing the test network in a second software, Matlab Simulink. Despite some modeling differences in the two software, a strong correspondence is obtained between the eigenvalue profiles, verifying the power system and wind turbine modeling.

Calculation
The synthetic inertia derivator is a powerful system state. The gain affects the size of the power reference modification and the resulting inertial contribution. The derivator gain can potentially make the wind turbines contribute with inertial power larger than a synchronous generator, larger than what the stored kinetic energy allows, causing excessive speed change in the wind turbine. Increasing the size of the inertial contribution improves the inter-area mode damping. The time constant of the synthetic inertia derivator defines the shape of the inertial contribution. Decreasing the time constant makes the derivator more sensitive to frequency changes, resulting in an inertial contribution shape more similar to that of a synchronous generator. In addition, decreasing the derivator time constant replicates increasing synchronous generator inertia towards the system eigenvalues. Hence, the apparent inertia the wind turbines represent towards the small-signal stability is defined by the sensitivity of the synthetic inertia derivator. Therefore, by correctly adjusting the derivator parameters, the wind turbines can impact the small-signal stability with inertia similar to a synchronous generator, and at the same time, contribute to frequency support by an inertial contribution in accordance with the wind turbines' stored kinetic energy.



Conclusion

The synthetic inertia derivator should be adjusted to replicate the apparent inertia causing the most favorable impact on both the inter-area- and local modes. This can be achieved by replicating the inertia of the synchronous generator being replaced or, generally, the inertia of a typical synchronous generator. Changing the time constant of the synthetic inertia derivator, both the shape and size of the inertial contribution are affected. Therefore, as the time constant is adjusted, the gain of the derivator must be adjusted accordingly to ensure an inertial contribution in accordance with the stored kinetic energy. By this recommendation, wind turbines equipped with frequency service controls, including a synthetic inertia controller, can both provide frequency support through an inertial contribution and have a favorable impact on the power system's small-signal stability.

A Control Strategy for Seamless Interconnection of Microgrids in a Multigrid Configuration

Student: **Oda Skeie**
Supervisor: **Olav Bjarte Fosso**
Contact: **Salvatore D'Arco, Merkebu Zenebe Degefa**
Collaboration with: **SINTEF Energy Research**

Problem description

Microgrids are gaining a lot of attention in relation to the increasing amount of distributed power generation being implemented in the power grid. Microgrids have the great advantage that they are able to operate in both islanded and grid connected mode. Thus, they are seen as a suitable approach to enforce electrification of rural areas where the geographical location or the economic situation of a community prevents connection to the utility grid. Microgrids may be an economically advantageous alternative to extensive expansions of the utility grid.

Traditionally, microgrids can operate in both islanded and grid-connected mode. However, with microgrids situated in rural areas, connection to the utility grid might be difficult. The interconnection of several neighboring microgrids to a multigrid configuration can thus be an advantageous alternative. It will result in a more reliable and flexible system, in contrast to systems where microgrids operate solely in islanded mode. However, the interconnection of microgrids, and the possible connection of the multigrid configuration to a utility grid, will present several technical difficulties. A central challenge is that the microgrids need to synchronize before interconnecting to avoid high inrush currents and transients in the system.

The task

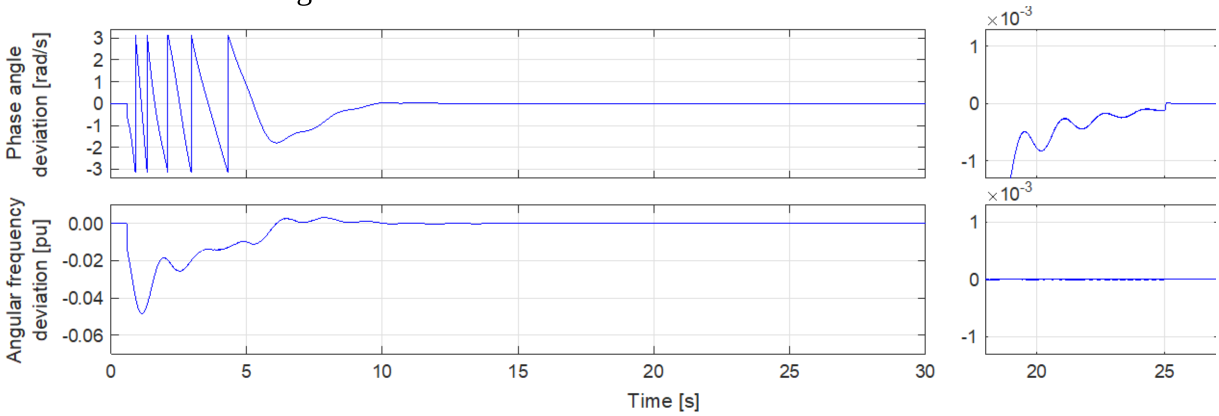
The purpose of this thesis is to propose a synchronization control strategy that provides a seamless interconnection between stand-alone microgrids. The synchronization strategy needs to enable a transition from stand-alone to interconnected operation without the risk of high inrush current transients. To ensure this, frequency and phase angle deviations between the microgrids need to be diminished within allowable limits.

Model

The proposed synchronization technique is tested through simulations to verify that the requirements for transitioning from stand-alone to interconnected operation are fulfilled. The simulation model consists of two simplified microgrids, almost equal in size, that are connected through a switch. Both of the microgrids have two sources of power that together supply a common local load. The two power sources in the microgrids are a synchronous generator, with a gas turbine prime mover, and a converter-based generating unit. The source of power on the DC-side of the converter is not specified and is, for simplicity, modeled as a constant current source. The proposed synchronization technique consists of parallel PI controller loops that are to eliminate deviations in phase angle and frequency. The control loops send frequency offset signals to the synchronous generator which speed up or slow down according to the control demands.

Results

The results from the simulations show the deviation in phase angle and frequency between the two microgrids for a simulation period of 30 second. The switch connecting the two microgrids is closed at 25 seconds. From the figure below it can be seen that the proposed synchronization loops diminished the deviations in both the frequency and phase angle within the allowable limits. The allowable limits of deviation for phase angle and frequency were both set to 0.001. Additional simulations showed that the synchronization control loops also could handle different grid conditions.



Conclusion

It can be concluded that a synchronization technique using the synchronous generator in one of the grids to synchronize the two microgrids shows promising results, and that the use of PI controllers to eliminate the deviations in phase angle and frequency is effective. However, more tests should be conducted on more detailed microgrid models and with more variations to the grid conditions.

Transformer insulation stressed by power converters

Student: **Fanny Skirbekk**
Supervisor: **Kaveh Niayesh**
Co-supervisors: **Øystein Hestad and Hans Kristian Meyer**
Collaboration with: **SINTEF Energy Research**

Problem description
In order to include more renewable power sources in the grid, with as little power loss as possible, an increasing number of power electronics are being integrated as well. The switching of the power electronics leads to more and larger transients, which might harm the electrical insulation. Partial discharges (PDs) can lead to degradation and ageing of the insulation system. Studying the PDs occurring in the insulation can therefore give a good indication to the state of the insulation.

The task
The objective of this project has been to study the partial discharges in two different transformer insulation systems, in order to gain a better understanding of how transient voltage stresses affect the insulation compared to sinusoidal voltage stresses. Nytro 10XN, a mineral oil that is commonly used in transformer insulation, was used as the insulation liquid in one of the systems. Midel 7131, a biodegradable synthetic ester that is becoming a popular alternative to Nytro for use in transformer insulation, was used as the insulation liquid in the other system. The insulation systems were stressed by a sinusoidal voltage in order to see how the systems behave under "normal" conditions, and by a bipolar voltage pulse in order to see how they behave when stressed by fast repetitive voltage pulses.

Model/ measurements
The PDs have been detected and measured using photomultiplier tubes (PMTs) and a current transformer for both voltage stresses. For the measurements with a sinusoidal voltage stress, Omicron MPD 600 and a high-speed video camera was used as well. Finding the partial discharge inception voltage (PDIV) for the two insulation systems under the two different voltage stresses has been the main focus. The patterns in the PD-plots and the visible ageing on the insulation caused by the PDs have also been studied.

Results
The PDIV was found to be much lower, for both insulation systems, when the systems were stressed by a bipolar voltage pulse. The PDIV for void discharges was approximately three times higher when the systems were stressed by a sinusoidal voltage. The PDIV for surface discharges was approximately twice as high when the insulation systems were stressed by a sinusoidal voltage. Some slight differences were observed between the behaviour of the two insulation systems.

Conclusion
The difference in PDIV suggests that PDs, which might lead to deterioration and ageing of the insulation systems, occur at lower voltages if the insulation system is stressed by fast repetitive voltage pulses compared to if it is stressed by a sinusoidal voltage. The results have therefore reaffirmed the hypothesis that fast repeating voltage pulses are more harmful to transformer insulation than a sinusoidal voltage.

Charging flexibility from electric vehicles via autonomous chargers in a workplace

Student: **Skogland, Teis Kloster**
Supervisor: **Lakshmanan, Venkatachalam**
Collaboration with: **DTU**

Abstract

As a part of the ongoing project Autonomously Controlled Distributed Chargers (ACDC), This thesis have designed an autonomous charging controller, with a distributed control architecture incorporating virtual aggregator capabilities.

In order to limit global warming, as stated by the Paris agreement 2015, decarbonising of the energy sector is key. Large scale electrification, and reduction of fossil fuel bases energy production is needed. To enable high penetration of uncontrollable renewable energy sources, demand side flexibility is needed. Sector coupling is also suggested as a solution. This could be done by integrating the transportation sector into the power sector. The idea is to use the storage capacity from Electric vehicles (EV) to benefit the electrical power system.

Electrification of the transportation sector is also necessary. To enable high penetration levels of EVs, it is important to integrate them to the grid in such a way that they could be of benefit to the system, instead of increasing peak loads and becoming a burden. The way of doing this is by use of smart charging.

This thesis have been focused on designing an autonomous charging controller, by use of a distributed control architecture. The model is capable of coordinating the charging of 18 EVs connected via nine chargers, with two outlets each, which is typically found in a workplace parking lot. The model uses historical EV data from 18 Nissan LEAFs. The idea is that by use of a distributed control architecture will enable high penetration of EVs in a cost effective and simple manner. The controller could operate independently, but also contribute with flexibility by responding to demand-response signals, such as power limitation, and load balancing. A virtual aggregator is incorporated in every charger which distributes a dynamic power signal. This signal can be changed to provide flexibility to the grid operator, or to provide behind-the-meter services.

The model have been developed in MATLAB Simulink. The model utilises historical EV data consisting of arrival time, departure time and State of Charge (SOC). The model autonomously coordinates charging of the 18 EVs, while keeping the power within desired limits.

To analyse the results, a total of 3 different cases with smart charging have been analysed, in addition to a base case utilising uncontrolled, dumb charging. By distributing the demand throughout the day, and with times of surplus power, the smart charger reduces peak loads. The result show that smart charging can reduce the required charging power by a factor of three, compared to dumb charging, and still deliver satisfying results when considering the total charged energy, and the SOC for every EV. From an economic perspective, taking this power difference into consideration could make the total investment of smart chargers cheaper compared to dumb chargers.

Sikker vernutkobling i elektriske installasjoner i svake lavspenningsnett

Student: **Nikolai Tøllefsen Skyrud**
Veileder: **Eilif Hugo Hansen**
Utføres i samarbeid med: **SINTEF Energi**

Bakgrunn for problemstilling

De siste 10-15 årene har nettselskapene fått bedre verktøy til å beregne minste kortslutningsstrøm tilført til de elektriske installasjonene i lavspenningsnettet. Nettselskapene har derfor avdekket områder der minste kortslutningsstrøm er lavere enn først antatt. I disse områdene har nettselskapene per dags dato to valg. De kan enten forsterke nettet eller redusere merkestrømmen på vernene. Det er ikke sikkert at kunden går med på å sikre ned, fordi det kan påvirke den daglige driften. Kostnaden av å forsterke svake lavspenningsnett til en tilstrekkelig styrke er estimert til mellom 9 og 33 milliarder. Billigere alternativ til nettoppgraderinger vil kunne spare samfunnet for store kostnader.

For å oppnå sikker vernutkobling må utkoblingstiden til vernet være kortere enn tiden det tar isolasjonen å gå fra maksimal tillatt driftstemperatur til maksimal tillatt temperatur ved en kortslutning. Med NEK 400:2018 som grunnlag må en kortslutning i tillegg kobles ut innen 5 sekunder.

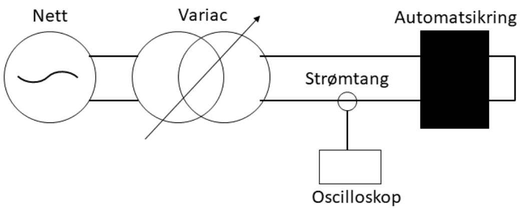
Oppgaven

Problemstillingen blir å svare på:

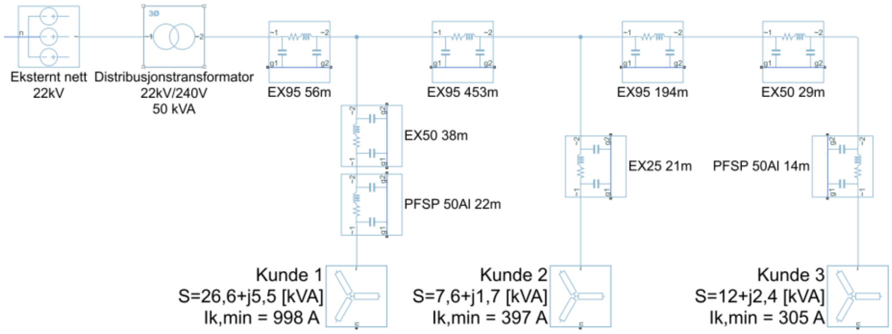
- Hvordan kan sikker utkobling av vern i elektriske installasjoner oppnås med NEK 400:2018 som grunnlag.
- Hvilke alternative tiltak til en nettoppgradering kan redusere kostnadene, samtidig som sikker utkobling av vern oppnås.

Modell/målinger

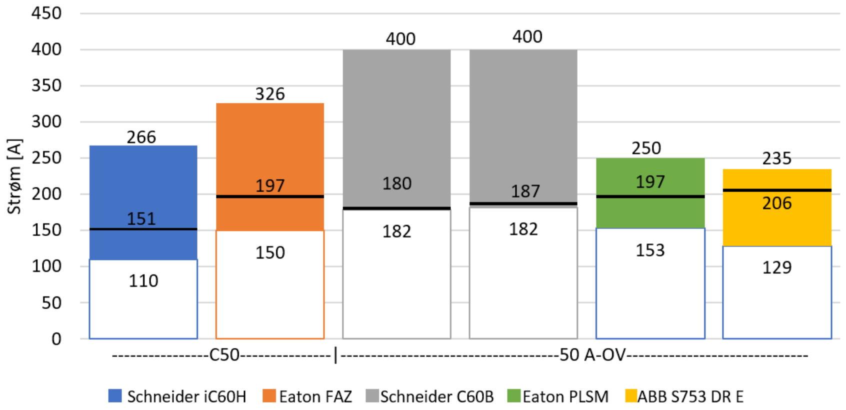
For å svare på den første problemstillingen kartlegges strøm/tid-karakteristikkene til hovedsikringer på 50 A, 63 A og 80 A og kurssikringer på 10 A og 16 A. Dette ble gjennomført med FebDok sitt vern-register og ved labtest. Figurene under vises testoppsettet.



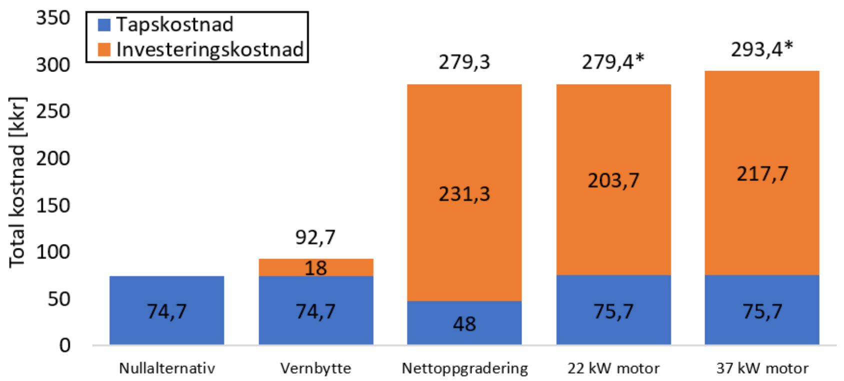
For å besvare problemstilling nummer to ble et radialnett benyttet til å gjøre tekniske og økonomiske beregninger. Kunde 2 og kunde 3 i nettet har lav kortslutningsytelse. Tiltakene som ble analysert var vernbytte, nettoppgradering og tilkobling av en asynkronmotor.



Beregninger
Figuren under viser resultatene av kartleggingen av strøm som kobler ut 50 A-hovedsikringer på 5 sekunder. Stolpene som er farget er strømintervallet som vernprodusentene oppgir skal gi 5 sekunders vernutkobling (ved verndimensjonering benyttes øvre strømverdi). Streken inni stolpene er den målte strømmen i lab som kobler ut vernet på 5 sekunder.



Figuren under viser kostnadene av alternativer for å oppnå sikker vernutkobling i radialnettet med lav kortslutningsytelse. Analyseperioden er 30 år.



Konklusjon

Hvordan kan sikker utkobling av vern i elektriske installasjoner oppnås med NEK 400:2018 som grunnlag:

- Med hovedsikring på 50 A, 63 A og 80 A kan sikker vernutkobling oppnås ved en tilført minste kortslutningsstrøm på 230 A, 290 A og 400 A.
- Med minste kortslutningsstrøm på 230 A vil kurssikringene på 10 A og 16 A oppnå sikker utkobling ved relativt lange forbrukerkurser. Det forutsetter relativt rask C-karakteristikk, eller B-karakteristikk. En hovedsikring på 50 A vil være den begrensende faktoren ved en tilført minste kortslutningsstrøm lavere enn 230 A.
- Labtester viser at strømmen som kobler ut automatsikringer på 5 sekunder ligger betydelig lavere enn øvre strøm/tid-kurve ved 22 ℃. I praksis betyr det at vern dimensjoneres med en relativt god sikkerhetsmargin.

