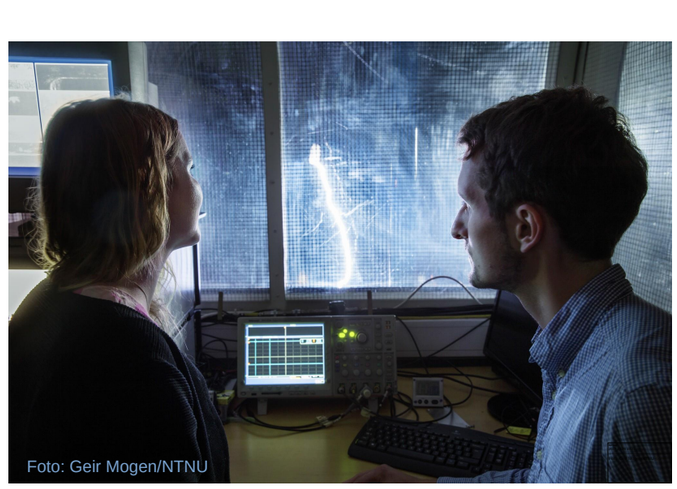
Masteroppgaver 2017

NTNU
Norges teknisk-naturvitenskapelige universitet
Institutt for elkrafteknikk

Summary of Master's Theses 2017

Department of Electric Power Engineering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Summary of Master's Theses 2017

We are proud to present this internet published pamphlet, which gives a summary of all Master's theses submitted to the Department of Electric Power Engineering in 2017.

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

We also take the opportunity to invite existing and new partners to contact us to discuss topics for future Master Theses.

NTNU, October 2017

Ole-Morten Midtgård (sign)
Head of Department

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Condition Assessment of Medium Voltage Cable Joints – Dielectric Spectroscopy of Field Grading Materials

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Collaboration with: **TU Delft and SINTEF Energy Research**

Problem description

A significant part of the medium voltage cable distribution network in Norway is already older than the expected lifetime of 30 years. Cable joints have shorter lifetime than the cables themselves. Specifically, those installed in the 80s have led to significant service failures, due to overheating of the metallic connector in the joint. Additionally, the introduction of renewable energy sources such as wind turbines will increase the current loading of the existing cable network, which could give a further rise in the failure rate.
Field grading materials are usually used in cable joint and termination designs for obtaining the desired field distribution in such way to avoid local field enhancements and the possible subsequent insulation failures. Field control ability of these materials is a function of their dielectric properties. The latter will be affected by the level of applied voltage, but also temperature, aging degree and also humidity will influence the resulting field distribution.

The task

The project work is mainly experimental. Physical, mechanical and dielectric properties of a field grading material are characterized as a function of electric field, temperature and level of aging of the material. The influence of humidity is also important and is investigated during the master work.

Model/ measurements

The electrical properties of a widely used stress control tube for medium voltage heat-shrink joints are examined in this master thesis by using non-destructive laboratory methods. They were determined by use of dielectric response test in time domain while changing the DC electric field, the temperature and the level of humidity.
In order to determine the physical and mechanical characteristics of the material at different aging stages and conditions both differential scanning calorimetry and tensile test measurements were performed on stress control tube samples.

Conclusion

- Measurement results show that polarization currents for stress control tube Raychem JSCR 42/16 are strongly depend on temperature and oxidation degree (thermal aging level) of the material.
- Depolarization currents for highly aged stress control tube samples become voltage independent.
- No significant field dependence is observed.
- Conductivity and rate of aging are strongly dependent on the temperature at which the material is exposed.
- Conductivity is strongly dependent on humidity level of cable joint environment and moisture absorbed by stress control tube.
- The highest conductivity increase of around six decades is observed when a significant level of thermal aging is combined with high humidity presence.
- Experimental work done during this master thesis along with the obtained results show that there is a high probability that low resistance (high conductivity) of cable sections, detected during on-site test diagnostics is due to service aged cable joints, subjected to overheating and humidity. If this is the case, repairing of a cable joint is much cheaper than changing a cable, which will lead to a considerable cost and time reduction for maintenance activities.

Low Frequency Alternating Current Trasmission Systems for Offshore Wind Farms

- Case Studies on the Use of LFAC, Based on the *Horns Rev 3* Offshore Wind Farm

Student: **Kim Allgot**
Supervisor: **Prof. Elisabetta Tedeschi**
Contact: **Esa Virtanen**
Collaboration with: **ABB Transformers, Finland**

Problem description

For long distance power cables, there are problems due to substantial reactive power production in AC systems. This gives substantial amounts of charging currents, which results in less available capacity for active power transmission through the cable.
The thesis investigates the use of low frequency AC transmission of 16.7 Hz in the offshore power system and power cable and how this affects the maximum distance of the cable and the need for reactive power compensation.

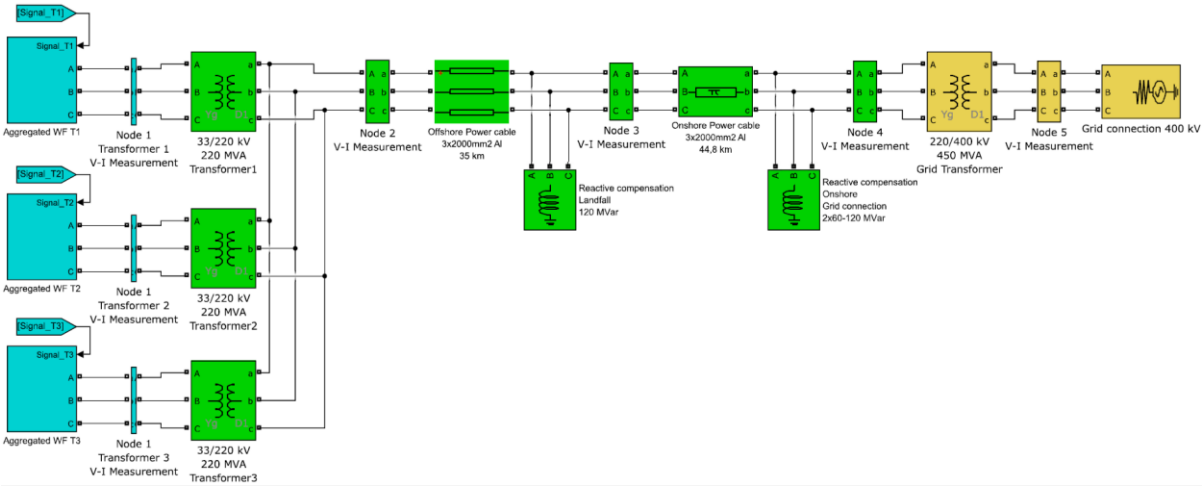
The task

This thesis investigates the use of low frequency alternating current (LFAC) for the long-distance transmission of the power extracted from offshore wind farms. It is based on the measurement of power flow in different nodes in the system simulating an offshore wind farm being built outside the coast of Denmark, *Horns Rev 3 (HR3)*. The results for scenarios simulating different lengths of the offshore cable and the operating frequency of the system are compared. Reactive power compensation is used to improve the power flow of the system and to counteract the reactive current from the capacitance in the long offshore cable.

Power flow, voltage- and current limitations of the offshore cable, and varying the reactive power compensation in the different nodes are used to assess if the different scenarios described are feasible or not. Considerations related to size and operation at reduced frequency on the different power system components are mentioned and discussed briefly. The thesis does not include any detailed analysis with regards to a possible increase in cost for the different components operating at reduced frequency.

Model/ measurements

The problem has been investigated by building a model in Simulink, operating the system depicted at both normal and low frequency operation using different cable lengths.



Calculation
One of the simulations in the thesis is shown in the figure, where the current in different points of the offshore cable, using reactive power compensation on a 200 km offshore cable.