Hvilke alternative tiltak til en nettoppgradering kan redusere kostnadene, samtidig som sikker utkobling av vern oppnås:

- Ved å bytte vern i de elektriske installasjonene til kunde 2 og kunde 3, uten å sikre ned, kan totale kostnader reduseres med 66,8 % sammenlignet med en nettoppgradering de neste 30 årene.

Title: Demand response verification using baseline estimation and load disaggregation

Student: **Ole Andreas Sloth**
Supervisor: **Jayaprakash Rajasekharan**
Contact: **Morten Tylden**
Collaboration with: **ENFO AS**

Problem description
Baseline estimation refers to the estimation of the normal operation of the appliances participating in the flexibility process. However, this estimation is difficult due to the measurement of the power consumption usually are at the building level and not appliance level, and baseline estimation do not offer any information regarding the origin of the flexibility. Without the origin of flexibility, the flexibility settlement can be inaccurate. Load disaggregation is the process of acquiring individual appliance information from aggregated consumption measurements. It can provide additional information regarding the individual appliance consumption, such as a power profile for the flexible appliance and the origin of the flexible power. As there are uncertainties in both baseline estimation and load disaggregation, combining the methods can create a more accurate flexibility settlement.

The task
The master thesis aims to create an accurate flexibility settlement process for small scale commercial consumers by combining baseline estimation and load disaggregation. The combination of baseline estimation and load disaggregation is tested at real costumer locations provided by ENFO AS.

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Model/ measurements
The model compares the performance of three different baseline estimation methods: a long short-term memory recurrent network method, an artificial neural network method and an averaging method and examines the possibility for additional verification of demand response by load disaggregation.

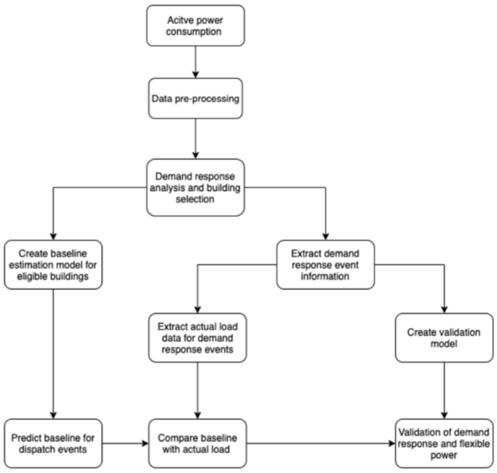


Figure 6: Complete overview of the system model

Conclusion

Due to low resolution, only active power consumption and the fact that the flexible appliance is multi-state, a large majority of edges are too similar to distinguish the edges connected to the demand response from the other edges. Given the current system setup, load disaggregation can not validate the demand response, and the flexibility settlement solely rely on the choice of baseline estimation method. The baseline estimation techniques have pretty significant differences in the estimation, and the result of flexibility settlement will greatly depend on which algorithm is chosen. The LSTM method provides the lowest error compared to the actual load. However, the machine learning models are prone to miss in some situations. The averaging X of Y model is more consistent, but it will seldom be completely accurate.

Bruk av DC for energiframføring i husstander med solcelleanlegg og batterilagring

Student: **Dag Slålien**
Faglærer:
Veileder: **Steve Völler**
Utføres i samarbeid med: Ingen

Problemstilling
Målet med dette arbeidet er å undersøke i hvilken grad det er mulig å forsyne lastene i en husstand med DC. Det er i dette arbeidet utarbeidet to alternative system-løsninger til dagens AC-system. Et hybrid-system der energien forsynes både med AC og DC, og et rent DC-system der alle lastene er antatt å være DC-laster. De to alternative system-løsningene er sammenlignet med det originale AC-systemet på punkter som effektivitet, og i hvor stor grad systemene er avhengig av å energi fra nettet. Disse systemene er modellerte ved bruk av Matlab/Simulink. I tillegg er det økonomiske aspektet vurdert sammen med aspekter som leveringskvalitet og sikkerhet.

Oppgaven
Tradisjonelt sett har AC vært å foretrekke foran DC for energifremføring i husstander. Dette har vært tilfellet siden Nikola Tesla med sitt AC-system utkonkurrerte Thomas Edison med sitt DC-system på slutten av 1800-tallet. I senere tid har DC-systemet tatt igjen noe av forspranget, særlig når det kommer til overføring av energi over lange strekninger.

I dag er en stor andel av lastene vi bruker daglig avhengig av DC-teknologi for å fungere. Dette være seg PC, TV, mobiltelefon eller annen elektronikk. Alle disse lastene konverterer AC-spenningen fra nettet til DC-spenning, enten internt eller via en ekstern adapter. I tillegg til denne endringen på lastsiden er det et økende fokus på å produsere ren og fornybar energi. Dette gjøres økende i grad av privatpersoner med private solcelleanlegg. Siden solcelleanlegg også er DC-teknologi er det tenkelig at et DC-system for energiframføring i husstander kan være en mulig løsning i framtiden.

I dette arbeidet er det derfor undersøkt om et system som helt eller delvis forsyner lastene med DC-spenning kan være et alternativ til det eksisterende AC-systemet. Dette er gjort ved at det er desginet to alternative systemløsninger, et hybrid-system og et rent DCsystem. I hybrid-systemet forsynes lastene med intern DC-spenning fra en egen DC-bus gjennom en AC-DC-konverter, mens de originale AC-lastene fortsatt forsynes fra ACnettet. I DC-systemet er det antatt at alle lastene kan forsynes fra DC.

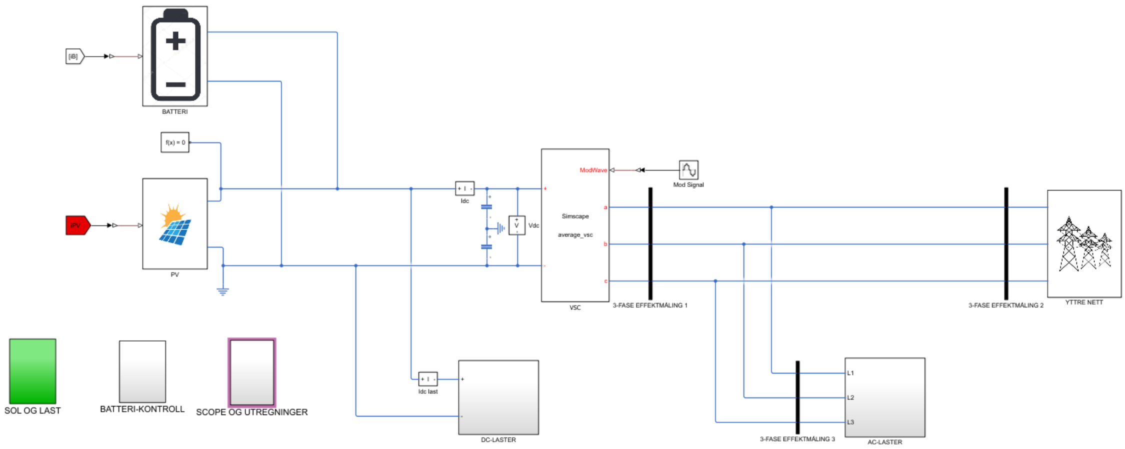
Systemene er undersøkt ved modellering i programmet Matlab/Simulink. Her er de tre systemene simulert for tre scenarier, med en tidsperiode på henholdsvis 1 dag og 1 uke. Scenariene er; kun nettilkobling, nettilkobling og solproduksjon, og nettilkobling, solproduksjon og batterilagring.

Simuleringene resulterte i en gjennomsnittlig systemeffektivitet for AC- hybrid- og DCsystemet på henholdsvis 94,0 %, 96,2 % og 92,5 %. En feil gjort under simuleringene gjør at effektiviteten til DC-systemet egentlig er noe lavere enn 92,5 %. De årlige tapene sammenlignet med AC-systemet er 45 % lavere og 11 % høyere for henholdsvis hybridog DC-systemet. I tillegg er virkningen av batterilagring i systemer med lokal produksjon av solenergi undersøkt. Her er det funnet at graden av importert energi fra nettet kan reduseres til under 10 % sommerstid.

Det er, basert på simuleringene, samt sikkerhet og økonomiske vurderinger konkludert med at hybrid-system kan være et bra alternativ til dagens AC-system. Det understrekes likevel at det fortsatt kreves mye arbeid når det gjelder utvikling av praktiske løsninger, samt standarder for DC-baserte løsninger.

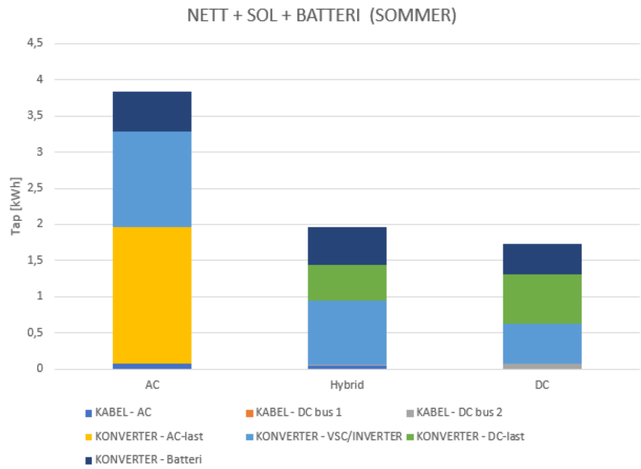
Modell/målinger

Figuren viser modellen i Matlab/Simulink. Denne består av ytre nett, AC-laster, DC-laster, VSC-konverter, solcelleanlegg og batterilagring. Modellen er brukt til å simulere ulike scenarier for de ulike systemene.



Beregninger

Figuren viser tapsfordelingen i systemene når de er tilkoblet nett, har solproduksjon og batterilagring.



Konklusjon

Simulasjonene resulterte i en gjennomsnittlig systemeffektivitet for AC- hybrid- og DC-systemet på henholdsvis 94 \%, 96,2 \% og 92,5 \%. En feil gjort under simuleringene gjør at effektiviteten til DC-systemet egentlig er noe lavere enn 92,5 \%. De årlige tapene sammenlignet med AC-systemet er 45 \% lavere og 11 \% høyere for henholdsvis hybrid- og DC-systemet. I tillegg er virkningen av batterilagring i systemer med lokal produksjon av solenergi undersøkt. Her er det funnet at graden av importert energi fra nettet kan reduseres til under 10 \% sommerstid.

Design of the Near-Sonic Double-Sided Linear Induction Motor for the Hyperloop Propulsion System

Student: **Roman Anatoljevich Souvorov-Pedersen**
Supervisor: **Jonas Kristiansen Nøland**
Co-supervisor: **Matteo Leandro**
Contact: **Alexey Matveev**
Collaboration with: **Alva Industies**

Problem description

With the introduction of Hyperloop in 2012, presented by Elon Musk, the interest in high-speed railway transportation has increased substantially. Several different prospects and challenges of the Hyperloop transportation system have already been presented and reviewed. One of the suggested systems for Hyperloop is a Double-Sided Linear Induction Motor (DSLIM), with a short primary and long secondary design. This design is less explored than a Single Linear Induction Motor (SLIM), which make it a viable solution to be explored.

The task

This thesis aims to investigate the performance of a DSLIM for applications such as the Hyperloop transportation system. Two types of model design for COMSOL Multiphysics were provided, while two additional modified versions were created and included afterward. The models consisted of a toothless design, different sizes, ironless, and a general design with teeth. A thorough literature review was performed to find calculation methods and results from alternative simulation software used as a resource. This provided information that the DSLIM had a smaller sample size of studies and almost no studies using COMSOL Multiphysics software. In addition, a simple analytical method is also included, which was found through the literature review.

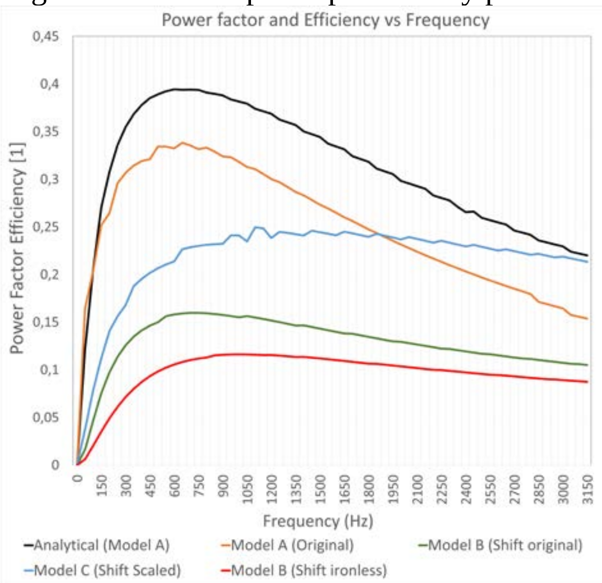
Model/ measurements

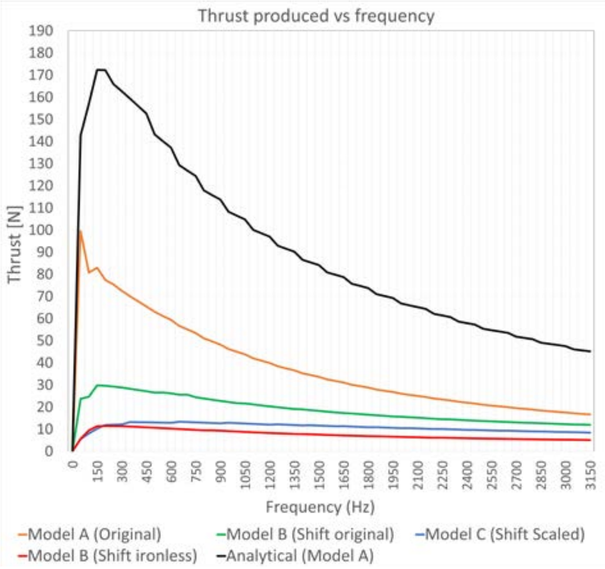
The first DSLIM model is provided by the students who are working with Sift Hyperloop organization at NTNU. This model is toothless DSLIM, with litz wire windings, and is designed according to the standards used for the European Hyperloop Week in Spain this summer. The second model is a DSLIM with teeth and has no particular restriction in the design aspect. To compare these two models, another Shift DSLIM model is created that has been scaled up to the second version. By doing the following, a direct comparison of both the models is achieved. All of these models are then simulated using COMSOL, and different values are compared between them. This study aims to analyze the performance of the given models, provide the groundwork, and establish an understanding of DSLIM for future studies. Another object is to provide the estimation of the values using the result provided by COMSOl.

Results

It is provided that larger machines reach the highest performance across the simulated frequencies. The result also demonstrates that a machine with teeth is more efficient when working with frequencies range up to 2000 Hz. A toothless machine on the other hand may be more suitable for frequencies above 2000 Hz. However, the toothless model has substantially lower thrust force, especially at the lower frequency range.

The analytical method did not provide accurate estimation compared to the COMSOL results, where the deviation was between 1% - 70% across the simulated frequencies. However, this method provides a rough estimation that can validate the performance of a DSLIM to some degree and as an input to preliminary parametric analysis.





Conclusion

The main findings that were found between the simulated models and the analytical method are listed below:

- The length, width, and pole pitch determine heavily how the machine will perform. However, the machine weight will increase when increasing the size. Dependent on what the machine is supposed to be used for, it would be reasonable to find a working point between size and performance. For applications such as Hyperloop, DSLIM that are larger are more suited for such tasks. In addition, the end-effects will be more present in shorter DSLIM because not enough time to build up the magnetic field.
- The toothless model showed to be a more efficient machine when it comes to high velocity and frequency. However, a machine that lacks teeth will result in low thrust force produced. A higher input current could be applied to compensate for low thrust force, but it will result in overall lower machine performance. An ideal machine for Hyperloop would be a DSLIM with teeth and a relatively large slot area for the coils.
- A DSLIM solely focused on the highest produced thrust force will experience lower performance when it comes to the other results. If Hyperloop is supposed to have passengers and battery packs on board the pod, the thrust force needs to be adequate to both accelerate and move the pod. This will result in lower efficiency and power factor for the given machine.
- Larger models that operate with higher current and frequency will need to include iron losses since they will be more relevant. The iron losses can also be estimated in smaller models, but most of the time, they are ignored because of a lesser impact on the performance.

Optimal Utilisation of Grid Capacity for Connection of New Renewable Power Plants in Norway

Student: **Viljar Stensaker Stave**
Supervisor: **Ümit Cali**
Co-Supervisor: **Magnus Korpås**
Contact: **Ane Meisingset Elgsem and Gjermund Sætermo**
Collaboration with: **Statnett SF**

Problem description

The Norwegian power system today is dominated by flexible reservoir hydropower. However, the share of wind power is expected to increase and constitute a significant part of the power production in the coming decades. Nevertheless, the most favourable wind power resources in Norway are located in areas with poor transmission capacity, which will cause an increase in congestion issues in the transmission system.

As a means to face these challenges and maintain the economic incentives to invest in Variable Renewable Energy Sources (VRES), Norwegian Water Resources and Energy Directorate (NVE) revised the Regulation on grid regulation and the energy market (NEM)[1] in 2019. This revision enables new power producers to connect to the grid with terms on production restriction according to grid limitations, and intends to avoid costly grid investments and improve utilisation of existing capacity. As new producers often are based on VRES, however, they might experience loss of power potential. Nevertheless, it is reasonable to believe based on the predicted increase in wind power production that there will be an increase in cases where VRES are connected according to the revised provisions in NEM.

The task

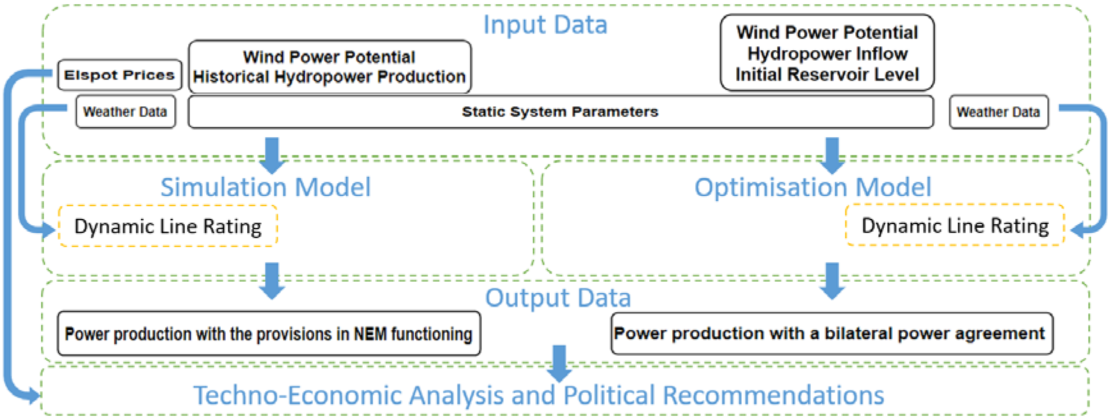
This thesis is done in collaboration with Statnett SF and aimed to investigate and address the following questions:

- How does the connection of wind power with terms of production restrictions affect grid utilisation, wind power integration and operational patterns in a local part of the power system?
- Can a bilateral power agreement designed to activate the flexibility of neighbouring reservoir hydropower plants improve wind power integration and is it financially sound?
- How is wind power integration, operational production patterns and grid utilisation affected by the utilisation of DLR?
-

For this purpose, a case study of a suitable area in Northern Norway, consisting of wind power with production restrictions, hydropower and limited transmission, is performed. Measured data of the period 2011 to 2015 from the studied area were provided by Nordkraft. Furthermore, a simulation is conducted to identify the impacts of the revised provisions in NEM. Moreover, an optimisation model designed to replicate the operational pattern induced by a bilateral power agreement is derived to explore how the hydropower flexibility might enable optimal grid utilisation and ease wind power integration. Lastly, the DLR of the transmission line is estimated and added to the two models to comment on the third question.

[1] NEM is the official law abbreviation and is therefore used throughout the thesis. The abbreviation is based on the Norwegian name of the regulation, *Forskrift om nettregulering og energimarkedet*

Model/ measurements
The main idea behind the chosen approach has been to replicate how the aforementioned political regulation and agreement affect the studied system. These operational patterns have been replicated by utilising a simulation model using a local energy balance and a Linear Programming (LP) optimisation model minimising energy loss. Both models illustrate power production in the studied system over a time period of one year, thus enabling an analysis of the parameters of interest. Python and excel have been used for adaptation and revision of input data, modelling and calculations. The following figure shows the overall calculation flow of the methodology, highlighting the needed data, the resulting power production of producers in the studied system, as well as the different regulations that are functioning.



Conclusion
The overall result from the simulations showed that the wind power producer with production restrictions according to NEM experienced an average annual amount of wind power curtailment equal to 16.41GWh. This constituted 4.20% of the annual wind power potential and induced an average revenue loss of 4.67MNOK each year. However, utilisation of grid capacity was found to be only 54.24% on average, indicating that there should be sufficient capacity to capture the wind power curtailment. Combined with financial estimates, the overall simulation result therefore implies that NEM might be a better alternative than conventional connection regulations. Moreover, grid expansion costs and building delays are avoided. Still, a more extensive investment analysis is deemed necessary to obtain a precise assessment of this matter.

From the optimisation results it could be seen that a bilateral power agreement between the power producers was able to eliminate all curtailment. Thus, the grid utilisation was increased by 1.01 percentage points. The generated operational pattern also revealed that the hydropower production was shifted to periods with low wind potential, utilising the flexibility of the reservoir. Furthermore, the observed changes in cash flows indicate that a bilateral power agreement provides a financial advantage to the wind power producer and the overall system.

Implementation of DLR was found to reduce the amount and frequency of wind power curtailment experienced in the simulations by 11.89GWh and 893.4 times per year, respectively. This observation, combined with the results from the sensitivity analysis, indicates an advantageous positive correlation between DLR and wind power potential. Consequently, grid utilisation was seen to increase by 0.97 percentage points in the simulations compared to utilising Static Line Rating (SLR).

Contact Degradation in Air Load Break Switches by Making Operation under Short Circuit Condition

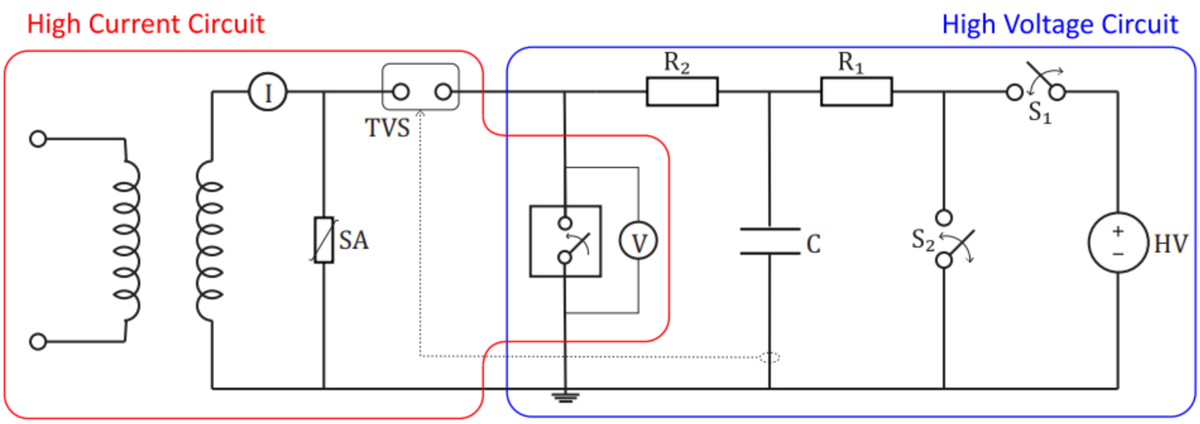
Student: **Marius Strand**
Supervisor: **Kaveh Niayesh**
Co-Supervisor: **Naghme Dorraki**

Abstract

The operation of electrical switchgear is essential for a functional and reliable power grid. In the distribution network, load break switches can be utilized as a cost-competitive alternative to circuit breakers. However, this raises other issues. Load break switches are required to perform several making operations where a high short circuit current passes through. During making operation, an arc is established when the contacts are closing. This is due to a dielectric breakdown. The arc leads to high energy dissipation between the contacts, which results in contact erosion and eventually welding. This is highly undesirable and may affect the future functionality of the switch.

In this thesis, this phenomenon has been investigated. By utilizing a synthetic test setup consisting of an HVDC source and a high current transformer, the contacts have been exposed to stresses during making operation. Four different test cases have been applied to improve the understanding of this process. The energy dissipation depends on the arc voltage, the short circuit current, and the arcing time. All these parameters have been recorded during the experimental testing. Additionally, the effect of the main contacts has been examined.

Pre-strike arc energy and mass loss measurements have been performed for each test. The results clearly show that higher short circuit currents will critically increase the arc erosion on the arcing contacts. Additionally, an increase in closing velocity will decrease the contact degradation. The mass loss was highest for the worst-case scenario with a closing velocity of 2.9 m/s and a short circuit current of 20kA. Welding was achieved after 7 and 4 tests, with and without main contacts, respectively. This clearly shows that the main contacts are important during making operation and will extend the lifetime of the switch. The results also show that welding is dependent on both arc energy and the degree of contact erosion that gradually occurs by repeated making operations.



Schematic of the test circuit. High current circuit (red) and high voltage circuit (blue)

Conclusion

After analyzing and discussing the obtained results, the following conclusions can be drawn:

- If an LBS, including both arcing and main contacts, is exposed to short circuit currents of 20 kA with a closing velocity of 2.9 m/s, there is a probability that the arcing contacts will be welded after six or seven making operations. As a result, the switch will not operate properly during the next interrupting operation.

- Higher short circuit currents will increase the erosion on the arcing contacts. At a closing velocity of 2.9 m/s, the total mass loss was approximately three times higher at a short circuit current of 21.3 kA compared to 15.7 kA.

- By increasing the closing velocity from 2.9 m/s to 3.8 m/s during making operation, the arc energy will decrease. Consequently, the mass loss and erosion will decrease, and the lifetime of the switchgear will be extended. During making tests at higher velocities, no samples were welded.

- The main contacts play an essential role during making operation and can increase the lifetime of the switch. However, there is still a probability of switch failure with main contacts after several making operations. With the main contacts, the arcing contacts were welded after seven making operations. Without the main contacts, welding was achieved after four making operations.

- The welding of arcing contacts is dependent on both arc energy and the degree of contact erosion that gradually occurs by repeated making operation.

Eroded surface of arcing contacts after making operation.

Dynamic Ratings in Overhead Power Lines

Student: **Jakob Strompdal**
Supervisor: **Erling Ildstad**

Problem description

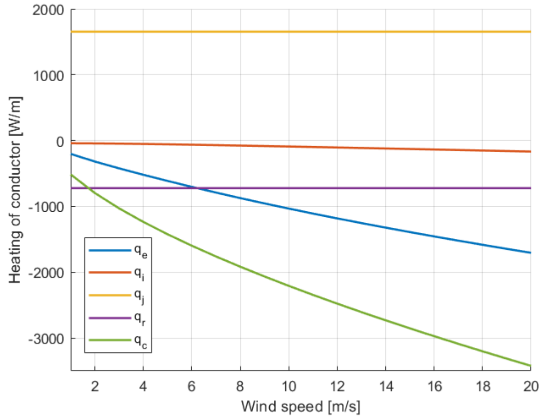
The demand for electrical energy is increasing all over the world. The complexity and variations in both production and consumption are also increasing due to more renewable energy sources. Because of this development, it is essential to utilize the capacity of existing power lines better. Earlier, static ratings have been the most common way to operate power lines. However, with new technology, it is easier to monitor and apply dynamic ratings based on real-time weather parameters. Dynamic rating is a potential solution to the development in the energy sector and the new challenges.

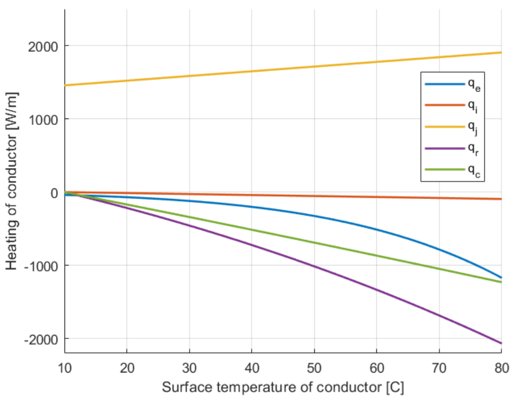
The task

This thesis consists of a literature review regarding already existing technology for measuring Dynamic ratings. The model recommended by CIGRE for calculating dynamic ratings have been investigated and has been further developed by implementing terms for evaporative cooling and impingement cooling based on other articles and standards. The main focus was to look into the correlation between a change in different weather parameters and evaporative cooling. The reason for this was to get a better understanding of the potential amount of cooling from evaporation and in which weather conditions and climate it can be reasonable to implement evaporative cooling in the model used to calculate dynamic ratings.

Model/ measurements

It was expected that evaporative cooling was highly dependent on the precipitation rate. In addition, the investigation of models recommended by CIGRE and IEEE showed that ambient temperature, conductor surface temperature, wind speed and air pressure also affect evaporative cooling. Results obtained from simulation showed that for a precipitation rate equal to 1, increasing wind speed from 1 to 20 m/s lead to an increase in evaporative cooling from 75 W/m to 1 368 W/m. Increased conductor surface temperature from 10 to 80 degrees lead to an increase in evaporative cooling from 24 W/m to 1 170 W/m. The change in ambient temperature did not affect the evaporative- or impingement cooling significantly. These results confirm that the implementation of evaporative cooling in the models used to calculate dynamic ratings for power lines can increase the potential current capacity significantly.





Conclusion

- The choice of monitoring device depends on the location of the power line being monitored. Conductors located in narrow corridors, due to vegetation or buildings, are more exposed to annealing, while for power lines in open areas, sag is often the limiting factor.
- Evaporative cooling and impingement cooling is often neglected from models used to calculate dynamic ratings. This is because it can be difficult to assess or because it is considered to have a low impact on the overall heating of the conductor.
- It is not only the precipitation rate that affects the evaporative cooling. Evaporative cooling is also affected by wind speed, conductor surface temperature, ambient temperature, and air pressure. The air pressure is almost constant, but variations in wind speed and temperatures are important when calculating the evaporative cooling on a conductor.
- It is a greater amount of evaporative cooling at high wind speeds and high conductor temperatures, while ambient temperature does not significantly impact the cooling from evaporation.
- Evaporative cooling has, more often than not, a lower contribution to the overall cooling than convective cooling and radiative cooling. Nevertheless, in certain weather conditions, evaporative cooling can be of importance for overall cooling.

Modelling Electrical Flexibility From Domestic Water Heaters

Student: **Ine Ingebrigtsen Svendsen**
Supervisor: **Jayaprakash Rajasekharan**

Problem description

Electric water heaters (EWHs) have gained a lot of attention in academic research because of their excellent thermal capacity, high rated power and fast response time, making them a great source of flexibility to provide grid services, such as load shifting and frequency control. Many researchers have looked into large populations of residential EWHs when studying the flexibility potential, leaving much to be studied on smaller populations, taking into consideration the discreteness of their behaviour.

The task

The objective of this master thesis is to explore the behaviour and estimate the flexibility potential of a small scale population of EWHs, both on an individual and aggregated level, by using different control strategies: activity and temperature control.

Model/ measurements

The method used can be divided into five parts:

1. The experiments were performed at the National Smart Grid Laboratory to obtain high frequency power and temperature measurements.
2. Parameter fitting of the TEC model, Extended TEC model and the stratification model.
3. Verification of the chosen EWH model.
4. Creating a population of EWHs.
5. Estimating the flexibility potential of the aggregated EWHs.

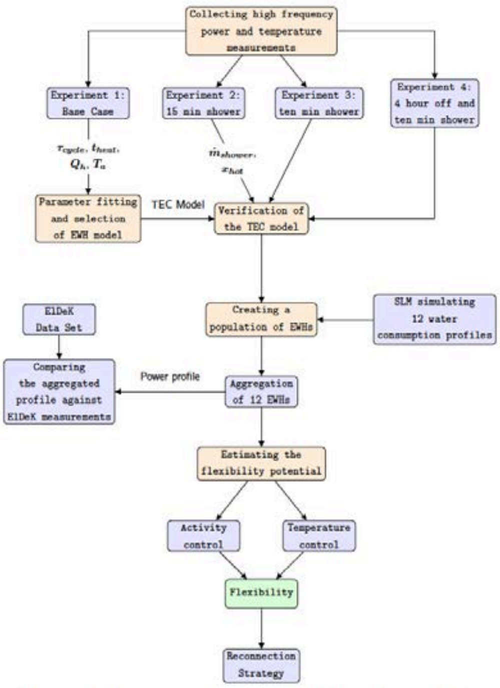


Figure 4.1: Overview of the System Model and Methodology

Calculation

The temperature control – scenario 1 managed to shift 7 kWh, with the use of a reconnection strategy, without causing a new instantaneous power peak that exceed the baseline power consumption.

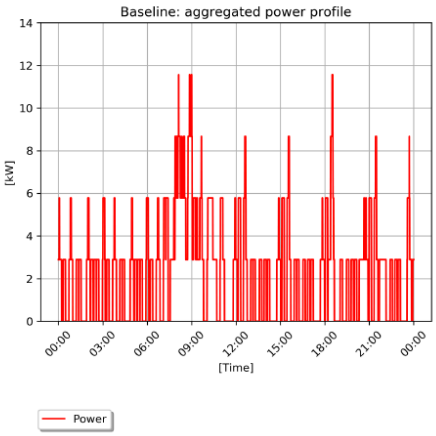


Figure 5.19: Baseline power profile of the 12 EWHs

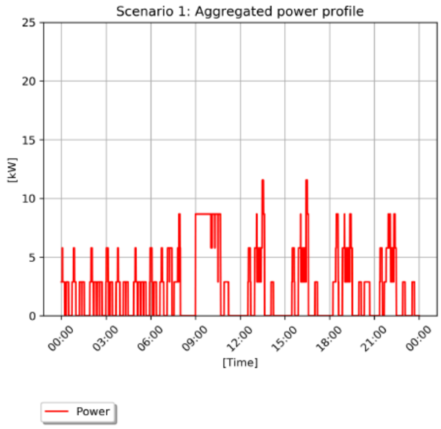


Figure 5.33: Temperature control - scenario 1, aggregated power profile

Conclusion

High frequency power and temperature measurements of an EWH at the National smart grid laboratory were used to create different models of an EWH. The simplest model was chosen to simulate the EWHs, since it matched well with the experiments done at the laboratory, with the temperature differing by at most 8%. The model was used together with a water consumption behaviour model to simulate a small population of EWHs, and the flexibility potential was estimated using two different controls techniques: activity and temperature control.

Despite the lack of Norwegian water consumption measurements, the simulated aggregated power profile performed very well with Swedish time-of-use data when comparing it to power measurements from EWHs in Norway. The same trend of morning and afternoon peaks could be observed, and the amplitude of the peaks matched reasonably well.

The aggregation of EWHs has a large potential for load shifting, and up to 7 kWh was successfully shifted to a later time without affecting consumer comfort. The results provide a detailed overview of both the behaviour and flexibility of the individual EWHs, as well as the aggregated flexibility. It is found that the reconnection of the EWHs is critical, and the proposed strategy for reconnection performed excellently by shifting all consumption during one hour without increasing the maximum instantaneous power consumption after reconnection.

The temperature control strategy is preferred over the activity control, since it can shift more energy and still cause smaller peaks in power consumption. In addition, this strategy is less sensitive to errors in predicted hot water usage.

Modeling Multi-Sectoral Decarbonization Scenarios for the Norwegian Energy System

Students: **Signy Weisz and Aksel Holbek Sørbye**
Supervisor: **Hossein Farahmand**
Co-supervisors: **Ingeborg Graabak** and **Sarah Schmidt**

Problem description

There is a pressing need to decarbonize the world's energy system to avoid the worst effects of climate change. However, developing reliable energy system models with results that can be used for decision-making in the energy transition is challenging. The H2020 openENTRANCE project aims to answer this challenge by developing and using a transparent modeling platform to assess decarbonization scenarios for Europe.

The task

The objective of the thesis is to analyze scenario-based energy system developments towards 2050 for Norway and the Norwegian bidding zones using GENeSYS-MOD with the four scenarios developed through the openENTRANCE project. These zones are useful to analyze because the power system is a dominating part of the Norwegian energy system, due to significant levels of electrification in the heating and transportation sectors. The thesis aims to answer the following research questions:

- Can the openENTRANCE implementation of GENeSYS-MOD be used to get useful insights about the future Norwegian energy system?
- Can the insights for the Norwegian energy system be improved by disaggregation?