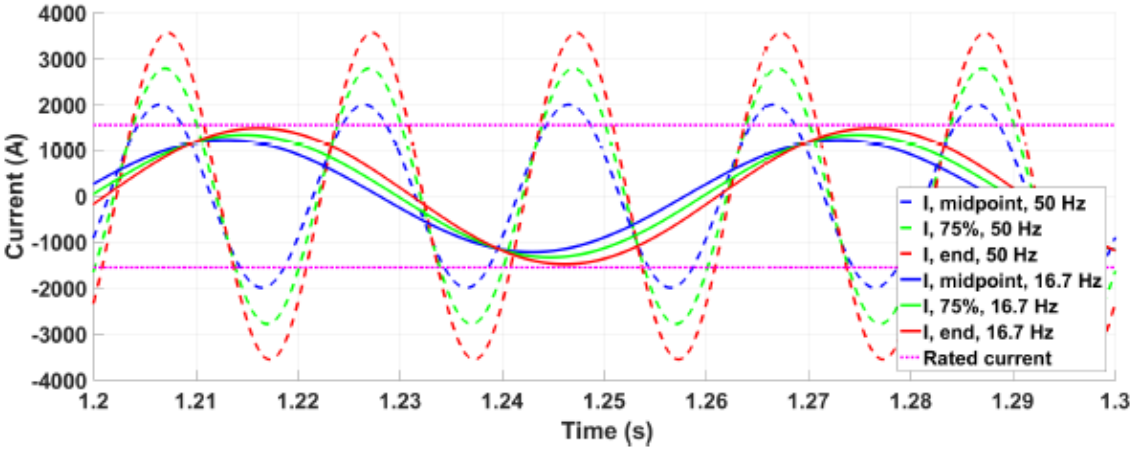


Figure 5.4.2: Current with reactive compensation, 200 km, f=50 and 16.7 Hz

Conclusion
The thesis concludes that the use of LFAC gives reductions regarding power losses, improving the power system efficiency. For the real case of *HR3*, using LFAC excludes the need for reactive power compensation. The thesis also proves that it is possible to transmit substantial amounts of power over longer distances than any other AC-cable in operation today. It is proved that using LFAC and reactive power compensation from shore, it is possible to transmit over 370 MW to the grid with an overall efficiency of more than 93 %, at a distance of 200 km using a 220 kV offshore cable. Including reactive power compensation from the offshore end of the cable, the distance can be increased to 300 km, delivering over 370 MW of power to the grid with an overall efficiency of 91 %.

However, the weight and size of LFAC transformers are considerably higher than the equivalent 50-Hz components, with up to 2.7 times the weight, this would be a challenge for the construction of the offshore substation transformers.

Beyond the scope of this thesis further investigations are needed regarding costs for the different components of the system, as this is not included.

Determination of AC Characteristics of Superconducting Dipole Magnets in the Large Hadron Collider Based on Experimental Results and Simulations

Student: **Sara Marie Ambjørndalen**
Supervisor: **Lars Einar Norum**

Abstract

The Large Hadron Collider (LHC) utilizes high-field superconducting Main Dipole Magnets that bend the trajectory of the beam. The LHC ring is electrically divided into eight octants, each allocating a 7 km chain of 154 Main Dipole Magnets. Dedicated de-tection and protection systems prevent irreversible magnet damage caused by quenches. Quench is a local transition from the superconducting to the normal conducting state. Triggering of such systems, along with other failure scenarios, result in fast transient phenomena. In order to analyze the consequence of such electrical transients and failures in the dipole chain, one needs a circuit model that is validated against measurements.

Currently, there exists an equivalent circuit of the Main Dipole Magnet resolved at an aperture level. Each aperture model takes into account the dynamic e˙ects occurring in the magnets, trough a lossy-inductance model and parasitic capacitances to ground. At low frequencies the Main Dipole Magnet behaves as a linear inductor. Cable eddy current losses are demonstrated by a flattening of the transfer function impedance in the $30 - 50$ Hz range. The time constant of such losses is dictated by the parallel re-sistance, and the relative size of the loss is given by a scaling parameter. Capacitive e˙ects become dominant around 10 kHz. Across the dipole magnet there is a resistor connected in parallel to dampen voltage waves.

Simulations of an Main Dipole Magnet in OrCAD Cadence PSpice, using the present parameters, and measurements from the LHC give a clear discrepancy. This necessi-tated an updated fit and three methods tailored to obtain each parameter were devel-oped. Firstly, the inductance value was obtained estimated from the initial slope of the impedance plot. Secondly, the numerical method chosen for the parameter fit is Particle Swarm Optimization. The algorithm iteratively minimizes the error between measure-ments and the analytical impedance transfer function, making it possible to estimate the value of the parallel resistor and the scaling factor. Finally, parasitic capacitance to ground was determined with Finite Element Method in COMSOL, as it is challenging to extract parameters from high frequency measurements. Values from measurements verify this method of estimating capacitance.

The measurements of the Main Dipole Magnets were performed while connected to the rest of the dipole magnet chain, which influenced frequency response measurements. Hence a proposal on how to reduce the sensitivity to this influence is outlined. More-over, the method of fitting was found to be modular, meaning each Main Dipole Magnet can be fitted individually. This is significant as it is not necessarily possible to perform measurements on a stand-alone magnet. To cross-check the validity of the method, Par-ticle Swarm Optimization fits from stand-alone measurements and measurements from the dipole magnet chain were compared. Both values of the parallel aperture resistance and scaling factor were di˙erent for the two cases.

Compared to the operating point of the Main Dipole Magnet, measurements were performed at low current, resulting in 20 % lower inductance than nominal value. Through COMSOL

simulations persistent magnetization was found to be the dominat-ing cause. Furthermore, at 1 A the magnet is in the Meissner phase, which introduces non-linearities in the superconducting cable due to persistent magnetization. Simula-tions indicate that this distorts the mid-range frequency AC characteristics represented by the parallel aperture resistance and scaling factor. However, measurements outside the Meissner phase are expected to provide similar parameter values to that of the work-ing point of the LHC. The approach presented has shown promising results and can be translated to a general method for fitting electrical parameters for accelerator magnets.

Sammenligning av målte og beregnede temperaturer langs strømbelastede Oslofjord kabler

Student: **Trine Singelstad Andersen**
Veileder: **Erling Ildstad**
Utføres i samarbeid med: **Statnett**

Problemstilling

I 2013 installerte Statnett ni 13 km lange AC kabler på tvers av ytre Oslofjord. Kablene driftes ved 420 kV og er designet for en maksimal strømbelastning på 1350 A. Tre av kablene er PEX isolerte mens seks er oljetrykks-papirisolerte kabler. Kablene ble utstyrt med optiskfiber, såkalt DTS system (Distributed Temperature Sensing), for overvåking av temperaturen langs kabelkappen.

Høsten 2016 ble det gjennomført en prosjektoppgave som viste at de maksimale kabeltemperaturene oppstår i strandsonen, der kabelen er forlagt i luftkjølt kulvert. Formålet med denne hovedoppgaven har vært å sammenligne resultatene fra ulike beregningsmetoder med målte temperaturer mottatt fra driftsoperatøren.

Besvarelsen forventes derfor å inneholde følgende elementer.

1. Et kort litteraturstudie, inkludert teoretisk basis, eventuelle normer, beskrivelse av andres erfaringer og vurdering av ulike beregningsmetoders muligheter og begrensinger.
2. Studie av ulike driftseksempel med presentasjon av beregningsresultater og sammenligning med relevante målte temperaturverdier.
3. Drøfting av beregningsresultatene med vekt på metodenes muligheter og begrensinger, blant annet knyttet til gyldighet av forenklinger og fysiske antagelser.
4. Om mulig fremme anbefalinger for videre undersøkelser og fremtidig bruk av temperaturmålinger ved drift av store kabelanlegg.

Sammendrag

En viktig aldringsmekanisme i strømkabler er høye driftstemperaturer, da dette kan påvirke kvaliteten på isolasjonen. Det er derfor viktig å overvåke temperaturene i kablene. For bedre utnyttelse av kabelanleggene er det viktig å undersøke hvilken påvirkning strømbelastning, omgivelsestemperatur, kabeldesign og forlegning har på temperaturforholdene langs en forlagt kabel. Forståelse for dette er avgjørende for at kabelisolasjonens tåleevne kan vurderes med tanke på kjøling og termisk treghet i kabelsystemet.

I denne hovedoppgaven har påvirkningen fra last og omgivelsestemperaturer på temperaturene i kablene som krysser ytre Oslofjord blitt analysert. En PEX-kabel og en oljetrykks-papirisolert kabel er undersøkt i delen av traseen hvor kablene ligger i en luftfylt kulvert. Videre er det foretatt temperatur- og lastberegninger ved å benytte både analytisk og numerisk metode. Den analytiske metoden benyttet er beregninger utført ved hjelp av IEC 60287, som er den internasjonale standarden for beregning av kablers strømføringsevne. Den numeriske metoden som benyttes er beregninger utført i simuleringsprogrammet COMSOL Multiphysics.