Model/ measurements

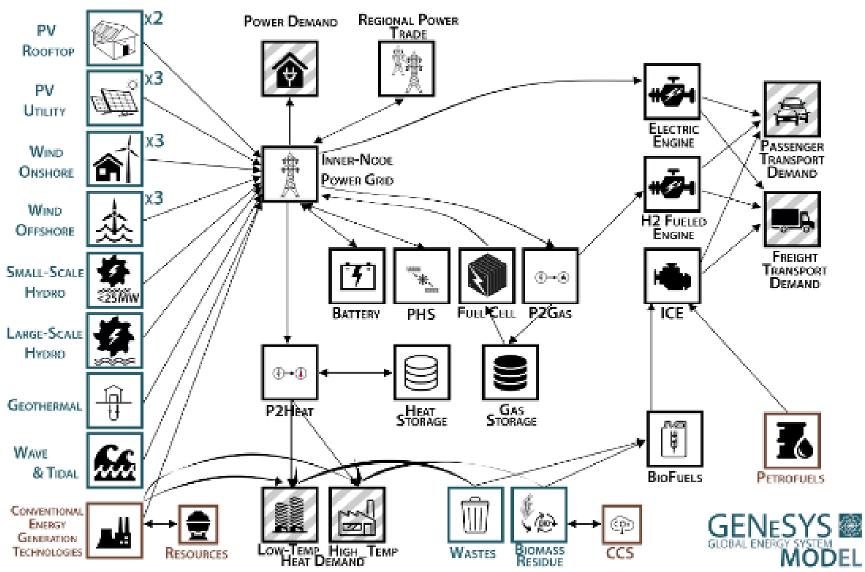


Figure 3.1: Model structure of GENeSYS-MOD v2.0 Source: [81]

GENeSYS-MOD is a linear, cost-minimizing, open-source energy system modeling framework which can model climate policy scenarios with a strong focus on sector coupling. To meet the exogenously set energy demands, the model provides the necessary capacities by calculating the optimal flows of energy carriers and services, illustrated in Figure 3.1. Four scenarios are modeled; three with a 1.5℃ global temperature increase limit (Directed

Transition, Techno-Friendly, and Societal Commitment) and one with a 2.0℃ limit (Gradual Development).

The research questions are answered by verifying the openENTRANCE implementation of GENeSYS-MOD, validating the Norwegian dataset, and implementing the dataset improvements in GENeSYS-MOD to gain a better representation of the Norwegian energy system. The Norwegian dataset is disaggregated into the five Norwegian bidding zones using available data and statistics.

Calculation

The results show significant levels of onshore wind and PV deployment in all scenarios. NO2, NO3, and NO4 show especially large increases in deployed capacities. The Gradual Development scenario shows significant offshore wind deployment in NO2.

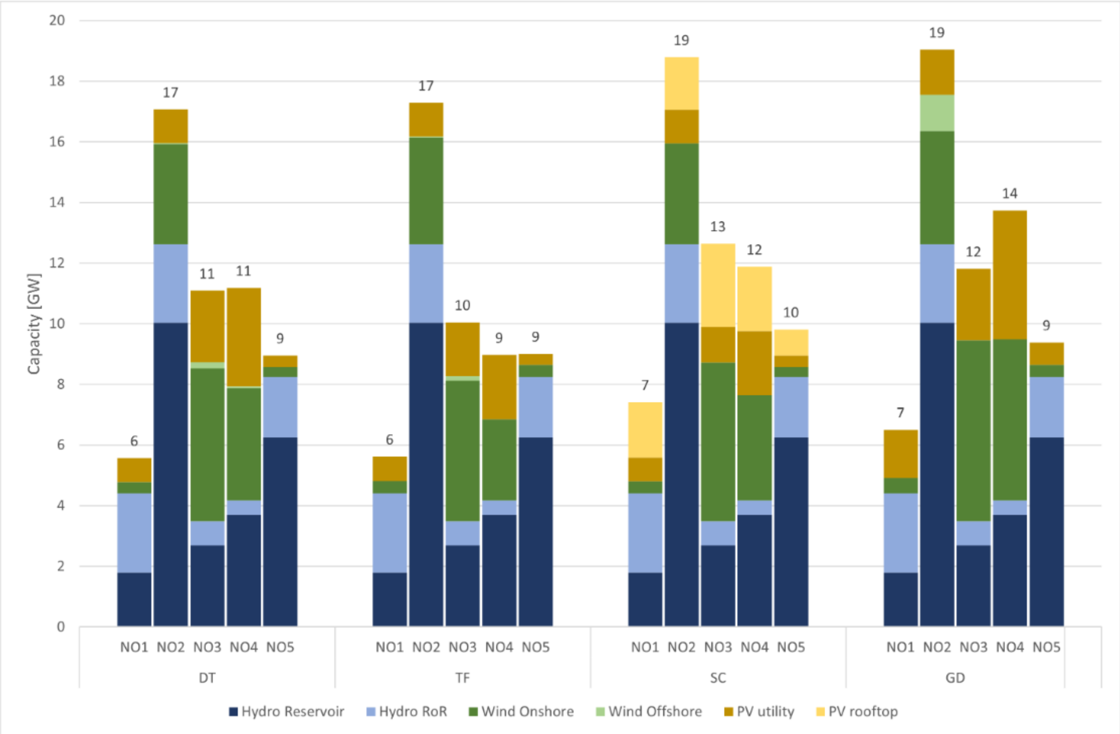


Figure 7.9: Regional 2050 power capacity in the disaggregated scenarios

Conclusion

The openENTRANCE implementation of GENeSYS-MOD can be used to get useful insights about the future Norwegian energy system. By improving the input dataset, modeled power productions and consumptions are now in line with statistical data for the base year. Insights include that it may be possible to cover the future power demand with onshore wind and PV, given that restrictions for onshore wind will cease and that new, power-intensive industries will not be commissioned.

The insights for the Norwegian energy system were improved by disaggregating Norway into the five bidding zones. Hydrogen showed to be an important energy carrier to decarbonize the transportation and industry sectors in all regions. In regions with low power production potential, such as NO1, it can be more profitable to import power for electrolysis than it is to import hydrogen produced in a different region. NO3 and NO4 show the potential to become important exporters of hydrogen to the Finnish and Swedish markets.

The Potential for Fuel Cells to Provide Electricity and Heat Supply in Norwegian Buildings

Student: **Even Glad Sørhaug**
Supervisor: **Steve Völler**

Problem description

The world will have to adapt considerable changes to stay below the 2-degree scenario goal of The Paris Climate Accord. Key among these changes will be the shift away from fossil fuels to more sustainable energy sources. To achieve this, hydrogen is often proposed as a central piece of the solution. Hydrogen technologies could play a major part in decarbonizing multiple sectors of the economy from industrial manufacturing to transportation and even energy production. Fuel cells convert hydrogen to electricity through an electrolyte membrane assembly and operates quietly, efficiently and with water vapor as the only exhaust. The potential for including fuel cells in the energy sector today is however limited by the relatively high investment and operational costs of hydrogen technologies compared to more mature alternatives. By utilizing the excess heat inherent in fuel cells during operation it could be possible to mitigate some of these costs and make them profitable to include as combined heat and power generators in Norwegian buildings.

The task

Energy use in buildings account for more than a third of the energy used in Norway. During this thesis the potential for utilizing hydrogen fuel cells to provide electricity and heat in Norwegian buildings were examined. This was done by providing an overview of the state of hydrogen technologies in Norway as well as in the rest of the world, presenting a theoretical foundation for fuel cell and energy system components, and creating an optimization model to examine the economic potential for the inclusion of fuel cells (FC) in a Norwegian energy system.

Model/ measurements

A mixed integer linear programming (MILP) problem was formulated to assess the techno-economic potential for FC combined heat and power (CHP) for different residential and non-residential buildings within Norway.

The FME ZEN pilot project of Campus Evenstad was used as a basis for the energy system optimization model developed during the course of the thesis. Campus Evenstad is equipped with PV and solar thermal collectors, a wood chip fuelled CHP unit, Li-ion battery, and was also given opportunity to invest in an FC-CHP. The objective was to minimize the annual cost of the energy system subject to various case definitions.

Calculation

The simulations were carried out on an hourly basis for periods lasting from one week to a year and included scenarios for investment in both the year 2020 and 2050 to account for the estimated cost reduction of hydrogen technologies. Several sensitivity analyses of system parameters like electricity and hydrogen cost were also examined.

Conclusion

From the research presented in the thesis it can be concluded that utilizing fuel cells to provide heat and power for buildings in Norway is not yet profitable, but could become so by the year 2050. By using green hydrogen from water electrolysis with a polymer electrolyte membrane FC-CHP it was found that the emissions from operation of the energy system was reduced by 61.9 % and the cost was reduced by 10.7 % compared to the base case scenario. In addition to the energy system at Campus Evenstad, six different building types were examined. Through these simulations it was found that apartment buildings, hospitals and nursing homes had the best potential cost reductions when investing in the FC-CHP with 18.9, 15.6 and 17.0 % respectively.

Based on the operation of the fuel cell unit found in the initial simulations, a periodic operation scheme of the FC-CHP unit was recommended to mitigate degradation caused by frequent start/stop-cycles during periods with lower thermal energy demand. By turning the FC off during the warmest months, June through September for the data used in this thesis, it was found that the number of start/stop-cycles were reduced from 219 to 39, potentially mitigating a permanent open-circuit voltage loss of 0.3 to 0.6 mV, which could in turn increase the lifetime of the fuel cell. By performing an LCOE analysis it was found that the price of hydrogen fuel would have to fall below 1.45 EUR/kgH2 for an FC-CHP to become profitable today. If the FC provides only electricity it would have to be as low as 1.11 EUR/kgH2. Both these critical hydrogen costs are unrealistic to achieve with the current state of hydrogen production. By accounting for estimated FC investment cost reduction towards 2050 it was however found that the critical hydrogen price increased by 20.1 % to 1.77 EUR/kgH2. This price of hydrogen is well within the expected range for green hydrogen production by the year 2050. To assess the potential for including FC-CHP in Norwegian buildings further the author recommends comparing the technology with suitable alternatives like heat pumps, batteries, and other forms of CHP. It would also be useful to quantify the benefits of combining fuel cells with water electrolysis and hydrogen storage for long-term energy storage, as well as the value of using them for peak shaving.

Artificial Intelligence-based Algorithm for Incipient Fault Diagnosis of Salient Pole Synchronous Generator using Multiple Sensor Fusion

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Collaboration with: **No-one**

Problem description
Develop a machine learning algorithm for detection of inter-turn short-circuit and static eccentricity based on measurements from a salient pole synchronous generator and sensor-fusion.

The task
This thesis examines the use of multi-sensor fusion in machine learning for the purpose of detecting inter-turn short-circuit (ITSC and static eccentricity (SE) faults in synchronous generators.

Model/ measurements
Measurements of stray magnetic field, vibration, stator current and stator voltage were extracted from a laboratory generator at NTNU. This generator is specifically designed to be representative of a typical hydropower generator. In addition, the generator can be imposed with faults, thus providing a foundation for the study of how various faults impacts hydropower generators. Measurements of 7 different faults under 6 different loads were extracted for the purpose of training and testing of the machine learning model. Sensor-fusion was performed in two scenarios: One with only stray flux and vibration, and one with stray flux, vibration, current and voltage. Features were extracted from the signals using FFT, DWT and Time Series Feature Extraction based on Scalable Hypothesis tests (TSFRESH). These features were filtered through Random Forest and TSFRESH. A wide arrange of classifiers were tested on task of predicting ITSC and SE. A hyperparameter grid-search was conducted to optimize the classifiers, and an ensemble classifier was constructed based on the highest performing classifiers. The laboratory setup is shown below.

Calculation
475 features were calculated through FFT, DWT and TSFRESH. The FFT and TSFRESH features paralleled in performance in the machine learning and outperformed that of the DWT features. The features were filtered by means of a Random Forest classifier and the TSFRESH algorithm for their relevance in classifying ITSC and SE. Random Forest filtered out a significantly higher number of features. The classifiers tested and trained on the dataset filtered through Random Forest consistently outperformed those trained on TSFRESH-filtered data. As such, Random Forest is preferred both due to performance of the classifiers and due to the dimensions of the feature space. A significant proportion of the features of highest importance for the logistic regression classifier were the FFT features of the stray field. This indicates a strong relationship between the frequency content of stray field and ITSC. Features from both stray field and vibration were among the most important features, indicating that sensor-fusion was beneficial in fault detection.

Conclusion
The idea of sensor fusion using current and voltage was discarded due to low amount of data. The classifiers that were tested on this dataset had an extreme sampling bias, which made the results highly questionable. Thus, the main results of the thesis are from sensor-fusion of stray magnetic field and vibration.

The proposed machine learning model for detection of faults was the Logistic regression classifier. This classifier was among the highest performing classifiers on all evaluation metrics and had an accuracy of 95% and a ROC AUC of 0.95 on the hold-out-data for detection of ITSC. This was an improvement of about 10% compared to a previous thesis with the same research question. It could not be concluded if this was a result of better data or sensor-fusion. However, it was found highly likely that sensor-fusion was a contributing factor in achieving a high performing classifier. The classifiers detected SE with a 100% accuracy, which was concluded to not be a factor of data leakage.

The generalizability of the algorithm to new domains was evaluated by testing the proposed algorithm on measurements obtained from industrial hydropower plants. The classifier detected ITSC with an accuracy of 100% and static eccentricity with and accuracy of 0%. This shows that the algorithm is able to detect ITSC across multiple generator topologies. Detection of static eccentricity relied heavily on the amplitude of the signals. The difference in amplitude of the generators were concluded to be the source of the bad performance.

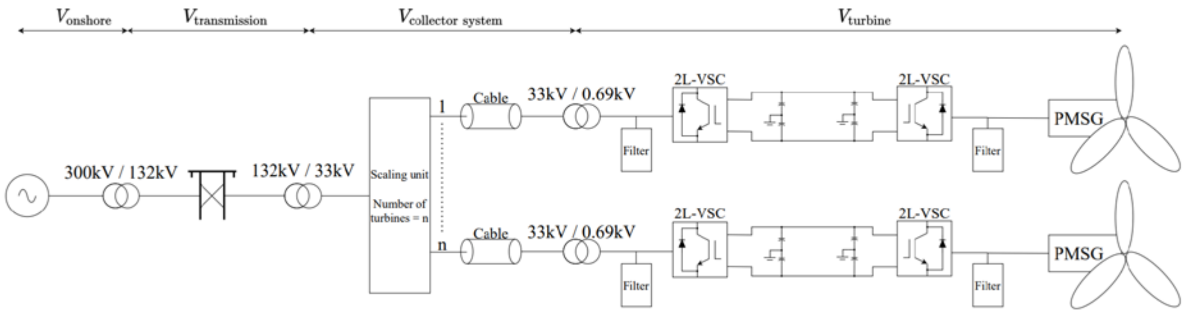
Harmonic Resonance Analysis of Offshore Wind Farm utilizing Type-IV Wind Turbines

Student: **Anders Teigmoen**
Supervisor: **Kjetil Uhlen**
Contact: **Kamran Sharifibadi**
Collaboration with: **Equinor**

Problem description
The dynamic between a lowered resonance frequency and increased number of power electronic devices may cause stability issues in weak AC grids, such as offshore collector grids. This lays the foundation for Harmonic Resonance Analysis, which can be used to investigate the impedance interaction between the installed converters and the grid. Although, a substantial challenge related to Harmonic Resonance Analysis is the need for impedance representations of the grid and converter. The control structure and parameter values of the converters affect its frequency response. Therefore, in order to get an accurate impedance model of the respective converters, full insight into the controller is necessary. Although, this is not disclosed information by the manufacturers of the converters due to intelligence property.

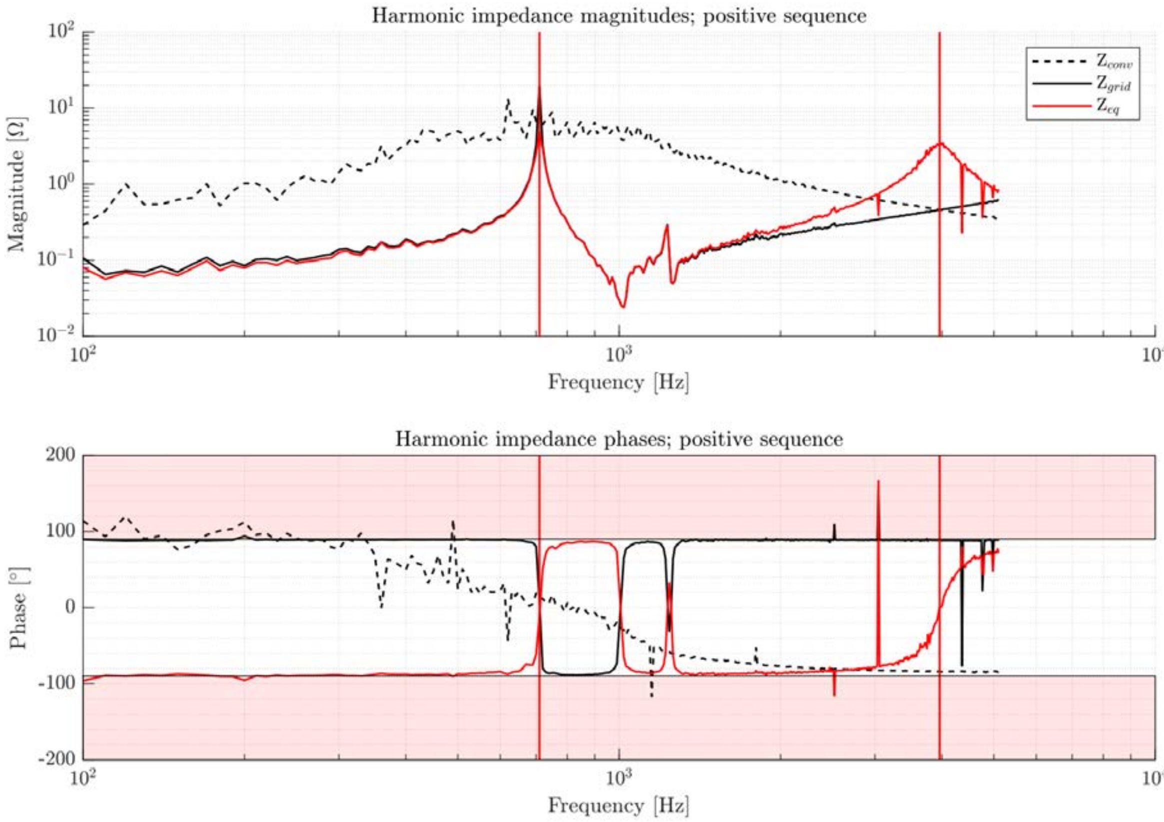
The task
The task of this thesis is to utilize a Harmonic Resonance Analysis technique to derive the frequency response of a type-4 wind turbine connected to an offshore wind farm. The technique applied is called the Current/Voltage Perturbation Technique, and enables the derivation of an impedance model without any knowledge of the controller structure or parameters.

Model/ measurements
An overview of the model is presented in the picture below. The wind farm is scalable in order to be able to present the effect of interarray networks of different sizes.



Calculation

Harmonic Resonance Analysis entails analyzing the interaction between the connected converter and the grid. The figure below depicts the converter-, grid- and equivalent impedances of a single-string OWF. the intersections between the converter- and grid impedances determine the parallel resonances of the equivalent impedance. The phase difference at the intersections determine the damping of the resonance, the closer the difference is to 180°, the less damping is present. The results reveal parallel resonances at 710 Hz and 3 960 Hz, highlighted by the red lines. The difference in phase angle at 710 Hz is 1.3°, while it is 178° at 3 960 Hz. As can be seen by the magnitudes, the system experiences more damping at the first resonance. However, for the resonance at 3 960 Hz, there is not much damping. Consequently, the equivalent resonance far exceeds the converter- and grid magnitudes. Additionally to the parallel resonances, there is one series resonance at 1 000 Hz.



Conclusion

It is found that the numerical method can be used to successfully determine the converter impedance. It is therefore a valuable tool for a system operator who rarely have full insight into the control parameters of the converters supplied to them by the manufacturers.

Dynamic Rating of power cables based on Analytical and Experimental methodology

Student: **Vaishnavy Thayalasingham**
Supervisor: **Erling Ildstad**

Abstract

Nowadays, the power companies show interest in maximizing the usage of cables due to constantly increasing energy demand and inconsistent power generation from the growing renewable energy resources, thus achieve optimal economy and reduce environmental impact. The ampacity of the cable is limited to the maximum thermal capacity of the conductor that is dependent on the heat generated by ohmic losses in the metallic layers of the cable. . Overloading the cable can overheat the insulation which accelerates its aging and thus reduces the successful service life of the cable and the stability of the transmission network operation. Therefore, it is important to study the rise of conductor temperature in other words thermal rating. As the static thermal rating is determined using the predicted worst-case conditions, the current carrying capacity of the cable can be improved by considering the transient thermal rating determined using the real-time measurements of current, temperature of cable surface and external environment conditions

The aim of this thesis is to analyze the transient temperature response of power cables to facilitate dynamic current rating. A literature review is conducted to provide an overview of the application of DTR followed by the inclusion of the theoretical background for the proposed approach of estimating the cable conductor temperature. Further, a calculative methodology is mentioned that describes the analytical method suggested based on the IEC standards for single-core and three-core cables. This method describes the appropriate thermal model which is used to calculate the conductor and screen temperature. The behaviour of transient temperature variation is investigated when varying current loads are applied to the power cables lifted from the floor (on air), placed on the floor, located in ducts/culvert and directly buried in soil.

An experimental methodology is presented that aims at measuring the transient temperature of the selected XLPE cables during varying current loads. A laboratory set up is established that measures the current applied and temperature at different layers of the chosen cables. This allows to compare and verify the measured results with the calculated results obtained from the analytical method It is found that the thermal resistance of the three core cable is comparatively low which allows it to carry more current for a longer period before thermally stressed. The external thermal resistance of the cable is found to reduce with the higher cable surface temperature. The results from the test with single-step current shows better estimated values compared to the measured results for rating temperature and for higher temperatures the deviation between simulated and measured temperature values is observed to increase with the temperature doubting the validity of the analytical approach for higher current. The analytical method based on IEC standard are computed upon many assumptions. The three core cable model was simplified by considering equivalent single-core cable which seems to be an unreliable approach to successfully estimate the conductor temperature for DTR application. Therefore, it is concluded that the improvements on the calculative method is essential for an accurate estimation of temperature response.

Small-Signal Stability Enhancement by Wide-Area Damping Control Using a Battery Energy Storage System Emphasizing Selection of Device Location and Controller Input Signal

Student: **Johannes Kalland Tjoland**
Supervisor: **Kjetil Uhlen**
Contact: **Hallvar Haugdal**

Problem description

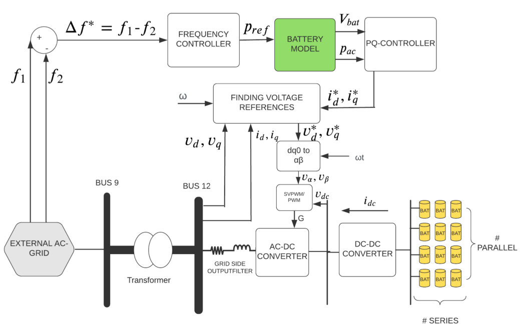
Power systems throughout the world are, to a more prominent extent, getting interconnected. Together with a higher share of renewable generation sources, this is causing stability issues in the grids. The amount of inter-area oscillations in power systems are increasing, which historically have been the cause for several blackouts. New measurement units such as synchrophasors/PMUs are improving situational awareness. These are essential for enabling wide-area measurement systems and wide-area damping control schemes for mitigating arising problems. Utilizing these measurements for controlling energy storage systems are promising solutions for damping inter-area oscillations.

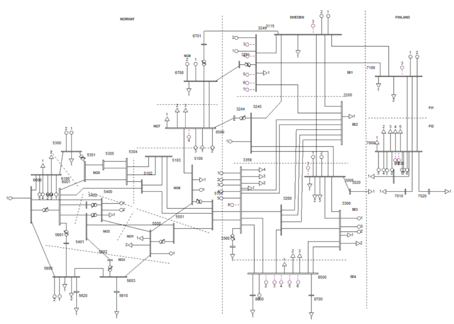
The task

In this thesis, a Battery Energy Storage System (BESS) model is developed and implemented in the Python Dynamic Power System Simulator (DynPSSimpy) developed by PhD student Hallvar Haugdal at the Norwegian University of Science and Technology.

The installed device's chosen control feedback signal and location considerably impact its performance and capability of providing power oscillation damping in the system. Using information about transfer function residues, observability, and controllability of a given mode, these can be selected optimally for providing the most extensive amount of damping in the pre-defined steady-state operation point of the system. In addition, the transfer function residues contain valuable information for appropriately determining the controller parameters. The performance and legitimacy of the method are through calculations and non-linear simulations in different versions of the Nordic 44 test network validated.

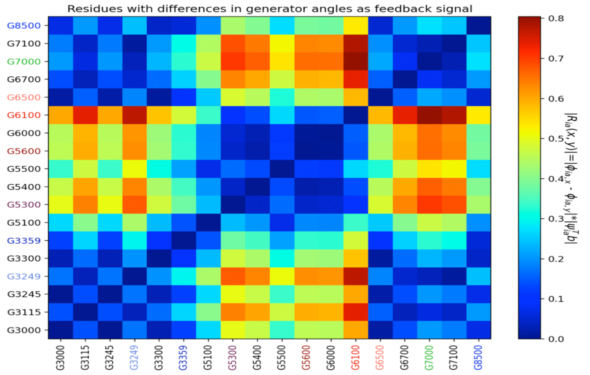
Model

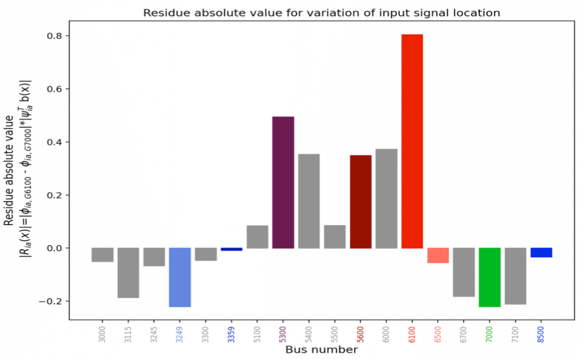




Calculation

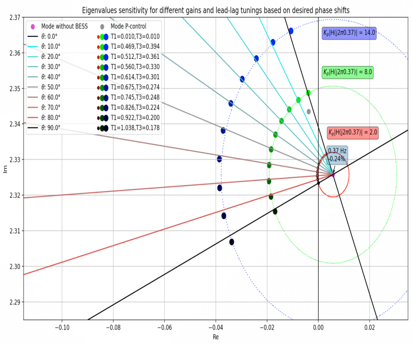
The following results are obtained for selecting the optimal controller input signal and BESS location, respectively, in the chosen version of the Nordic 44 test network for targeting additional damping of the poorest damped mode:

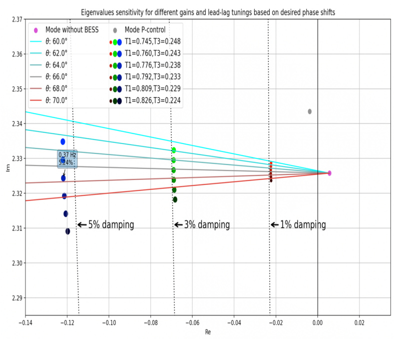


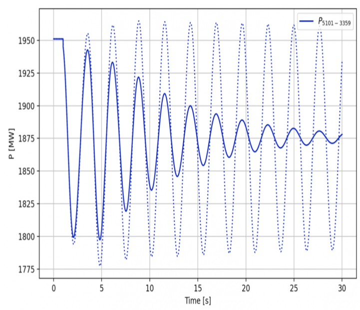


The results are further confirmed by performing the same procedure in other versions of the test network, and for targeting additional damping of other modes in the system, which serves for legitimating the selected method and the accuracy of it.

The BESS controller is then tuned to provide a left-wards shift in the complex plane for the mode of interest, targeting 5% damping which is deemed satisfactory for most systems.







When the controller signal and location of the BESS is selected, non-linear simulations (right figure) are carried out for validating the performance of the BESS and its corresponding control system. Dotted line in the Figure below shows the response of the system when the BESS is not included, and the solid line shows the response when the BESS is included.

Conclusion

Linear analysis is a valuable tool for selecting the feedback signal and BESS locations and proves beneficial for controller parameter tuning. However, the constantly chan- ging operating conditions of the systems and the power limitations of BESSs should be accounted for when employed for real-world applications. Further development and research are needed, but the potential benefits for systems operators utilizing avail- able phasor measurements and properties of the linearized power system as a tool for controller selection are evident.

Superconducting Multiphase Wind Power Generator

Student: **Tome Robles, Dany Josue**
Supervisor: **Nilssen, Robert**
Collaboration with: **TU Delft**

Abstract

An investigation into AC superconducting coils is performed with a permanent magnet generator for a wind power turbine of 15 MW. Two reference models are sized: on the one hand, a DTU and NREL 15 MW wind turbine model is taken as a reference to set the mechanical speed according to the output power and the mechanical constraints of the blades; and on the other hand, a 10 MW AC superconducting PM design by Dong Liu is taken as a reference to set the geometry and slot-pole combination, and resized the machine to 15 MW. Both reference models are fractional slot concentrated windings.
The aim is to study the effects of multi-phase symmetric windings on the AC HTS coils and the overall performance of a superconducting PM machine. Thus:
1) A comparison is made between 3-phase and 12-phase windings with the same machine geometry.
2) A design of a 24-phase winding is made to endorse the findings and comprehend the multi-phase symmetric windings and their advantages.
3) The AC superconducting losses are assessed for the different winding layouts with the same current and turns per coil, focusing on the behaviour of the magnetic fields into the HTS coils. The analysis found that multi-phase symmetric windings enhance the machine's magnetic behaviour by making it smoother and eliminating the space sub-harmonics. Furthermore, reducing the flux densities' rippling behaviour in the airgap and the iron causes a reduction in hysteresis and dynamic losses. Also, the better winding factor of multi-phase windings improves the output power, making the machine even more compact. Moreover, to achieve an excellent multi-phase symmetric winding layout, the phasors must be unique.

However, it is observed that using symmetric multi-phase windings cannot improve the AC losses and power factor. On the first hand, the hysteretic superconducting losses for HTS tape coils depend on the magnetic flux line's incident angle. On the other hand, the power factor strongly depends on the magnetic energy stored in the magnets, related to the volume and remanent flux density. Furthermore, it is found that having AC superconducting armature coils, the magnetic field repulsion creates a fluctuating behaviour in the airgap, affecting the tangential and radial forces in the machine. Therefore, a parametric sweeping is done to vary the HTS coil's angular position, finding that perpendicular flux lines to the coil's side reduce further the AC losses. Nonetheless, this creates more repulsion of magnetic fields, making a stronger fluctuating magnetic flux density in the airgap, producing higher radial forces that can harm the machine's structure.

A new design is proposed to improve the power factor and prove that having unique phasors into multi-phase symmetric winding layouts enhances the machine's performance. Finally, three main conclusions are made: 1) multi-phase symmetric windings enhance the machine's performance by using unique phasors, helping to reduce further the magnetic rippling behaviour. 2) AC hysteresis superconducting losses and the Meisner effect for HTS tapes firmly depend on the flux lines angle. Thus, a 3D coil must be designed and assess. Finally, 3) Superconducting machines with bulkier permanent magnets can achieve better power factors.

Grid Tariffs for Fast Charging Stations in the Norwegian Distribution Grid

Student: **Christian Fredrik Marquez Træland**
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Collaboration with: **FuChar, SINTEF Energy Research**

Problem description

Norway has become one of the global forerunners in e-mobility, having the largest fleet of electric vehicles (EVs) per capita for passenger use. Along with this, one has raised awareness of the potential impacts that mass-adoption of EVs can have on the Norwegian distribution grid. Although slow and semi-fast charging is considered to be the dominant way of charging EVs, it is also expected to be a growing need for public fast charging stations (FCS), especially between cities on highway corridors.

The task

An analytical method is developed to tune a proposed grid tariff structure that is suited for the development of FCSs in Norway. More specifically, it is done by means of both linear (LP) and quadratic optimisation (QP) problems solved in MATLAB. The proposed grid tariff structure is a capacity charge tariff with a capacity component billed on a daily basis. To prevent potential costly grid reinforcements, the grid tariff aims to give economic price incentives to the charging operator for investing in flexible resources. The flexible resources considered are energy storage system (ESS) and consumption flexibility. Load data for two representative FCSs in eastern Norway are investigated.

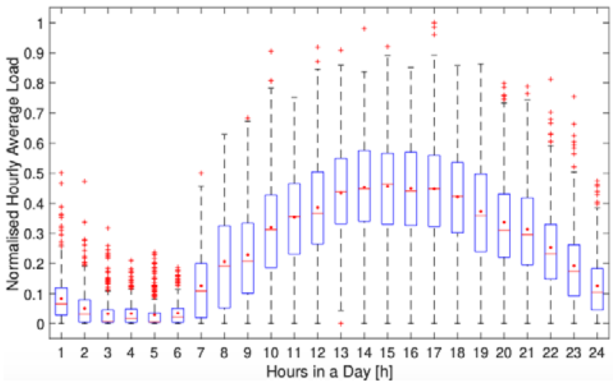


Figure 1: Normalised Boxplots of Daily Load for 2018 - FCS Highway

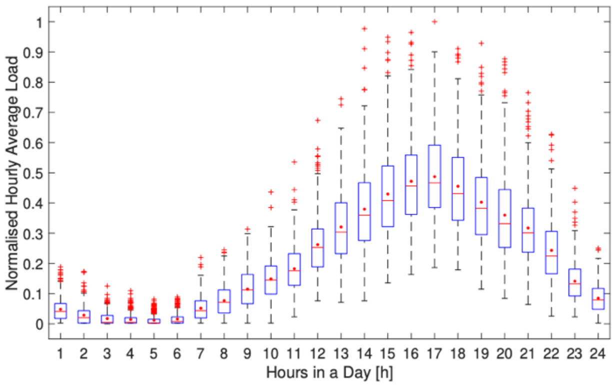


Figure 2: Normalised Boxplots of Daily Load for 2018 – FCS City

$$C_{CT} = \lambda_0 + \lambda_{en} \sum_{d=1}^{365} \sum_{t=1}^{24} D_{d,t} + \lambda_{cap} \sum_{d=1}^{365} \max\{D_{d,1}, \ldots, D_{d,24}\}$$

where,

C_{CT} : annual grid tariff costs in NOK/yr,
λ_0 : fixed annual component in NOK/yr,
λ_{en} : energy component in øre/kWh,
λ_{cap} : capacity component in highest peak-hour in øre/kWh,
$D_{d,t}$: energy demand for day d in hour t in kWh/h.

Figure 3: Proposed Grid Tariff Structure

Calculation

Overall, the results shows that the proposed grid tariff structure succeeds in giving economic incentives for a charging operator to enable flexible resources. Compared with the cost of electricity and the cost of energy component, the savings one can achieve on the capacity component is the primary economic incentive for implementing flexible resources. To determine if the investment in ESS can be economically viable, the investment cost is compared with the grid tariff cost alleviated by operating the ESS to reduce peak-loads. In addition, the EV users' ability to change their load pattern is investigated to see how much this impacts the charging operator's total costs. The results suggest that the EV users' actions can partly offset the need for an ESS, and reduce the charging operator's ESS investment costs.

The sensitivity analyses show that projected lower unit costs of lithium-ion batteries positively affect the economic viability. Moreover, it is shown how a daily billed capacity component can be economically advantageous for the FCS compared with a monthly capacity component. The EV users' ability to change their load pattern even more is also considered, where increased consumption flexibility leads to a diminishing need for an ESS. However, a larger ESS seems to have better performance in cutting grid tariff cost than the load shifting actions done by the EV users.

Conclusion

In conclusion of this master's thesis, it seems that grid tariff structures can be a good solution for enabling fast FCSs to invest in flexible resources. Together with other initiatives, this can pave the way for mass-adoption of electric passenger-cars and move Norway towards a carbon-neutral transport sector.

Recognizing snow on a solar module and melting it, prototyping and profitability

Student: **Thor Thinius Tuv**
Supervisor: **Steve Völler**
Collaboration with: **Norwegian University of Science and Technology**

Solar panels have the ability to provide renewable energy for a long amount of time, which makes them a good source of energy, now and in the future. The solar panel only generates energy when they are exposed to solar rays directly onto the solar cells. When the cells are covered by shade, snow or any other object, potential generated energy is lost. In this paper there will be focused on the removal of snow, in order to maximize the amount of renewable energy which can be extracted from the solar panels during the course of its lifetime. By removing the snow at strategic times, an extended period of sunlight before the next snowfall could generate energy otherwise squandered.