Formålet med temperaturberegningene har vært å sammenligne beregnede temperaturer i kablenes PE-kappe med virkelige målinger. Disse målingene er utført av et innebygd DTS-system (Distributed Temperature Sensing) som overvåker temperaturen langs kabelkappen. Lastberegningene er utført for

å undersøke kablenes maksimale strømføringsevne. Videre blir lastberegningene benyttet til å estimere tiden det tar for kablene å nå de høyeste tillatte driftstemperaturene ved maksimal last. Kabeltemperaturene har ifølge innledende analyse en klar sammenheng med omgivelstemperaturer i august, hvor omgivelsestemperaturen er høy og lasten lav. I januar, hvor lasten er høy og omgivelsestemperaturen lav, er det sterkest korrelasjon mellom kabeltemperatur og last. Det er foretatt en tidsavhengig numerisk beregning av temperaturutviklingen i kablene, der denne sammenhengen er undersøkt. I beregningene framkommer det ingen vesentlig korrelasjon, noe som kan tyde på ufullstendig beregningsmodell.

Beregningene som er utført i denne oppgaven, og de tilhørende resultatene er generelt svært følsomme for hvilken modell som benyttes. I temperaturberegningene er det store variasjoner mellom beregninger og de faktiske målingene, mens lastberegningene konsekvent gir høyere resultat ved å benytte analytisk metode enn når numerisk benyttes. I tillegg fører små endringer i last til store endringer i kabelens oppvarmingstid.

Bruk av smarte målere til feillokalisering i høyspente distribusjonsnett

Student: **Frida Berg**

Veileder: **Hans Kristian Høidalen**

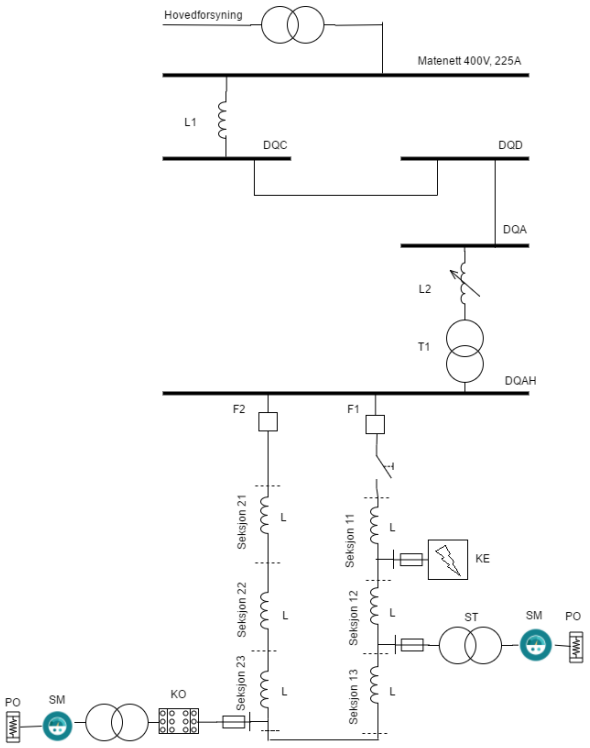
I samarbeid med: **Nordlandsnett AS**

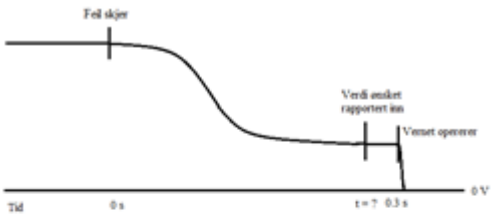
Sammendrag

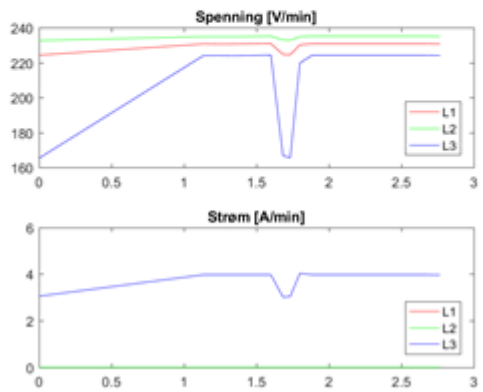
Tidligere har manuelle feillokaliseringsmetoder vært utbredt, der mye menneskelig og langvarende aktivitet har vært nødvendig for å både detektere og lokalisere feil. Varsling om feilsituasjoner har vært gjort ved signaler fra relèvern og innringninger fra kunder. Frem mot januar 2019 vil det monteres smarte målere (AMS) i alle husstander i Norge, som vil kunne bidra til en helt ny og detaljert sanntidsovervåkning av distribusjonsnettet. Dette vil blant annet kunne åpne opp for raskere lokalisering av feil. I denne masteroppgaven er det undersøkt nærmere hvordan smarte målere kan bidra til å lokalisere feil i det høyspente distribusjonsnettet på bakgrunn av spenningsmålinger.

Det ble tatt utgangspunkt i litteratur funnet i forbindelse med prosjektoppgave, utført simuleringer av distribusjonsnett tilhørende Nordlandsnett AS, i tillegg til testing av en Aidon 6550 smartmåler og videre undersøkelse av nyttegjørelse av smarte målere i dag i forbindelse med Demo Steinkjer prosjektet.

Testene av smartmåleren ble utført i distribusjonsnettmodellen i Smartgridlab, og er vist i figuren til venstre, mens forventet spenningsregistrering ved kortslutning og et resultatplot for fasebrudd i èn fase er vist i figuren til høyre.







Resultatene viser at feillokalisering ved hjelp av smarte målere er et relativt nytt og lite undersøkt område. Litteraturen viser til mye teori og lite praktisk testing, og fokuset for innstallering av smarte målere i norske nettselskap har vært innhenting av forbruk. Måleren måler spenninger for sjeldent (500 ms RMS) til at det kan brukes til å lokalisere feil i det høyspente distribusjonsnettet, og disse målingene kan kun bes om i sentralsystemet (Head End System). Målere installert i TN-nett kan derimot detektere sikrings- og fasebrudd ved at de kan måle spenningen så lenge èn fase og nøytral har høy nok spenning. Videre testing og undersøkelse omhandlet utnyttelse av spenningsmålinger fra smarte målere er nødvendig, i tillegg til utvikling av et system som mottar, bearbeider og visualiserer feilsted/-område.

Power Flow Tracing: Methods and Algorithms

Student: **Kjersti Berg**
Supervisor: **Vijay Vadlamudi**

Summary

With the advent of deregulation, power systems across the world have undergone major re-structuring. The unbundling of generation, transmission and distribution services has led to the emergence of electricity markets. One of the crucial issues encountered in such a scenario concerns the appropriate allocation of transmission costs based on actual usage. Power Flow Tracing (PFT), a method which makes it possible to attribute the power flowing on transmission lines to specific generators and loads, was originally conceived as a means of realising equitable transmission service pricing. Over the last decade and a half, significant attention has been devoted in the power system research community on improving PFT models, techniques and algorithms.

Though PFT finds practical application in the electricity markets elsewhere in the world, it has not yet found widespread use in the European electricity markets. However, of late, it has been identified that the application potential of PFT can be extended to diverse areas of modern power system design and operation, especially in systems with high penetration of renewable energy sources. Taking cue from this, this thesis sets out to build the foundation for an eventual comprehensive framework for applying PFT to practical European power system models, for research at the Department of Electric Power Engineering, NTNU.

The main objective of this Master's thesis is to look into select-few prominent mathematical methods and algorithms in vogue for PFT from the point of view of their comparative efficiency. In-house programming codes in MATLAB for select-few methods – the linear equation-based, the graph-based, and the node test-based methods, have been built, and their implementa-tion aspects studied. Results from the implementation of PFT are presented on the 6 bus Roy Billinton Test System (RBTS) and the 24 bus IEEE Reliability Test System (RTS); additional illus-trative systems are considered to demonstrate PFT in meshed systems with circular flows.

Further, the following applications of PFT are illustrated: loss allocation (transmission pricing-related), load shedding (power system operation and reliability-related) and CO2-emission ap-portioning (sustainability-related). The latter demonstrative application deals with flow-based market coupling in the Northern European network, and is a joint venture with a fellow Master's student at NTNU, Cecilia Bringedal.

Creation of step-by-step aggregation heuristic and aggregation models for hydropower systems

Student: **Martin Berg-Leirvåg**
Supervisor: **Magnus Korpås**
Co-supervisor: **Birger Mo**

Norway has in the recent decades utilised hydro as an energy resource, and the EMPS model has long been used as a simulation tool of the power prices in the Nordic energy marked. Det great number of hydro power plants and reservoirs in the Nordic power system conducts to an increased complexity in the model, and therefore an aggregated representation of the hydro system is used. The Nordic energy marked expects a closer connection to the European power market which consists of a larger quantity of non-regulated renewable energy. The present aggregation- and disaggregation methods used in today's EMPS model are not adapted to these new challenges.

The hydropower system in this project has been created in Vansimtap and then simulated in ProdRisk for the production planning of the local hydropower systems Røldalsvatn (RSK) and Leirfossen (TEV). The dataset and the software have been provided by SINTEF Energy and represent the current hydropower system. This task consists of a step-by-step aggregation heuristic that has been used on a serial system (TEV) and a parallel system (RSK).

The method was developed after creating two stepwise aggregation methods based on the degree of regulation. Step-by-step aggregation method 1 showed satisfactory results for the RSK system, but led to large flooding losses in the TEV system. Step-by-step aggregation method 2 was more flexible with regard to the parameters of energy equivalent, production capacity, and station discharge. This method showed better results for both systems and the developed heuristics are based primarily on this method. Furthermore, a comparison has been made between different aggregation models based on the degree of regulation and reservoir size. These consist of single-, two- and three reservoir models with the intention of comparing reservoir curves, station discharge curves and flood losses on the various models, for assessing which models yielded the best results.

The results in the RSK system showed small differences between the magazine models with respect to the degree of regulation. The magazine models partitioning with respect to reservoir size led to generally major discrepancies between the models and the detailed system. For the TEV system, there were greater discrepancies between the magazine models, but the partitioning based on the degree of regulation also showed the best method in this case.

In summary, the heuristics of a step-by-step aggregation method show satisfactory results for two different watercourse systems, and the results in the aggregation models show that aggregation by degree of regulation gives the best results for the waterways associated with this task.

Power System Operation on Oil and Gas Installations with Integration of Offshore Wind

Student: **Pål Mongstad Berge**
Supervisor: **Kjetil Uhlen**

Summary

This thesis investigates the operational aspects of integrating wind energy with the power supply to offshore oil and gas (O\&G) installations. The use of wind energy is an environmentally friendly and efficient way of supplying power to O\&G installations to reduce the dependence on gas turbines and lower the CO2 emissions. Wind measurements indicate excellent wind conditions offshore, and thus there is great potential to install wind energy to an O\&G installation. Wind power is a highly variable power source, and therefore the focus of this thesis is on frequency stability.

High wind penetration in the power system results in a different operational pattern for the system operators compared to conventional thermal power plants. Therefore, it is essential for the power system operator to understand how the integration of wind energy affects the power system stability. These impacts are investigated by conducting dynamic power system simulations.

A hybrid power system has been modeled consisting of two 13 MW gas turbines, a 6 MW wind turbine, and several loads. The level of complexity of the models is kept simple to reduce the computational requirements. The thesis presents dynamic models of the wind turbine and gas turbines, and how the components models are combined to generate the complete model. The system includes mechanical models of gas turbines and wind turbine. Wind model subsystems consist of wind turbine, drive train, blade pitch controller and maximum power point tracking controller. Gas turbine subsystems consist of governor, turbine and drive train.

A operator training simulator has been modeled and implemented in Simulink to give the power system operators knowledge on how wind power penetration affects the frequency variability on O\&G installations. The modeled operator training simulator gives the power system operators the chance to monitor and observe how the wind turbine and gas turbines perform under different load and wind variations. The power system operators also have the opportunity to execute simple control actions, for instance adjusting the speed reference set point of the gas turbine, perform load shedding and start or stop gas turbines.

In the simulation study, one gas turbine replaced either a 6 MW or 2.3 MW wind turbine. The wind turbine contributes with 10-45 \% of the total installed system capacity. The dynamic study investigates transient, steady state and periodic frequency deviations produced by variable operating conditions due to wind variations.

Wind events are simulated to study transient frequency deviations for different ramping capabilities of the gas turbine. Simulation results indicate that when the wind turbine operates at moderate wind speeds (10-16 m/s), it might cause undesirable periodic frequency deviations due to periodic power oscillations.
All other dynamic studies indicate that integration of the 6 MW wind turbine to an oil and gas installation is feasible.

Offshore Wind in Conjunction with an Offshore Oil and Gas Platform

Student: **Annar Pindsle Berntsen**
Supervisor: **Uhlen, Kjetil**

Summary
This thesis is part of the topic of wind power in combination with an oil and gas platform, and focuses on the interaction of an offshore wind farm, an energy storage system, and traditional offshore platform power generation supplying local loads.

Offshore oil and gas platforms require a large amount of power in order to maintain operations, which is usually generated locally by gas generators and diesel engines. These power sources represent the vast majority of greenhouse gas emissions on the Norwegian Continental Shelf. Utilization of offshore wind as a supplement source of power generation is therefore a relevant topic for both operators and others interested in decreasing emissions from offshore installations.

A simplified microgrid consisting of a wind farm with transmission system and a platform with gas turbine generator, energy storage and local loads has been constructed to illustrate the system, with an emphasis on energy storage system control modes. The model has been created in the simulation software MATLAB Simulink with use of its Simscape Power Systems module, and several test cases have been created and conducted simulations on.

The results presented depict the system performance during variations in load demand and wind power generation. The main focus has been on the behavior of the sources of generation and the energy storage system with its charge and frequency stabilization modes in response to different conditions.

The simulations show that the gas turbine generator and the wind farm are capable of supplying the local loads in tandem by fast response of the gas turbine. When wind power exceeds load consumption, the controllers in the energy storage system are capable of dynamically adjusting power flow to the battery in charge mode. When load demand exceeds wind power, the energy storage system helps stabilize the frequency by changing modes and allowing discharge of the battery.

Considering these results in the context of decreasing carbon emissions providing offshore oil and gas platforms with wind power, an energy storage system - where applicable - seems to play a significant part within the subject of wind power to offshore oil and gas platforms.

Utilizing EV Batteries as a Flexible Resource at End-user Level

Student: **Sigurd Bjarghov**
Supervisor: **Magnus Korpås**

Summary

As part of the agreement 195 countries signed in order to lower GHG emis- sions and reduce global warming, Norway has through the Paris Climate Agreement agreed to lower GHG emissions significantly in the future. While other countries are mainly reducing their emissions in the power production sector, Norway's electricity production is accountable for only 3 % of the national GHG emissions, due to a high share of hydro power. Respons- ible for 19 % of national GHG emissions, the road transport sector is a more efficient sector to cut CO_2 emissions. Through extensive subsidies of electric vehicles (EVs) and photovoltaic (PV) panels, the goal is to have a carbon neutral state by 2050.

With more than 300 GW installed PV power worldwide by the end of 2016, Norway is barely taking part in the solar revolution, being only ac- countable for 27 MW installed capacity, with 11 MW being installed in 2016. In comparison, worldwide installed capacity in 2016 was 75 GW. PV is experiencing this massive growth due to sinking costs, increased energy demand and more climate oriented policies. Meanwhile, because battery costs together with PV costs, have been dropping massively in the last decade, the question of profitability for such distributed energy systems has reached Norway, in spite of low energy prices, semi-low solar irradiation and high investment costs.

Due to massive subsidies, Norway reached 100 000 EVs in 2016. Although reducing national GHG emissions, an increased share of EVs could lead to problems in the distribution grid due to high power demand during charging. Meanwhile, an average vehicle is parked 95 % of the time, which results in a huge amount of high power high energy batteries being connected to the grid at all times. These are batteries that in theory could be utilized for load balancing.

With increased amount of unpredictable renewable energy production, new challenges arise. Increased distributed energy production leads to bidirec- tional power flow in the distribution grid, and can result in certain problems related to overloading and voltage deviations.

In order to face the challenges that come with increased distributed energy production in the shape of PV, the implementation of smart meters (AMS) will take place in every Norwegian residence before the beginning of 2019. With AMS, distribution grid operators can reshape their grid tariff structures, creating price incentives to control load in order to utilize the grid more efficiently. AMS also opens the possibility to use smart control to buy cheap energy from the spot price market for storage, in order to either sell or consume when the prices are higher. In order to promote efficient grid use, NVE is developing new grid tariff structures that assures economic advantage for those who take advantage of these. Four grid tariffs have been utilized in this thesis; energy based, power based, time based and subscription based.