By coupling a solar panel to an external power source, the possibility of automatically removing the snow on top of the panel is explored. The removal of the snow is achieved by applying an external current into the panel. When this external current is large enough, some of the energy will turn into thermal energy, heat, in the cells of the solar panel. By heating the panel, the goal is to remove the snow as energy efficient and easy as possible.

Several different scenarios and solutions connected to these scenarios using this method has been mapped. The main motivation throughout the project were to improve the efficiency of the melting process, to reduce the costs. Throughout the project it was enjoyable to attempt finding energy saving solutions. The purpose of this paper is to expand the reader's knowledge on the possibilities of increasing the profits of a solar energy generation system, by removing snow.

In Table 16 the energy spent for each of the relevant trials are presented. The trials where the snow did not slide is not included. Each of the trials represent a different scenario with different parameters.

Parameters:	Energy spent [Wh]	Energy saved [Wh]	Efficiency increase [%]
[0±, 0°, $Notape$]	273,11	0	0
[0+, 20 °, No tape]	65,1	208,01	76 %
[0+, 32 °, No tape]	37,3	235,81	86 %
[0+, 44 °, No tape]	19,8	253,31	93 %
[0-, 20 °, Tape]	44,04	229,07	84 %
[0-, 32 °, Tape]	31,29	241,82	89 %
[0-, 44 °, Tape]	22,37	250,74	92 %
[0+, 20 °, Tape]	29,79	243,32	89 %
[0+, 32 °, Tape]	17,04	256,07	94 %
[0+, 44 °, Tape]	8,12	264,99	97 %

Table 16: Energy spent for each scenario on average, in contrast to the base case.

In Figure 48, the snow has slid off the panel, as an effect of the weight of the snow and the applied heating. Sliding the snow off in contrast to melting it all off can offer increased efficiency to the system.

Figure 48: 15% of the snow is still remaining after the initial avalanche.

From the results, the profitability analysis and the discussion, there is evident that there is much upside potential which can be exploited. Solar panels at geographical locations which are affected by snow, could increase their yearly up time by a small percentage due to snow removal. This percentage would correlate to how much effort is put into the sliding incentives. In any case where the parameters are in the system's favour, there is a very strong possibility of profit, given there is expected an extended period of sun.

Investigating the Effect of Eccentric Conductor Positions on a Rogowski Coil in Laboratory and Finite Element Method Simulations

Student: **Anders Ulfsnes**
Supervisor: **Irina Oleinikova**
Contact: **ulfan@outlook.com**
Collaboration with: **-**

Problem description
Changes in the power system structure create new possibilities and challenges in the protection and operation of the grid. Digital substations are emerging, but these installations are not done overnight, and hence the transitions require new thinking in terms of interoperability in protection applications. The Rogowski coil (CT) is a current sensor which offers benefits in protection schemes. Preeminently that the air core does not saturate, compared to conventional iron core current transformers (CTs). But challenges limit its current applications. It is affected by several influencing quantities and in differential protection schemes this can cause malfunctioning.

The task
The goal of the work is to test the accuracy of a RC in an appropriate test rig and build a finite element method (FEM) model to simulate the RC. This model is to work as a basis for the future development of compensating techniques. Compensating techniques utilizes sensors to obtain parameter changes in the RC configuration, and applies digital compensation of the signal to increase the accuracy. For example, by using hall effect sensors to determine the conductor position. The model can be used to investigate how different parameters influence the signal, and to determine valid compensating techniques. The possibilities for such a FEM model are endless, at the cost of computational power. Because of the geometry of the RC 3D models must be used, which quickly increases the complexity of these simulations compared to the 2D counterparts. Such models are however valuable as it offers benefits for future research into the topic. The research on protection applications can benefit from this work because a compensated RC might be able to work interoperable with a conventional CT in a differential scheme. This benefits the digital substations as upgrades can be done gradually.

Model/ measurements
The test rig allows for adjustments of the conductor position inside the window of the RC. The FEM model is built in COMSOL Multiphysics and are tested with different configurations and conductor positions.

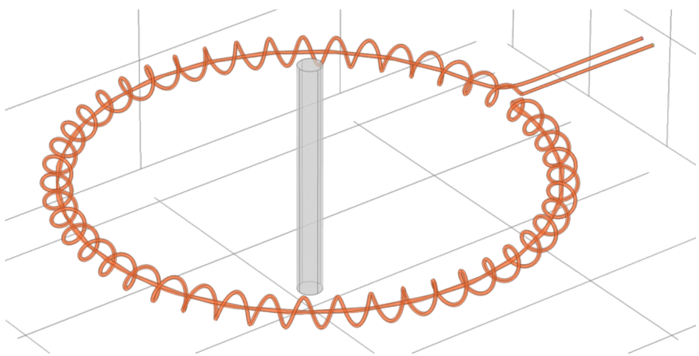


Figure 1: COMSOL RC model with 48 turns. The RC is shown in orange and the conductor is positioned in the centered position

Calculation
The measurement accuracy of a RC is tested in the setup. The conductor position is adjusted to investigate the effect on the output. The overall accuracy is about 1.6% error in the centered position. The accuracy changes up to 0.25 percentage points with the eccentric configuration. The RC output varies based on where the conductor is located, but trends in how conductor adjustments affect the error is not obvious.

The model is tested with several configurations and parameter changes. Initial tests with 16 turns result in composite errors with a magnitude which is a lot higher than what is achieved in the laboratory tests. To investigate how randomness in the winding distribution affects the output, an inhomogeneous winding distribution is used. The resulting output is only slightly changed compared to the homogeneous test. With 48 homogeneously distributed turns the error resembles the values achieved in the lab, but with clear patterns related to how the conductor adjustments affects the error.

Conclusion

- A laboratory setup is designed, and a commercial RC is tested under various conductor positions. The resulting output is difficult to evaluate due to lack of clear trends. The overall error in the RC is 1.6\% and varies with up to 0.25 percentage points when the conductor position is adjusted off-center.
- A FEM model of a RC is created. The model is simulated for different parameters to verify the integrity of the model. Simulations are performed for eccentric conductor positions in three configurations: low number of turns, low number of inhomogeneously distributed turns and high number of turns. Low number of turns results in high errors, and the inhomogeneous winding distribution does not randomize the output similarly the laboratory tests. The high number of turns results in low errors, equal the magnitudes in the laboratory tests, and clear trends.
- The laboratory results are hard to evaluate but emphasizes the need for compensation for the RC. The laboratory results are also important for verifying the simulation model. The laboratory setup and the equipment are not sufficient to achieve the appropriate results.
- The FEM model is a suitable method to simulate the RC in a complex environment with possibilities for adjustments and extensions. The FEM model can be extended to include integrators and compensation techniques and can hence be used to test these solutions in a controlled environment without need for extensive laboratory tests.
- Use of the model for research on the RC can improve the accuracy of the RC significantly by implementing compensation techniques and hence make it more appealing in interoperable differential protection schemes and reliable SPS operation.

Parallel Operation of Synchronous Generators in a DC Grid

Student: **Tomas Skaar Vadset**
Supervisor: **Mohammad Amin**
Contact: **Ulrik Havnsund**
Collaboration with: **Vard Elektro AS**

Problem description

In recent years, the usage of DC grids on board ships have become more common. DC grids have progressed from mostly being used for smaller boats to becoming a viable solution for larger marine vessels as well. The reasons for this viability, depend on what type of ship the DC grid is used for. It is chosen for ferries because it is more cost efficient than an AC grid and it can also be made into a hybrid system by using energy storage such as batteries. Offshore support vessels use DC grids because of the high fault tolerance, along with the previously mentioned benefits. Another advantage with DC grid is the opportunity to operate the engines with variable speed. When the system can operate the engines at different speeds, it is important that the stability for the system is kept.

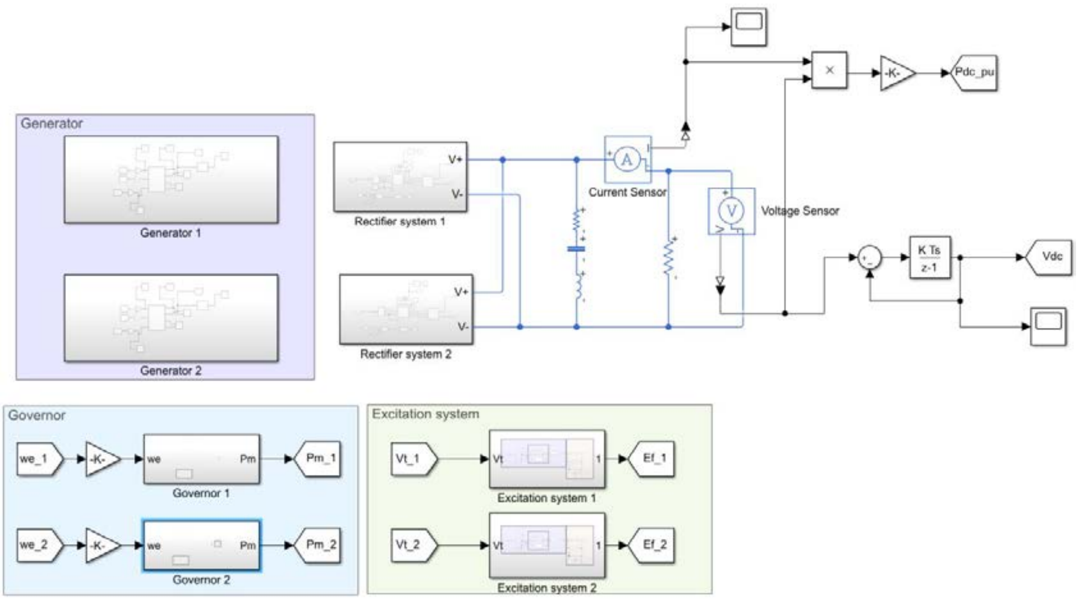
The task

In this master's thesis, the parallel operation of two generators in a DC grid will be investigated. An analytical model is created in Simulink and is used as the main simulation model. The main tasks for the project are:

- Create a simulation for a model consisting of two synchronous generators with control systems in a DC grid
- Implement droop control in the control system for the generator
- Implement a variable speed operation
- Simulate droop control and variable speed control separate and together
- Examine the simulation results and observe how the different components work separately and together
- Create a detailed model which can be used to verify some cases
- Create a linear model which can be used for stability analysis

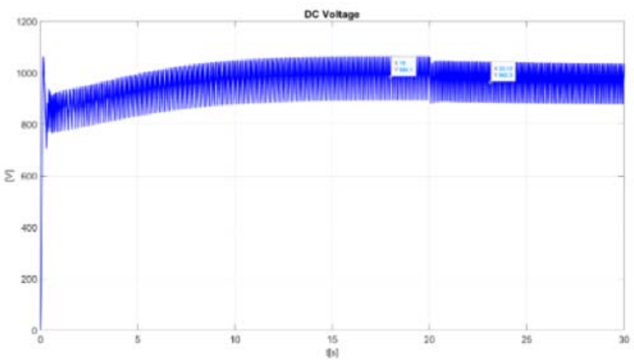
Model/ measurements

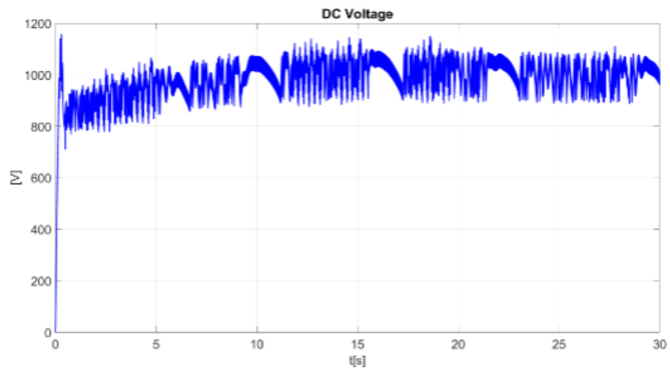
The main simulation model used in this project is an analytical model created in Simulink. This model consists of two synchronous generators, two diode rectifiers, two excitation system, two governors and a constant voltage load. For the excitation system, the AC8B type is used. For the governor, a PI controller is used and is later changed to a governor block from Simscape Electrical. The model starts of with normal parallel operation where both generators operate at a fixes speed and supply the same power. Then the droop control is implemented for both generators. Using droop control allows the generators to supply different amount of power to the load. Variable speed control is also implemented for the governor and when both the droop control and variable speed control works separately, they are simulated together to examine how the system behaves. The total system for the analytical model can be seen in the figure below.



Calculation

The two figures below are two of the results from the simulations. The right figure shows the DC voltage for the system when there is droop control and variable speed operation, and the governor has a PI controller. The left figure is the same case, but the governor is switched with a governor which does not have a PI controller.





Conclusion

By implementing variable speed operation, it is possible for the generators to operate more fuel efficiently. The analytical model had similar results as the detailed model during normal parallel operation. The droop control and variable speed operation worked separately, but when combined, the system became unstable. By some testing, it was discovered that the system behaved better when the governor with a PI controller was switched with a governor without a PI controller. This shows that PI and PID controller will affect the stability of the system when using variable speed operation with droop controller. The linear model created for the system shows that the system is unstable when it is not, and needs further improvements.

Analysis of Interdependence in Electrical Distribution Power Systems and corresponding Information and Communications Technology Systems using Monte Carlo Simulations

Student: **Matias Vistnes**
Supervisor: **Olav B. Fosso**
Co-supervisor: **Stine F. Myhre**

Problem description

Industrialised countries are experiencing an increased electrical consumption with the extensive electrification of, e.g., industry and transport and the changing consumption patterns at the end-users. Further increased electrification is also a response to climate challenges. This shift leads to a higher dependency on the continuous supply of electric power from the power systems, and in most cases, higher system utilisation and operation closer to the limits. Increased operation costs and significant investments in infrastructure development is needed to increase the power system`s reliability in such a setting. New Information and Communications Technologies (ICTs) could help lower costs and improve the system`s reliability through better monitoring and automated solutions. Since high reliability is the target, the behaviour and interdependencies with the existing power system need to be assessed.

The task

In this project, a Monte Carlo Simulation (MCS) tool was developed to increase the understanding of the consequences on the reliability of a distribution system when new ICT equipment is integrated into the power system.

Model

Physical and cyber interdependencies, with cascading failures, were the focus when implementing the modelling tool. The flow of the MCS is shown in Figure 1. Several cases were simulated using the MCS on the IEEE 69 bus test system. Each case changes one or more essential factors in the simulation, including; ICT components in the system, backup lines as a remedial action after a failure, and changes in failure rate or repair time of a component. The cases were discussed using both basic (Failure rate, unavailability, average failure duration, and Energy Not Supplied (ENS)) and aggregated reliability indices.

Results and Conclusion

In general, the power system with ICT was more reliable than the power system without ICT. Examples of the higher reliability is shown in Figure 2 and Figure 3. The sectioning time until a system failure is isolated plays a crucial role in the system`s reliability. The results may indicate that the reliability increases more with the introduction of ICT to have a quick sectioning time than having backup lines connected during failure in this power system. The scenario with ICT is sensitive towards line repair time, as well as transformer failure rate and repair time. In addition, the ICT components (i.e. Disconnector, Communication Hub, and Communication Line) show some impact on the model indices, but generally much less than the contribution of lines and transformers on system failure rate.

From simulations where different factors in the system were changed, Figure 4, it is reasonable to conclude that the power system model corresponds well with the predicted behaviour of a real-world power system. It is more difficult to conclude if the ICT system behaviour is realistic, as there is limited research on the topic. Nevertheless, one could predict

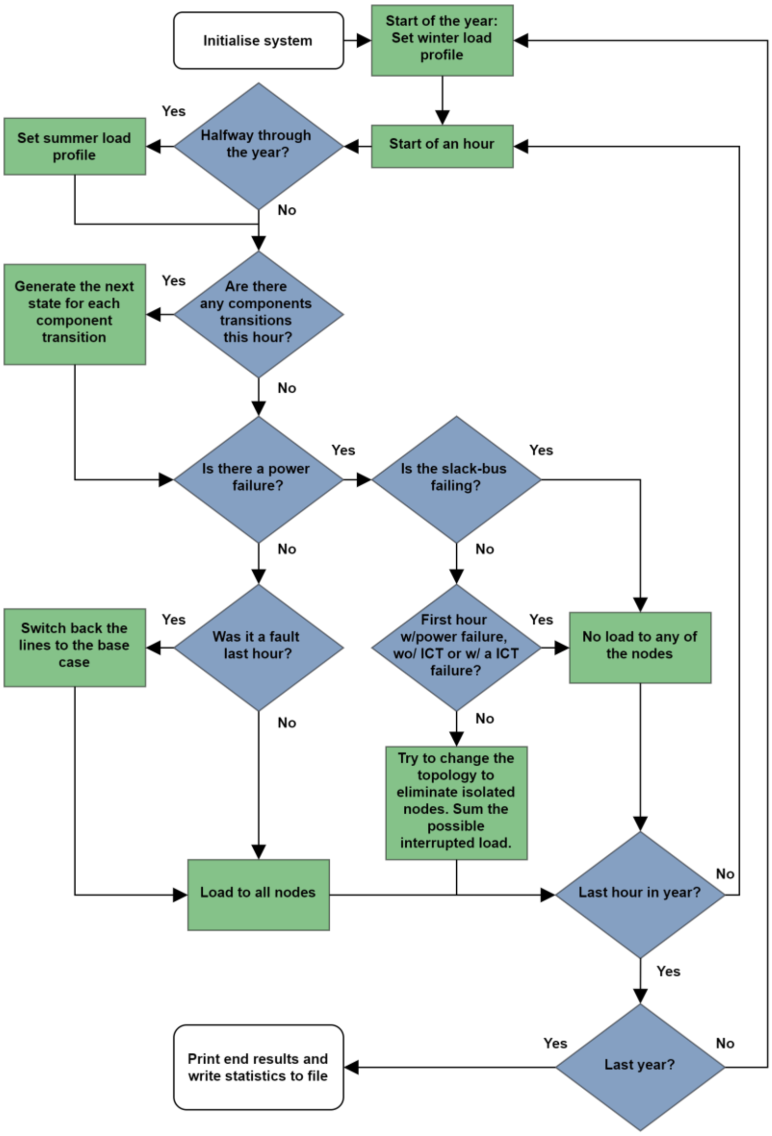


Figure 1: MCS flowchart

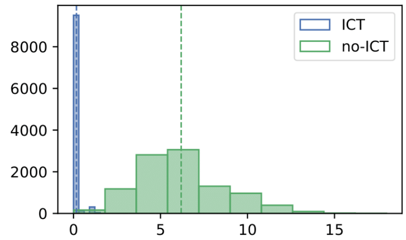


Figure 2: System Average Interruption Frequency index (SAIFI) histogram. The y-axis is the count of years inside the width of the bar.