By modelling a battery, PV and residence load by using load and irradi- ation data, a household is simulated throughout one year. Utilizing dynamic programming, an optimization algorithm is developed in order to find the optimal operation of the battery that ensures minimal cost for the customer, given that load, spot price, grid tariffs and PV production is known (de- terministic model). At the same time, the new grid tariffs are used to see how new price structures can lead to more efficient use of the grid, espe- cially through optimized use of distributed energy production and storage such as PV and battery utilization. The optimization is performed with both a stationary house battery and an EV battery, in order to compare how an EV battery can potentially replace a house battery.

Results show that PV as of 2017 in Norway is not profitable, but that it with lower investment costs and higher energy prices can be profitable in the future. In addition, EV batteries increases the savings by working as a balancing element, utilizing variations in the spot price and grid tariffs to provide 12.0 - 19.2 % savings in symbiosis with PV (depending on grid tariff structure), compared to the 8.9 - 14.4 % when using a house battery with PV (depending on grid tariff structure).

While only the subscription based tariff resulted in the decreasing load peaks, the remaining tariffs either increased or kept the existing load peaks of the household. The higher peak loads did not interfere with classic peak load hours on a national basis. To conclude, the new grid tariffs resulted in more efficient use of the grid while at the same time having potential for improvement.

Analysis of the Role of Energy Storage in Power Markets with Strategic Players

Student: **Bjerketvedt, Vegard Skonseng**

Supervisor: **Korpås, Magnus**

Abstract

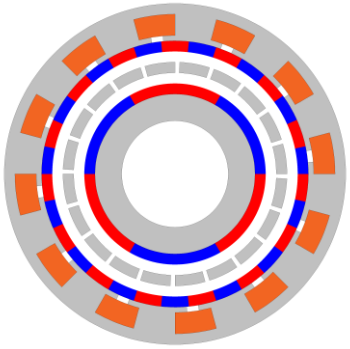
Energy storage has gained increasing popularity in both industry and research during the last decade, due to its valuable flexibility service for power systems. Some claim that energy storage may have a central role in the European power system towards a cost-efficient de-carbonization. In order to gain useful insight regarding the incorporation of energy storage technologies in large-scale market simulators and investment models, we present a thorough evaluation of its material impact on market prices and welfare. A storage facility is modelled under perfect competition and imperfect competition, in order to study the effects of potential strategic behavior at the supply side of an energy only market.

The objective of this Master's thesis is to investigate the role of energy storage in power markets with strategic players. The power market and the players` strategies are modeled by applying complementarity theory. The models are formulated as Mixed Complementarity Problem (MCP) and Mathematical Program with Equilibrium Constraints (MPEC), which is developed to mimic the strategic behavior of both conventional power generators and energy storages. Several simulations have been conducted in order to analyze the influence of strategic game of the energy storage, where the storage has either been operated as price setter or price taker.

A case study consisting of one generator and one energy storage unit is carried out in order to evaluate the effect of strategic behavior. This study reveals that the intra-day price variations get smoother as more storage capacity is added to the system. If the operator behaves strategic, it will exercise market power in order to increase its profits, but it is shown that the magnitude of market power is limited by the level of production capacity. At 93 % of the optimal production capacity, the energy storage facility can have a significant impact on market prices. During morning and evening peak demand, the market price increases from 40 EUR/MWh to 69 EUR/MWh due to strategic behavior in terms of withholding production capacity. The results point out the effects of strategic behavior of an energy storage in an imperfect power market. The proposed study has led to the conclusion that the qualitative effect of the ownership of the storage unit is clearly present. At the same time, the quantitative results emerge as realistic, but these are still heavily dependent on the underlying assumptions and input parameters.

Reversible Magnetically Geared Machine

Student: **Stian Bjornes**
Supervisor: **Robert Nilssen**
Co-supervisor: **Eirik Mathias Husum**
Collaboration with: **Rolls Royce Marine AS**



Summary
Magnetic gears have gained increasing interest over the past few years for replacing mechanical gears in different applications. With no contacting parts, the magnetic gear eliminates typical problems with friction, lubrication, noise and vibration.

This thesis investigates the feasibility of implementing the magnetic gear technology in a system for operating a low speed high torque active heave compensation winch. Most electrical systems for such applications today uses batteries or super-capacitors for storing of heave cycle energy, and it is interesting to investigate if this can be replaced by a mechanical energy storage, possibly reducing the costs. The aim has been to find a configuration that implements the magnetic gear and at the same time utilizes the potential of a mechanical energy storage in the form of a flywheel.

The proposed system integrates the magnetic gear with an electrical machine into a compact configuration known as Pseudo direct drive. The winch and flywheel are connected to separate shafts of the machine, having the stator control the flow of energy between them. An active heave compensation winch is required to rotate both in forward and backward direction, and as a flywheel is allowed to rotate only in one direction, it is found that a variable gear ratio is required.

With the winch required to hold the load, its torque should be fairly constant and in one direction. Analysis of the magnetic gear reveals that in steady state conditions, the torques on all shafts should add to zero. By having a constant direction of torque on the winch, the direction of torque on the shaft of the flywheel was then also found to be constant. This complicates the wanted operation of the system, as the flywheel must be able to vary its torque for energy to be supplied or extracted.

Finite element analysis is carried out by the software *COMSOL Multiphysics*, and is used to investigate the working principles of the system. Results of the simulations confirms that the direction of torques of both the winch and flywheel are constant, and therefore complicates the wanted flow of energy in the system.

Design, Optimization and Analysis of a Single Rotor Magnetic Gear Electric Machine

Student: **Gunnar Charlie David Bjørk**
Supervisor: **Robert Nilssen**
Contact: **Alexey Matveev**
Eirik Mathias Husum
Collaboration with: **Rolls Royce Marine AS**

Problem description

Magnetic gears have recently become serious contenders for mechanical gears in low speed applications that require high torque. A magnetic gear features benefits such as inherent overload protection and low maintenance, while having torque-handling capabilities similar to mechanical planetary gears. Integrating these gears into electric machines have resulted in machines with very high torque density. This thesis aims to investigate whether such a machine is a suitable for use in marine applications, more specifically for propulsion in an azimuth pod.

The task

The task is to design, optimise and analyse a magnetic gear machine for use in marine applications. FEM simulations and particle swarm optimization aid this. An intuitive way of understanding the working principle is also presented.

Model/ measurements

The machine is developed through a careful design process, which is validated by the finite element method in COMSOL Multiphysics. During the design process, heavy calculations where performed on the supercomputer Vilje, which enabled the computation of very large parametric sweeps. Parallel to manually designing a machine, a particle swarm optimization of the same design, under similar limitations, was performed on Vilje. Both the final designs were analysed in the time domain.