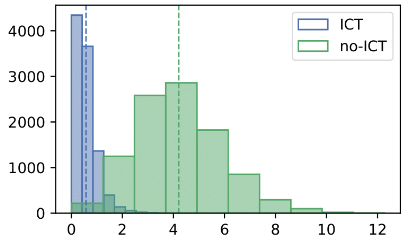


Figure 3: Average Energy Not Supplied (AENS) histogram. The y-axis is the count of years inside the width of the bar.

that the general increase in reliability observed in the simulations using an ICT system could occur. The conclusion is still uncertain, as the failure rate for the ICT components is questionable. However, an increase in the failure rate of the communication hubs showed a decrease in the system reliability, thus indicating their importance to reliability.

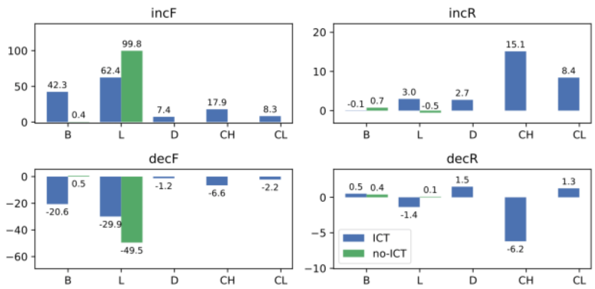


Figure 4a: SAIFI

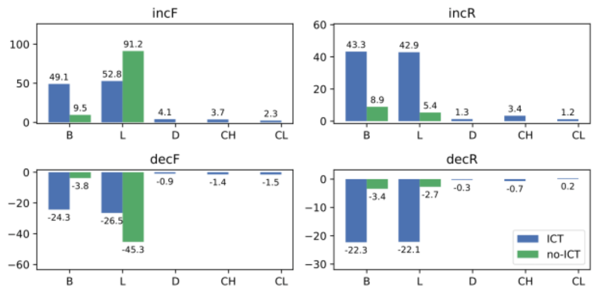


Figure 4b: AENS

Figure 4: Factorial experiment change from base case in percent. Bus (B), Line (L), Disconnector (D), Communication Hub (CH), and Communication Line (CL). Increase in failures (incF), decrease in failures (decF), increase in repair time (incR), and decrease in repair time (decR).

Partial Discharges at HVDC stress

Student: **Georg Volden**
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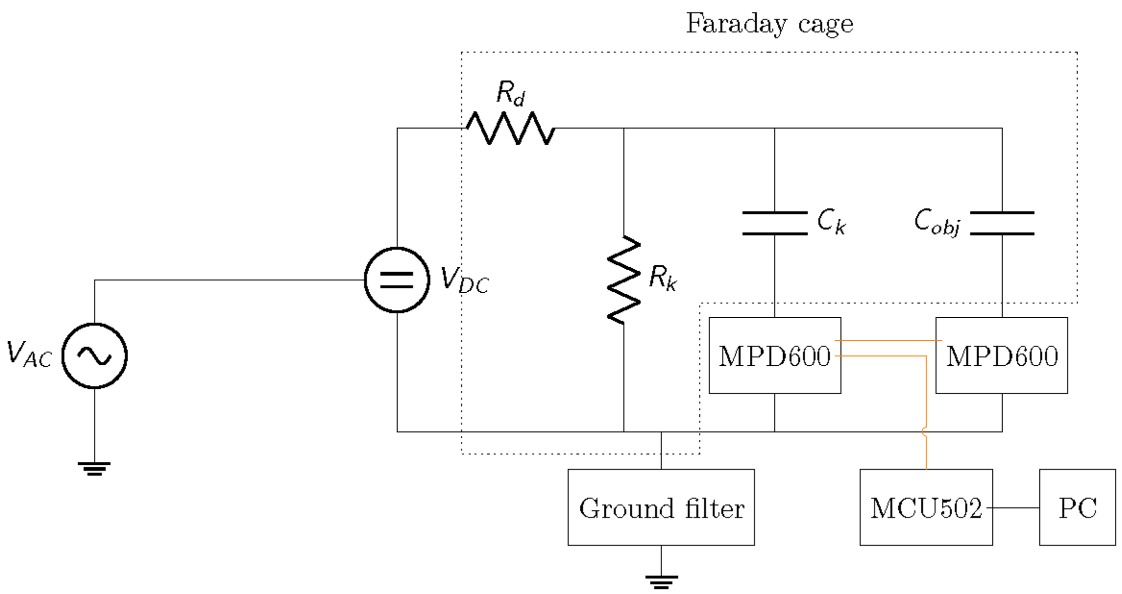
Co-supervisor: **Pål Keim Olsen**

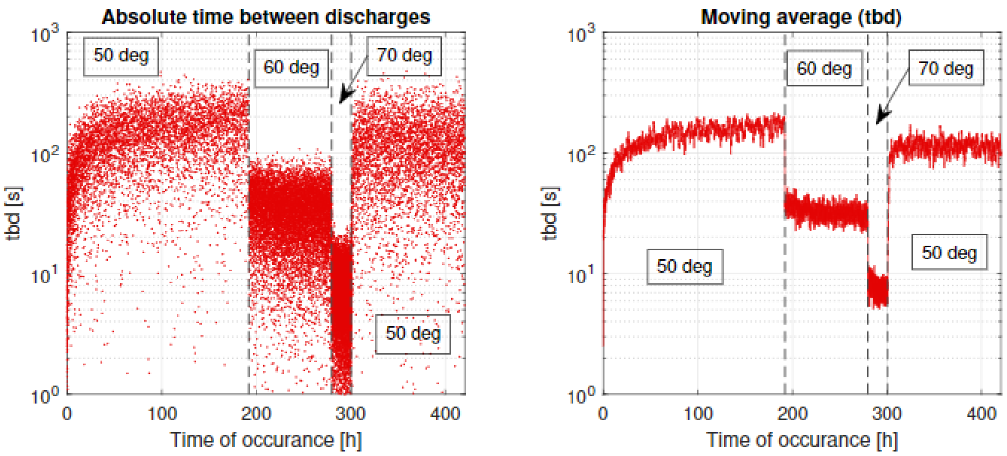
Problem description
To interconnect power grids across the North Sea is a necessity to balance a European power grid with large penetration of renewables. The connection is done by high voltage direct current power cables, that could be cheaper and better with the use of polymeric insulation. Extruded polymer cables have internal cavities in the insulation, filled with air and gasses from the production, that are subject to degradation from partial discharges.

The task
To investigate this phenomenon, that is little researched, partial discharges in cavities in PET and HDPE were measured at a range of temperatures and test voltages that affects the time between discharges and discharge magnitude.

Model/ measurements
The test circuit is a straight circuit for partial discharge measurement. The DC source is a ultra-stable source, as opposed to other's experimental setups, that not necessarily have used ripple free sources. In the experiments, the PD detectors, Omicron MPD600, were connected in both branches. Each detector has a limited range and accuracy, so the pair of them was calibrated at different magnitudes. The detector in series with the test object is the most sensitive one and was therefore calibrated at5 pC to detect the smaller discharges, while the detector in series with the coupling capacitance was calibrated to50 pC to detect the discharges of higher magnitude. The detectors are connected in series with an optical cable and forth to a fiber optic bus controller, MCU502.



Results



(a) Absolute time between discharges. (b) Moving average time between discharges.

Figure 4.19: Absolute and moving average time between discharges for a 10 kV measurement series with periods of 50 °C, 60 °C, 70 °C and 50 °C respectively.

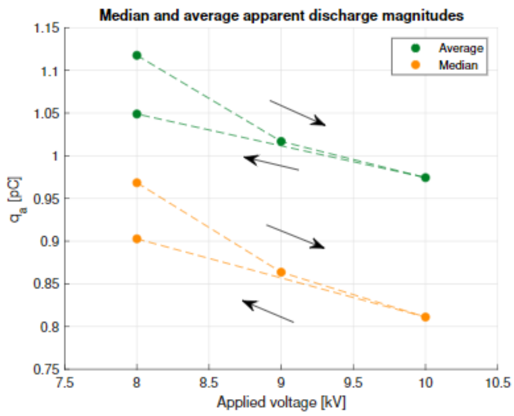


Figure 4.27: Averages and medians for each measurement period of 75 °C measurement series with test voltages of 8 kV, 9 kV, 10 kV and 8 kV respectively. Note that the median and average is lower in the last period of 8 kV than in the first.

Conclusion

The effect of field first and foremost is an impact on the time between discharges. The median apparent discharge magnitude is according to others not much affected, but the Townsend coefficient does depend on the applied field.

The effect of temperature is mainly on the time between discharges due to the increased conductivity in the insulation material and that the increased temperature increases the start electron generation rate. In one of the measurements at 10 kV, the average time between discharges was 125.199 s at 50°C, 32.787 s at 60°C, 7.504 s at 70°C and 105.899 s when the temperature was adjusted back down to 50°C.

Degradation after increased temperature is measurable. The two test series with effect of temperature show different result: The first one show an increase in both apparent discharge magnitude and time between discharges, while the other shows the opposite. The latter seems like the most reliable result, but it may be that the test sample can be affected in different ways. In the first series with the largest discharge magnitudes, the discharges were much fewer than in the second. Either way, avoiding overloading of cables and other components using extruded insulation would be beneficial for minimizing PD activity and increasing the service lifetime.

Digital tvilling for storskala demonstrasjonsprosjekt vedrørende intelligente distribusjonsnett

Student: **Sofie Morud Vågen**
Faglærer: **Kjell Sand**
Veileder: **Kjell Sand**
Utføres i samarbeid med: **Elvia AS**

Masteroppgaven er skrevet i tilknytning til forskningsprosjektet "Intelligent distribusjon av elektrisitet" (IDE), der nye teknologier demonstreres som alternativ til tradisjonell nettforsterkning i distribusjonsnett med spenningskvalitetsproblemer. Målet med denne masteroppgaven er å utvikle en digital tvilling som simulerer tilstanden i nettet så nøyaktig som mulig, og dermed kan benyttes til å identifisere brudd på Forskrift om Leveringskvalitet (FoL).

Som følge av utrullingen av AMS-målere for alle norske strømkunder, åpnes det nye muligheter for å anskaffe og anvende informasjon om den elektriske tilstanden i lavspentnettet. Dette kan blant annet være nyttig for å identifisere brudd på FoL i nett med spenningskvalitetsproblemer. For å best mulig gjenspeile de usymmetriske forholdene som kan oppstå i svake nett, er det behov for en digital tvilling som benytter AMS-data og usymmetriske lastflytberegninger som verktøy.

I forbindelse med arbeidet med utvikling av en usymmetrisk lastflytmodell som benytter AMS-data, oppstår en utfordring knyttet til estimering av ukjente verdier. Informasjon om sammenhengen mellom lastenes fasetilknytning i nettet og fordelingen av last mellom fasene er ikke tilgjengelig fra AMS. Denne rapporten har derfor to del-leveranser som er sentrale for å realisere en digital elektrisk tvilling som kan simulere usymmetriske forhold i distribusjonsnettet:

- En digital tvilling som benytter AMS-data og usymmetriske lastflytberegninger er implementert i Python. Herunder er det implementert en metode for estimering av lastfordeling mellom fasene, ettersom kun sum last er tilgjengelig fra AMS-målere. Tvillingen er testet på et case-område med spenningskvalitetsproblemer.

- Ulike metoder for identifisering av faserekkefølge basert på AMS-data er implementert og testet på et datasett. Metoder basert på PCA og k-means clustering er implementert i Python og kan benyttes som verktøy for å estimere faserekkefølgen i et nett ut ifra tidsserier av spenningsverdier fra AMS.

To av metodene for faseidentifisering gir tilnærmet identiske faserekkefølger. Resultatene av lastflytanalyser med disse faserekkefølgene er også tilnærmet identiske for demo-caset, med kun 0,9 V avvik mellom simulerte og målte linjespenninger i den svakeste delen av nettet. Gitt forutsetningene og begrensningene i datagrunnlaget fra AMS, gir den etablerte digitale tvillingen en god nok representasjon av de fysiske forholdene i caset. Den kan derfor være et nyttig verktøy for simuleringer av virkningen av ny teknologi i demo-kretsene i IDE-prosjektet som et supplement til reelle tester.

Long-term Peak Power and Energy Forecasting in Norwegian Electricity Grids

Student: **Wang, Jacob**
Supervisor: **Uhlen, Kjetil**

Abstract

The electric power industry is in these times experiencing major changes and rapid development within many technological areas. The introduction of green technologies and more digital solutions lays the foundation for new opportunities for producers, consumers and everything in between. This thesis treats the challenges facing a particular intermediate level, namely the grid owners. The grid owners are making considerable investments in new electrical infrastructure to ensure future security of supply, but are facing great challenges because of the named development in technology. Because of this there is an increased demand for tools that enable better understanding of future conditions in the electricity grid. The main tool used for this is forecasting, the process of making predictions based on past and newer data, as well as including relevant trend analyses. This type of work is taking place at all DSOs participating in the Norwegian grid. However, there is little or no framework or guidelines for them to follow.

This thesis dealt with this particular issue seen from a Norwegian DSO perspective and aimed to present an overview of all the most important aspects relevant to DSO forecasters. It also suggested a new methodology for future use. The source material of this topic has been very limited. Nevertheless, examples from various articles, both practical and theoretical in form was reviewed to find relevancy for the Norwegian system. The suggested methodology in this thesis was partly based on this literature review and partly based on ideas from a field known as "Futures and Foresight Science". The main takeaways of the study is the discussions themselves about the complexity and the greatest challenges of the task, as well as ways to combat these. The main challenges are the lack of flexibility in the methodology, lack of industry standards and lack of available data. Firstly, the thesis argues that these threats can be combated by an increased level of cooperation and a common framework for them to relate to. A common software and framework will automatically generate professional environments and forums for experience and knowledge exchange. Secondly, the thesis offers framework that can be further built upon. It is believed that these two measures are enough to significantly improve forecasting accuracy as well as give forecasters more belief in own work because of proper documentation and sufficient scientific justification.

Predicting Domestic Hot Water Consumption in Buildings in Norway Using Machine Learning

Student: **Henrik Waterloo**
Supervisor: **Karen Byskov Lindberg**
Contact: **Karen Byskov Lindberg**
Collaboration with: **SINTEF Community, FME ZEN**

Problem description

Moving towards zero emission buildings, energy can be managed in a flexible way, to achieve i.a. reduced power peaks, reduced energy use, reduced CO2-emissions, increased self-consumption of locally produced energy, or provide flexibility services to distribution system operators (DSOs). This thesis will investigate the potential for intelligent energy management in households, using data gathered from different sources, i.e. Varmtvann2020 and ElDek/Useload. The thesis will compare the different data sources, and improve or establish a new model that can replicate the measured load data (i.e. predicting the load). 31% of electricity use in Norway is consumed in households. The student shall discuss which flexibility services households could provide, and the potential for flexibility that households may provide. The student will do a literature review of other load prediction models and compare measured load data on domestic hot water (DHW) from different research projects. The Master thesis will establish an improved or new statistical model for load prediction, and possibly also try to estimate the flexibility potential of the domestic hot water load.

The task

This thesis explores how machine learning techniques can be used for medium-term domestic hot water load prediction. A total of six models have been trained, fitted and validated with DHW consumption data from the Varmtvann2030 data set. The data set contains consumption data for 4 apartment buildings, 4 hotels and 4 nursing homes. The six models are the sum of Prophet and XGBoost models for each building type. The XGBoost model is a mathematical optimization process that uses regression tree gradient boosting to minimize the prediction error. The Prophet model is an additive model consisting of a trend component, a Fourier series to fit seasonality in the data, and a holiday component to adjust for holidays. The theory behind the two models is thoroughly explained in this thesis. Predictions on unseen test data are performed for all six models, and the results are displayed and compared for the three building categories.

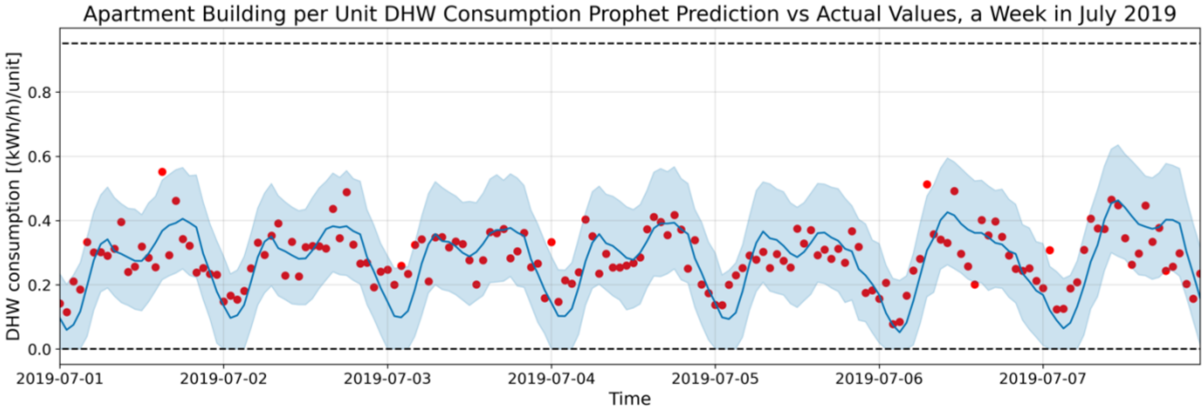
The correlation between the DHW load, the area of the building and the number of units in the building are discussed and investigated through decomposition of the XGBoost- and Prophet models. A set of hyperparameters were tuned for the Prophet models both manually and through cross validation. These hyperparameters regulates the fitting of the trend- and seasonal components in the Prophet model.

The apartment building DHW load was predicted by a Prophet model and a XGBoost model with a Mean Absolute Percentage Error(MAPE) of ≈ 32% and ≈ 30%, respectively. None of the models made to predict the hotel DHW load performed MAPE values under 100%, but the Normalized Root Mean Squared Error(NRMSE) values of 0.49 from the Prophet prediction and 0.47 for the XGBOOST prediction shows that the prediction is not as far off as the MAPE values imply. The MAPE is heavily affected by low true consumption values, as this error metric is calculated by dividing the prediction error in each timestep by the true value.