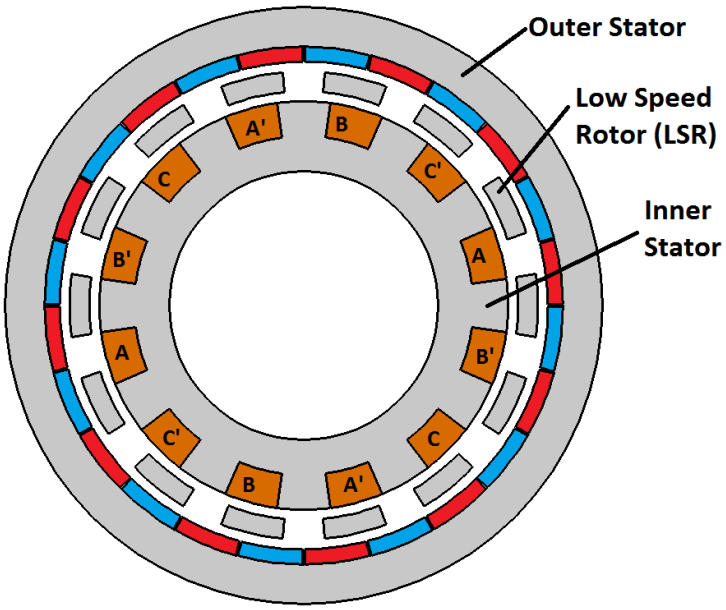


Figure 1: An integrated magnetic gear electric machine

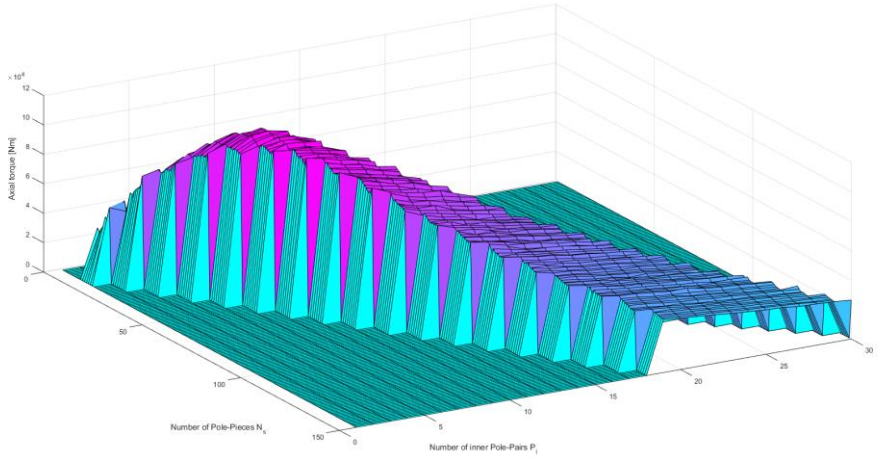


Figure 2: Example of a large parametric sweep run on a supercomputer

Calculation

The resulting machine designs achieved torque densities of 98.8 kNm/m^3 and 105.9 kNm/m^3 respectively, which make them better than most existing direct-drive solutions in terms of compactness. However low power factors of 0.187 and 0.188 means that they require large and expensive converters, which is undesired in Marine applications.

Conclusion

Two different designs of a magnetic gear electric machine was developed. Both showed very good torque densities, but suffered from poor power-factors. This increases the needed converter VA-rating, and makes the topologies less attractive for use in marine applications. However, the topology could be attractive for applications where the torque density of the machine outweighs the additional cost and size needed for the converter. The topology was also shown to be very similar to Vernier PM machines.

Adjustable Speed of Synchronous Machine for Hydro Power Application

Student: **Erik Hildre Bjørkhaug**
Supervisor: **Trond Toftevaag**

When Europe is transitioning from fossil fuels to renewables, hydropower plants will have an important role in the integration of large quantities of fluctuating sources in the power system, such as wind and solar. With the development of variable speed of hydrogenerators, the objective is to further improve the flexibility and efficiency of the plants. If applying this technology in hydropower plants, Norway can be a green battery in the European power system.

This thesis focuses on the development and preparation of a lab set-up with a converter fed synchronous machine, for research on variable speed of hydrogenerators. This includes testing and documentation of the synchronous machine, modelling and simulation of the lab set-up, development and simulations of possible operating scenarios which later can be tested in lab.

A large part of the work covers determination of parameter values of the 8kVA synchronous machine. Several tests have been conducted in lab, to determine its most important parameter values, while other parameters were estimated based on typical values. Those were needed for modelling of the machine, and tuning of the control system.

A simulation model has been developed to simulate variable speed control of the lab machine, where the machine is fed by a two-level voltage source converter. The objective has been to make the simulation model representative to the lab set-up so that it can be relevant for further lab research. The simulations show that the converter set-up is suitable for adjustable speed control of the synchronous machine.

Synthetic inertia contribution by a converter fed synchronous machine has been simulated, by implementing a control loop that deaccelerates the machine in case of a frequency drop in the grid. This was done by letting the frequency signal pass through a derivative controller, which either affects the torque or the speed reference in case of a frequency drop. Highest impact was achieved by letting the derivative controller affect the speed reference, where the power boost lasted 0.7s and peaked at 18\% increase in the presented simulation. A significant impact was also achieved by affecting the torque reference for the inner control loop. However, this impact only lasted 0.1s, since the speed controller quickly compensated for the injection from the derivative controller. For further work, these operating scenarios can be tested in the lab set-up.

Allocation of Capacity for aFRR Exchange on NordLink

Student: **Ellen Dypvik Bogen**
Supervisor: **Gerard Doorman**
Collaboration with: **Statnett SF**

Summary

A growing share of intermittent power production leads to challenges in power system balancing and requires improvement of system regulation capability. Cross-zonal exchange of balancing services is a step towards harmonized European balancing markets and an instrument to meet these challenges. In order to exchange balancing services, reservation of cross-zonal capacity(CZC) should be executed. The allocation of CZC for exchange of balancing services should maximize social surplus.

A market-based reservation model is one of the methods, described by the Network Code on Electricity Balancing, in which socioeconomic efficiency of the reservation of CZC can be demonstrated. In a market-based reservation model the marginal value of the CZC in the different markets are compared, to decide on a reservation volume that maximizes social surplus.

Simulations with case studies in a marked-based reservation model was performed, with the aim of quantifying the possibility of cross-zonal automatic frequency restoration reserves(aFRR) capacity exchange. The simulations in the marked based reservation model was performed with weekly auctions on aFRR.

Six different case studies were developed; three historical case studies and three future case studies. Each of the case studies was developed by generating aFRR bid curves, using a regression model and historical aFRR bid prices. Historical Day-ahead market(DAM) prices were used for the historical case studies, while the future case studies used DAM prices simulated in Samlast and BID.

Socioeconomic benefit was demonstrated for all the case studies when simulated in the market-based reservation model. Germany was the main provider of aFRR for all the case studies. The latter result contradicts the expectations provided in a qualitative analysis of the thesis, in which Norway was considered to have a competitive advantage in providing aFRR.

The main reason for the simulation results appear to be non-representative inputs of aFRR bids. The aFRR market designs in Norway and Germany are too different, resulting in the distribution of the cost of offering aFRR appears to be shifted in opposite direction between energy and capacity bids.

Therefore, a sensitivity analysis was conducted to study the effect of market development in the direction expected in the qualitative assessment. The results showed that if Norwegian aFRR capacity bids became cheaper than German aFRR capacity bids, increasing the price difference between the countries leads to an increasing socioeconomic benefit.

Quantifying Norway’s Carbon Footprint from Electricity Imports in 2020
A Flow-Based Market Model

Student: **Cecilia Bringedal** (Times New Roman, 12 pkt, bold)
Supervisor: **Hossein Farahmand**
Co-Supervisor: **Vijay Venu Vadlamudi**

This master thesis aims to quantify Norway's carbon footprint from electricity imports in 2020. This is done through the combination Flow-Based Market Modeling (FBMM), Power Flow Tracing (PFT) and CO_2 conversion factors. Each of these methods represents one of three steps of the solution approach.

The first step involves performing a FBMM simulation on a 2020 scenario. This simulated scenario includes Norway, and all the countries that Norway's electricity transmission grid is directly connected to. These countries are Sweden, Finland, Denmark, The Netherlands and Germany. The optimal market solution it estimated for every hour of 2020. The generation at each individual generator and the power flow in all lines are thus found for every hour.

The second step is where the PFT is performed on the results of the FBMM simulation. This step is done in cooperation with master student Kjersti Berg. Her master thesis involves making a PFT program, which is the program used in this thesis. This program may only process the results of one hour at a time, and the input information from the FBMM results must be filled in manually. This limits the amount of hours that it is feasible to analyse, and four cases, representing four hours with different types of power flow are therefore picked.

In the third step, the carbon footprint from electricity import for each of the cases is estimated. It is fond that the carbon footprint for the cases varies between 0 and 3209 tonnes of CO_2. Most of this emission is found to come from lignite coal generators in Germany, due to their relatively very high emission compared to other types of generators. It is also found that this amount of emission from electricity import to Norway is so high that it will significantly affect Norway's total yearly emission. However, it will not affect the total global emission. Perhaps the most important conclusion to extract from the results is that Norway's electricity demand does affect the total global emission despite Norway's electricity generation being renewable.

A Substation Level State Estimator for Local Data Processing

Student: **Bård Haga Bringeland**
Supervisor: **Vijay Venu Vadlamudi**

Modelling power systems with substation details in State Estimation (SE) has several advantages. An increased measurement redundancy is possible, because the measurements can be evaluated individually instead of being aggregated to the bus-branch level. Conventional SE methods, relying on bus-branch models, cannot provide an efficient topology error processing. Though Generalised State Estimation (GSE) overcomes this limitation, with its built-in ability to estimate the state of the system by using node-breaker models, the problem size and solution times render it infeasible to build an estimator based on centralised GSE for real-time monitoring of large power systems. A reasonable trade-off for the design of an efficient state estimator for real-time monitoring would be to use a two-level method:

- Level 1: In the substation level, a local SE is performed by utilising only *some of the salient* features of the GSE algorithm.
- Level 2: The validated pre-processed measurements obtained as output of Level 1 are then fed to a SE processor at the Transmission System Operator (TSO)-level, which runs on the conventional SE algorithm.

The central research question investigated in this thesis is whether or not a suitably designed substation level state estimator, naturally restricted in size, is able to retain the same advantages as the centralised state estimator based on GSE with respect to accuracy, bad data, and topology error processing.

Based on extensive literature survey and critical analysis of its consequent findings, this thesis provides the conceptual basis for a two-level state estimation: linear and computationally non-demanding substation level estimation, based on GSE, integrated with conventional state estimation at the TSO-level. Though the designed framework is mostly theoretical in nature, conceptual tests have been conducted for demonstration and preliminary testing, paving the way for addressing further identified research questions in this area. A modified 14-bus IEEE test system has been employed as the case study of choice for conducting the relevant investigations for realising the proposed two-level state estimator.

The proposed implementation logic and design choices for the two-level state estimator have been presented and executed in MATLAB, including the program needed to perform conceptual testing.

PD-testing av høytemperatur motorkabel

Student: **Sylvi Brækken**
Faglærer: **Frank Mauseth**
Veileder: **Frank Mauseth**
Utføres i samarbeid med: **SINTEF Energi**

Det er viktig å få testet kabler for partielle utladninger (PD), da partielle utladninger over tid kan skade kabelen og føre til gjennomslag.

Hovedfokuset i denne masteroppgaven har vært å PD-teste motorkabler uten ytre halvleder som i hovedsak blir brukt i neddykkbare elektriske pumper (electrical submersible pumps, ESP). Produsenter av denne typen kabler har problemer med å teste kablene for partielle utladninger, fordi kablene ligger i vann og det da oppstår partielle utladninger i luftbobler på overflaten av isolasjonsmaterialet.

Det er gjort forsøk der kabelen er lagt i vann tilsatt Tween 80, og forsøk der kabelen har ligget i rent vann. Ved å tilsette 10 % Tween 80 i vann, vil overflatespenningen reduseres så mye at det ikke dannes luftbobler på overflaten av isolasjonsmaterialet. Det vil ikke oppstå partielle utladninger i en frisk kabel dersom det ikke er noen luftbobler på kabelens overflate. Det er derfor lagt mest fokus på forsøk der kabelen har ligget i rent vann.

Det vil kun oppstå partielle utladninger i luftbobler på kabelens overflate når kabelen ligger i rent vann dersom det er surret en metalltråd rundt kabelen.

I forsøk der luftboblene ble fjernet, og det deretter ble initiert luftbobler manuelt med en sprøyte, har det vist seg at det trengs mange luftbobler for at det skal registreres partielle utladninger. 11 luftbobler gir ikke utladninger, mens 300 luftbobler gir utladninger. Tennspenningen varierer fordi systemet er dynamisk, men i 4 av 5 forsøk der det ble lagt på 300 luftbobler var tennspenningen 12.5 kV.

Antall partielle utladninger og utladningenes størrelse reduseres ved en konstant spenning på 20 kV i 2 timer. Dette er fordi mange luftbobler sprekker opp eller beveger seg slik at de ikke lenger blir påvirket av den påtrykte spenningen.

Luftbobler sprekker ofte opp ved at to nærliggende luftbobler går sammen og deretter sprekker opp. Større luftbobler sprekker ofte opp uten å gå sammen med en nærliggende luftboble. At luftbobler beveger seg, går sammen og sprekker opp er observert også før det oppstår partielle utladninger. Når mange nok luftbobler påvirkes av den påtrykte spenningen, vil det oppstå partielle utladninger.

COMSOL Multiphysics ble brukt for å modellere laboratorieforsøkene. Det har vist seg at det elektriske feltet vil være høyere i en luftboble med større kontaktareal mot kabelen enn en luftboble med et lite kontaktareal mot kabelen. Spenningen i et område på 0.1 mm ble regnet ut til å være 100 V i en luftboble med diameter 2 mm, der luftboblen var en halvkule.

Aktivering av balanse-energi med flaskehalser

Student: **Jonas Bøe**
Faglærer: **Gerard Doorman**
Veileder: **Gerard Doorman og Martin Håberg**
Utføres i samarbeid med: **Statnett**

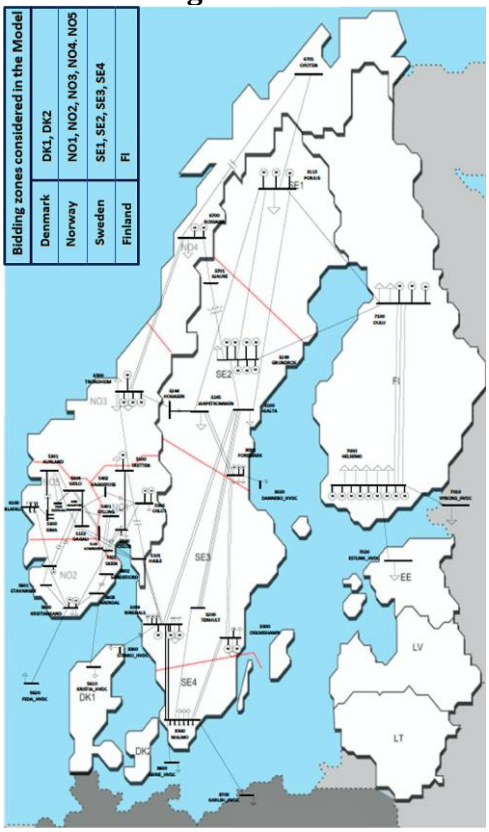
Problemstilling

ENTSO-E Electricity Balancing Network Code krever etablering av standardprodukter, som skal utveksles mellom land. I tillegg vil land kunne ha spesifikke produkter. Det skal også utvikles en Activation Optimization Function, som skal brukes for optimal balansering mellom flere land. En kan se for seg at en variant av denne håndterer både standard og spesifikke produkter, og tar hensyn til nettet. Formålet med oppgaven er å utvikle en prototype av en slik funksjon for det nordiske systemet.

Oppgaven

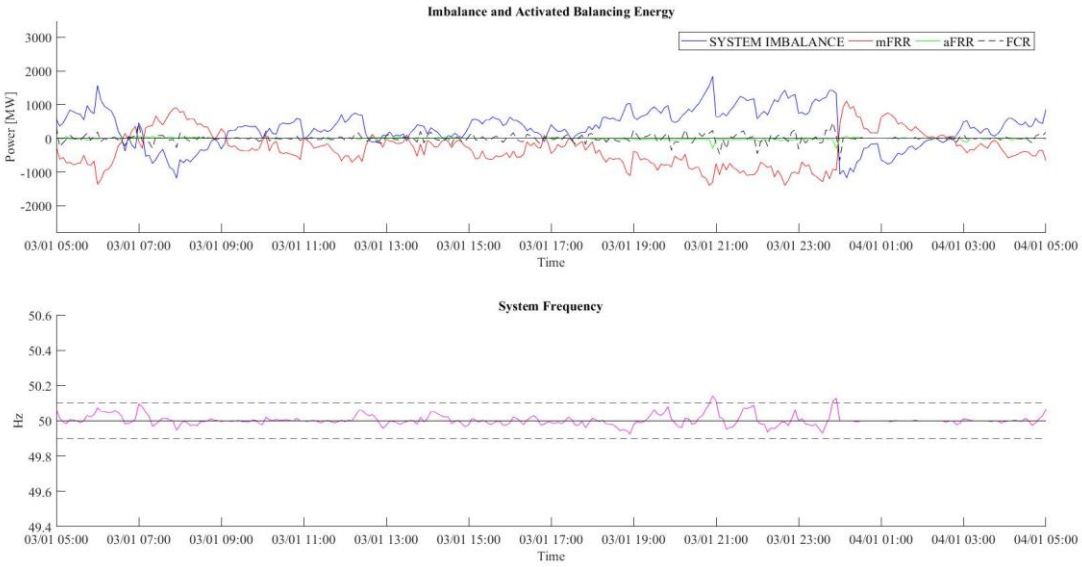
I denne oppgaven er det blitt utviklet en prototyp for AOF basert på DCOPF i det nordiske synkronsystemet. Optimeringsmodellen for aktivering av balanseenergi tar hensyn til kraftflyt i nettet og lager kostnadsoptimale aktiveringsplaner for primære, sekundære og tertiære reguleringsreserver for å regulere historiske nordiske kraftubalanser. En nettverksrepresentasjon av det nordiske kraftsystemet blir innmatet til modellen sammen med en felles nordisk budliste for regulerkraft og prognoser for fremtidige ubalanser. Den nordiske systemfrekvensen er modellert ved en simplifisert nordisk regulerstyrke og aktivering av primærreserver. Stokastiske avvik i ubalanseprognoser er representert ved en fiktiv skaleringsfaktor for prognoseavvik. Det har blitt utviklet 5 scenarioer for å undersøke modellens oppførsel ved endring i Standard Produkt-definisjoner og nettverkkarakteristikker.