However, no good predictions were made for hotel DHW load. The nursing home DHW load was most accurately predicted by the XGBoost model, with a MAPE of 37% and NRMSE value of 0.27.

Calculation

Prophet prediction of apartment building DHW load for the first week of July 2019, prediction line vs true values in red dots:



Conclusion

In this thesis, Prophet and XGBoost machine learning models have been tested for medium-term DHW load prediction. The models have been set up, trained, and validated for apartment buildings, hotels, and nursing homes. The models are trained and validated on measurements from the Varmtvann2030 data set [10]. The Prophet models are trained only on DHW consumption data in per unit format and the time variables (year, quarter, month, week, day of the year, day of the week, hour), meaning no other explanatory variables were added to these models. The XGBoost models for the apartment buildings, hotels, and nursing homes utilize the number of units in the buildings and the total area of the buildings in addition to the time variables. The hotel XGBoost model also takes in the number of booked rooms- and the number of guests checked in at any time.

The XGBoost model produced strong prediction results for the apartment buildings and nursing homes with NRMSE around 0.25. The hotel consumption is not captured properly by either of the models in this thesis, which is clear from the fact that non of the models performed a NRMSE under 0.45. The differences in consumption magnitude between the different hotels may have played a part in this. The Prophet model predicts the apartment building data with a NRMSE of about 0.28. The XGBoost models in the thesis have not been tuned much, so they are easy to apply to new data, and perform the best predictions of the models studied in this thesis. XGBoost is a good option in terms of medium-term DHW load prediction for apartment buildings and nursing homes.

A Stochastic Simulation Tool for Generating Hourly Load Profiles for Residential EV Charging, Based on Real-World Charging Reports

Student: **Maria Claire Westad**
Supervisor: **Karen Byskov Lindberg**
Contact: **Åse Lekang Sørensen**
Collaboration with: **SINTEF Community and FME ZEN**

Problem description

The electrical vehicle (EV) fleet is increasing in Norway. To plan and operate the long-term power system and evaluate EVs' effect on the power grid, accurate load-profile generation models are needed. Such models are also needed to analyse optimal EV charging strategies.

Today, most EV load profile generation models are based on detailed bottom-up models, mainly using assumptions on driving distance, EV battery capacity, plug-in time, plug-out time and the initial SoC of the battery when plugging in. However, these data are not available from real-world measurements, and therefore these models are solely based on assumptions. In this thesis, instead of these assumptions, real measurement data provided by charging reports from charging point operators (CPOs) are used. The data provides information on the date, user type, user ID, plug-in time, connection duration, and charged energy for every measured charging session. The goal is to make a stochastic simulation tool to generate realistic load profiles for dumb private home charging based on these data. Because the model will also provide information for the connection time, the perspective of using the model in other applications is taken into account.

The task

The purpose of this thesis is to develop a model to simulate realistic hourly load profiles for dumb private home charging based on real-world EV-charging data. The data shows that charging habits depend on the EV type and the day type and are factors considered in the model.

Model/ measurements

EV load profiles depend strongly on user behaviour, such as weekly charging frequency, plug-in time and plug-out time. In addition, load profiles depend on the type of car, such as battery capacity, charging power level and energy need. These are all parameters used to simulate the load profile in the model. The simulation tool is written in Python, using Spyder IDE.Figure 1 gives a simplified overview of the model used to simulate the aggregated load profile.

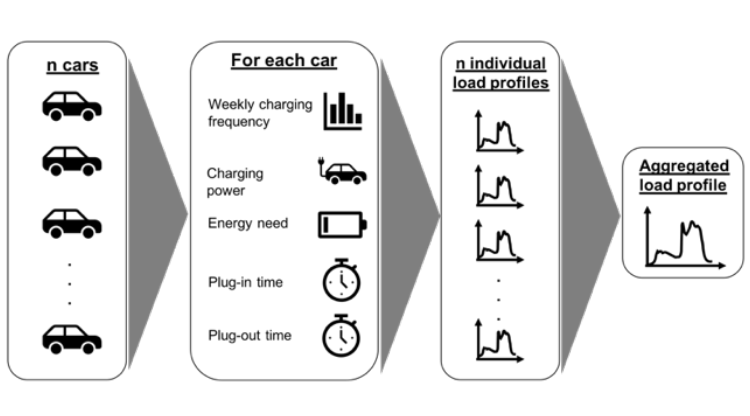


***Figure 1**: Simplified system model for generation of EV load profiles*

Three different cases simulating load profiles for 1000 EVs are used to analyse and evaluate the model: BASE, LOW, and HIGH. In LOW, the EVs are set to “small EVs” with a maximum charging power of 3.6 kW, and in HIGH, EVs are set to “large EVs” with a maximum charging power of 7.2 kW. In BASE, EVs’ battery sizes and maximum charging power reflect the situation of the data and is a combination of the two other cases.

Results

Figure 2 shows the simulated aggregated load profiles for all three cases. The aggregated load profiles have the same shape in all three cases, and the daily average peak power occurs at the same time for the different day types. As the load profiles base on dumb charging, they reflect the distribution of the plug-in time for the different day types used in the model.

The power peak and annual energy need are largest in HIGH and smallest in LOW, while BASE is between the two. The idle hours are higher in LOW, and the shiftable energy level is higher in HIGH.

To further study the model, load profiles are simulated for the same cases using flexible charging. Compared to the load profiles for dumb charging, the peak powers are reduced by 35-38\%. In addition, they are moved to occurring at night in all three cases.

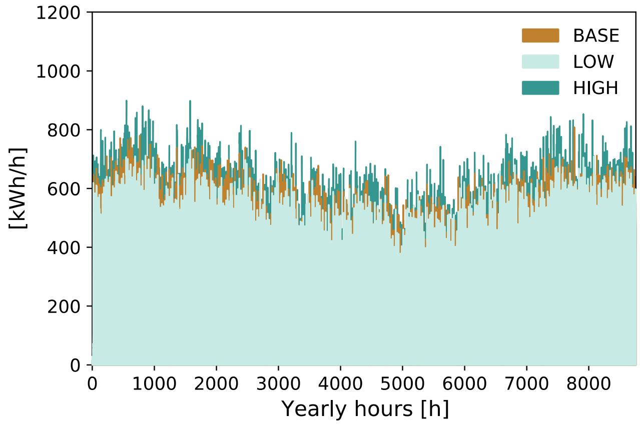


Figure 2: Yearly aggregated load profile, all cases

Conclusion

The results validate that the model can account for factors such as charging frequencies, energy need, plug-in and plug-out time being dependent on the EV type and day type. Generally, EVs having increasing battery sizes and maximum charging powers are seen to decrease the number of idle hours. It is important to be aware of this trend when planning to use EVs as e flexible source.

All in all, the model gives realistic results for the aggregated load profile. However, to make it more robust, more charging data should be analysed and included.

Power Flow Tracing for Norwegian Offshore Electrification

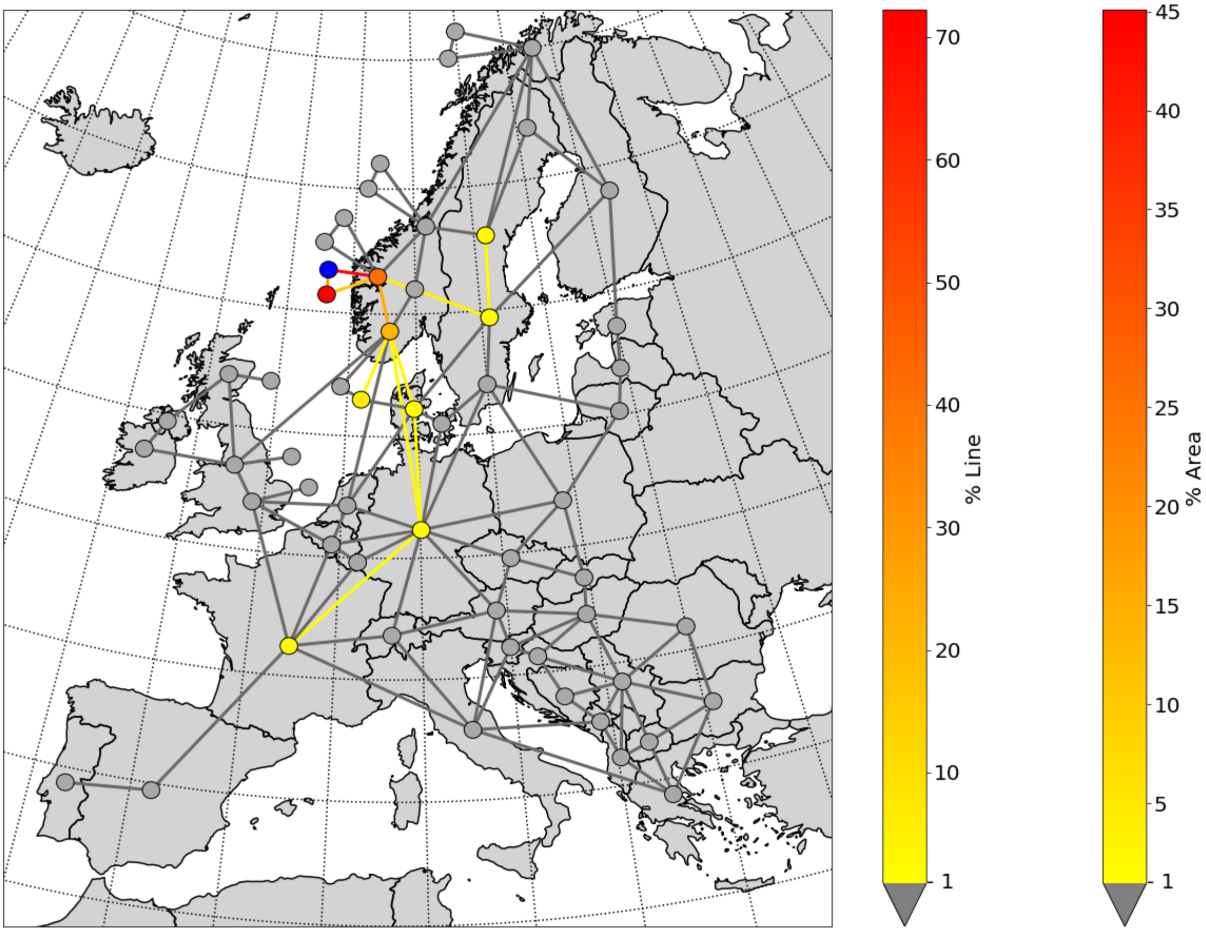
Student: **Ingrid Espmark Wibe**
Supervisor: **Steve Völler**
Co-supervisor: **Vijay Venu Vadlamudi**
Contact: **Ingrid.wibe@hotmail.com**

Abstract

It is generally known that in power systems with more than one supplier and one consumer, electric power cannot be physically traced. Janusz Bialek explained this by saying that it is "impossible to 'dye' the incoming flows (to a node) and check the colour of the outflows". With Power Flow Tracing (PFT) it is possible to theoretically trace the electric power, and by that give estimations of how energy flows from specific generators to specific loads. Before performing PFT on a power system there is need for a power flow analysis or historical measured values. PFT can be used for e.g. transmission service pricing, efficient use of load shedding and CO2-emission apportioning. The latter is becoming very relevant due to the climate changes and global warming, it could improve knowledge about how power consumption affect the emission of greenhouse gases.

In this Master's thesis a model based on PFT has been developed in the programming language Python. The model, which is confidential and meant for in-house use at NTNU, is called the PFT Model. It both calculates generators and loads contribution to the power system, and visualises the results in a map of Europe. It was demonstrated on scenarios with offshore electrification in Norway. The power flow analysis of these scenarios, which provided the input data to the PFT Model, was done in EMPS in the specialisation project. The scenarios included two degrees of electrification of offshore platforms: full and partial, and they were set to year 2025.

The results from simulations with the PFT Model revealed how energy would flow to and from installations on the Norwegian continental shelf, if they were to be electrified. Even though some of the imported power was found to be produced with CO2-dense coal, the total emission associated with the platforms would be reduced with electrification. Seasonal and daily variations that impact the power system, e.g. most wind in the winter and most power demand during the day, were discovered and explained as well. With these sensible results, and an assessment of limitations, it was concluded that the PFT Model was successful.



Figur 1: The PFT Model

Figure 1 is included as an example of the simulations with the PFT Model. The figure shows how power would flow towards an area called NCS4-A (a cluster of oil platforms) if it was to be fully electrified.

A Practical Application of an Active Distribution Grid Planning Framework in Relation to a Pilot Area for New Energy Solutions

Student: **Erlend Øye**
Supervisor: **Kjell Sand**
Co-Supervisors: **Eivind Solvang and Iver Bakken Sperstad**
Collaboration with: **SINTEF Energy Research**

Problem description

The work performed is based around the development of an area in Bodø, referred to as Molobyen, and is related to the FME CINELDI pilot project *Development area Molobyen.* The overall objective has been to investigate alternative ways of connecting this area to the grid, considering both technical and economic aspects, with a focus on including flexibility solutions (e.g. batteries). In order to do so, a grid planning framework combining elements from traditional grid planning and from active grid planning frameworks in the research literature, has been proposed. Also, to capture the operational benefits of batteries, a model for battery optimal dispatch was developed.

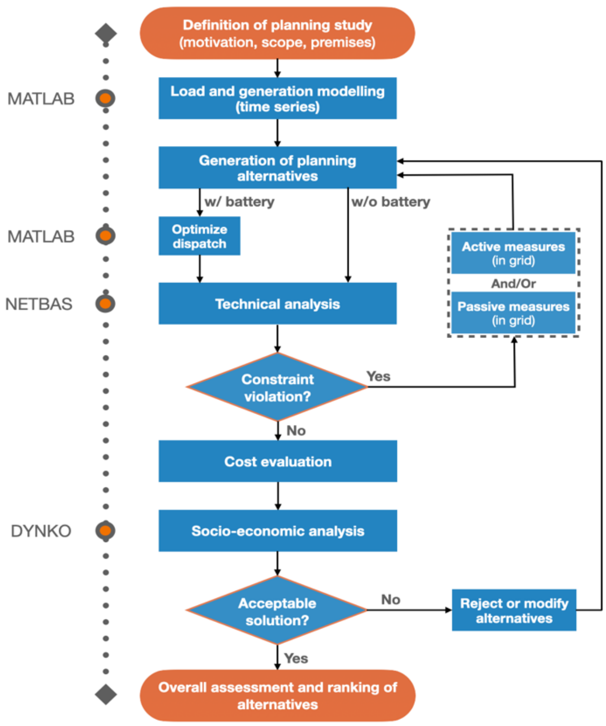
The task

By utilizing time series from an energy system analysis performed in FME ZEN, load demand and solar PV generation of the area were modelled, before alternatives for connecting the area to the grid were defined. If these alternatives included batteries, the model for battery optimal dispatch was utilized. From there on, power flow analyses were performed in order to ensure no technical constraint violations, as well as to calculate power losses. For several alternatives, PV generation turned out to be the dimensioning factor of nearby transformers and cables, as large amounts of power were fed back to the grid during summer months. Due to this, some alterations had to be made to the traditional approach for calculating cost of losses. By also calculating investment costs, socio-economic analyses were performed and the different system solutions ranked.

Model/Methodology

The proposed planning framework, along with the software used for the different stages, is presented in the figure on the right-hand side. The different elements mentioned in the above section, *The task,* can be seen within this framework. Some interesting considerations related to the framework are:

- The use of time series, both for load and generation modelling and for power flow analyses.
- The inclusion of active measures in the grid planning process, in terms of batteries, and hence a model for battery optimal dispatch.
- The approach for calculating cost of losses.



Calculation/Results

The most promising system solution involving batteries was only about 3% more expensive than the optimal solution, which involved upgrading nearby transformers. However, it suffered from not being capable of reducing the maximum loading of nearby transformers, caused by PV generation, sufficiently. Hence, to connect the area of Molobyen to the grid, the more traditional approach of upgrading the nearby transformers appeared as a better solution, both from a technical and economic perspective.

Conclusion

The major new elements included in the planning framework utilized, are:

- active measures, in terms of batteries, and hence a model for battery optimal dispatch,
- the use of time series, both for load and generation modelling and for power flow analyses, and
- the approach for calculating cost of losses.

All these elements could be adopted in the current grid planning process of grid companies, although the use of optimization may need some time to mature before it becomes viable.

The results showed that the most promising system solution involving batteries, did not manage to reduce the loading of nearby transformers as much as the more traditional solution of upgrading the transformers. A larger decrease in loading could have been achieved by increasing the battery energy capacity, but this would also increase the investment cost, deteriorating the economic performance of the battery system solution.

One of the major limitations of this work, is the absence of quantitative considerations regarding interruption costs. As a fully charged battery could supply end-users that otherwise would have been affected by an outage, batteries could reduce the cost of energy not supplied, and hence the expected interruption costs. This should make the system solutions involving batteries perform better, in terms of economic considerations. At the same time, not including battery degradation affects the battery in a positive manner, but whether or not this counteracts the negative impact of not including interruption costs, is not known.

Finally, the main contributions of this work are related to the proposed grid planning framework, the model for battery optimal dispatch and the method for calculating cost of losses.

The development of *calc*GenProg and GenProg*App.* Visualisation and graphical user interface for design of salient pole generator.

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Problem description

The goal of the project was to further improve the *GenProg* application developed in the Autumn of 2020. From the preceding iteration the overall user experience needed to be improved, and the core script *GenProg* needed a major overhaul.

The task

- Fix bugs and issues related to GenProg script.
- Streamline and optimize the core GenProg function.
- Comprehensive input sanitation.
- Create a robust framework for performing a control of the calculated parameters, and display this to the user.
- Increase the fidelity of the cross-sectional view by means of vectorization.
- Add new functionality to the cross-sectional application.
- Develop the app as for use as an educational tool.

Result

The core script was reworked into a set of functions and child functions, and a total rework of the armature slot parameters was performed. A proposed rework of the rotor calculations is presented, but not implemented. The graphical user interface was further developed with new or improved additions. The cross-sectional view was completely vectorized. A method of indexing the three phases was also developed and implemented.

Conclusion

Unfortunately, effort remains for GenProg to fulfil its potential as a design software for salient pole generators. However solid foundation has been laid out which serves as a platform for future development. Such as the rotor parameter rework, and expansion with FEM analysis.