Modell/målinger



Nettverksrepresentasjon er hentet fra [L Vanfretti, SH Olsen, VS Narasimham Arava, G Laera, A Bidadfar, T Rabuzin, Sigurd H Jakobsen, J Lavenius, M Baudette, and FJ G´omez-L´opez. ”An open data repository and a data processing software toolset of an equivalent Nordic grid model matched to historical electricity market data”. Data in Brief, 2017]

Beregninger



Konklusjon

Det er observert økt aktiveringskostnad i scenarioet der ingen balansekraft kan utveksles mellom Norge, Sverige og Finland. Dette følger av økt aktivering av dyre primær- og sekundærresserver når mer rimelige tertiærreserver er utilgjengelige på grunn av lav markedsintegrering. Når balanseenergi kan utveklses over landegrensene, reduseres aktiveringskostandene med 22 % og ubalansenettingen øker med 18 % for samme ubalanser og nettverk. Det konkluderes med at en stor andel mFRR-aktiveringer gjøres for å forhindre brudd på overføringsrestriksjoner mellom markedsområder ettersom modellen evner å følge budpris-rekkefølgen i større grad ved økt overføringskapasitet.

En produsents evne til å levere fleksible balanseprodukter gjør at mer ubalanse kan reguleres av mFRR og reduserer total ressursbruk og aktiveringskostnader. En 9 % reduksjon i aktiveringskostnader er observert når alle mFRR-bud har minimum leveringsvarighet på 5 minutter, og en 3 % økning i aktiveringskostander n˚ar antall bud med full aktiverings-tid (FAT) på 15 minutter økes.

Resultatene viser at tilstrekkelig overføringskapasitet mellom balanseområder er en nøkkelfaktor i å øke sosial velferd ved aktivering av balanseenergi og redusere ineffektiv ressursbruk. Verdien av produsentfleksibilitet blir også presentert ved favorisering av bud med kort FAT og minimumsvarighet på leveranse.

Modeling, simulation and control of the alternate arm converter

Student: **Donatas Dembinskas**
Supervisor: **Elisabetta Tedeschi**

Summary

The fast evolving technologies have resulted in an extensive use of the power electronics. More intelligent grids can be made by implementing the power electronic devices. In response to global increasing energy demand and significance of the clean and sustainable future the renewable energy sources, like sun, wind and water are exploited. Power elec-tronic devices together with the renewable energy resources create a new type of grids. The new type of grids create a new challenges. Nowadays more often the new energy production resources are moved outside the land in the seas or the oceans, while the land is used for the accommodation of people. The energy resources moved outside the land require the transmission of the energy, where it is used. Connecting all those three dots: power electronic devices, sustainable and clean future and the new location of the renew-able energy sources results in the question how to create the grid for energy transmission and transit the energy in the cheapest and the most sustainable way.

The offshore energy mostly are delivered to the land by the cables. With increasing length of the cable losses increases, in order to avoid losses the AC voltage are transformed to the DC voltage. The transformation of the voltage from AC/DC requires somewhere in the sea or ocean a substation. A substation contains a converter where the all nearby distributed energy resources are connected. The voltage is transformed to DC in these substations. The voltage are transformed again from DC/AC in the next substation usually located onshore. The costs and the reduction of the substation size requires to look for a new and better voltage transformation topology.

In this study a new hybrid voltage source converter based topology is modeled, simulated and controlled. This new topology is usually known as alternate arm converter. For the simulation developing MATLAB/Simulink software is used. With the MATLAB/Simulink software the model of alternate arm converter is developed from the scratch. Firstly the simple one-phase average mathematical model is developed and implemented in the sim-ulation. Then the balancing control between the arms voltages is implemented in the one-phase model. The simple one-phase with a simplified control model is evaluated. Then the three-phase model is created in the same MATLAB/Simulink software. Firstly the three-phase model is evaluated as working in the island mode, which means that it is working alone, not connected to the grid. The improved control is implemented in this 3-phase model in order to increase the performance of the converter. The 3-phase model with im-proved control model is connected to the grid by using MATLAB/Simulink software. The grid connection is simulated with the voltage sources and phase locked loop control. The phase locked loop constantly adjust the voltage in order to lock onto the phase and fre-quency. Furthermore it is extract a voltage angle for the used dq0 transformation, which simplifies control. The grid connected model is simulated and evaluated. After this eval-uation the MATLAB/Simulink simulation model of the alternate arm converter, together with control is connected in the point to point scheme. The point to point scheme represents the energy transmission from the one point to another or in the different case it can also transmit the energy in the other side. The point to point system is represented in the MATLAB/Simulink model, together with additional droop control,

which controls the DC voltage accordingly to the active power. If the active power reaches the maximum value the DC voltage decreases accordingly to the drop value and the way around. The six study cases are simulated in the MATLAB/Simulink software, with the point to point connection. In the first case the operation points are evaluated of the system and the behaviour of the AC voltages, AC currents, DC voltage, arm voltages, arm currents and circulating currents are observed in the terminal 1 and terminal 2, which is AC/DC and DC/AC converters, respectively. The second study case is aimed to inspect the DC side capacitance effect to the DC voltage. In this study case is evaluated that by increasing the DC side capacitance the DC voltage ripple reduces, therefore the AC currents with less harmonic distortions are presented. The third case shows the droop control behaviour for the different drop values. When the drop value is increasing the gain value of the droop control decreases and the smaller deviation of the active power is presented. The forth, fifth and sixth cases arise, because of the problem confronted during the operating point case simulations. The volt-ages between the upper and lower arms in some of the operating points are not balanced. This issue creates an arm voltage balancing problem, which in the forth study case is solv-ing by increasing overlap time. The observation is made, that by increasing overlap time the balance between the arm voltages becomes better, but the alternate arm converter are forced to approach and change the topology to modular multilevel converter, when the 10 ms is reached in this case. The fifth study case investigates the cell capacitance effect for the arm voltage balance. In this case was found that increasing or decreasing the cell ca-pacitance in the submodules, do not fix the arm voltage balancing problem. This approach makes voltage balance between the arms even worse. The last study case introduces the case of the arm voltage balance technique by using third harmonic current flow together with 1 ms overlap time. This study case requires a minor changes in the point to point sys-tem. The results of this technique are evaluated and it shows that this type of the balancing technique is the best technique of the voltage balancing between the arms in this system of the point to point connection.

Integration of Photovoltaic into grid using Modular Multilevel Converter

Student: **David Krogager Dolva**
Supervisor: **Lars Norum**
Co- supervisor: **Anirudh Budnar Acharya**

Summary:

The integration of solar energy into the grid is a challenging task. Many configurations and control methods have been studied in the past. In this thesis, the Modular Multilevel Converter is used to integrated Photovoltaic (PV) into the grid. The focus of this thesis is divided into two parts. The focus of the first part is to investigate how to integrate photovoltaic into the grid by using the MMC. First the topology of the MMC is introduced, and form this a mathematical model is derived. Then different aspects considering the control of the MMC is discussed, such as capacitor voltage balancing and suppression of circulating current. The modulation technique applied to the MMC is the phase- shifted carrier (PSC) pulse width modulation (PWM).

This section is followed by an introduction of PV systems. A review over different configurations of how to integrate PV into the grid, is given. This is followed by review of how this integration is done by using MMC. One specific configuration is chosen to investigate more closely. This configuration is a multistring configuration, where the PV panels is connected at the DC link of the submodule with and DC/DC buck converter between the PV panels and the submodule. This configuration is implemented in Simulink, with the MMC connected to the distribution grid.

In the second part of the thesis different maximum power point tracking (MPPT) algorithms is studied in detail. PV modules have a characteristic nonlinear I-V curve with a distinct MPP. To extract maximum power out of the PV module, the PV modules should operate at their MPP despite changes in environmental conditions. The four MPPT algorithms that are investigated and implemented in Simulink is the Perturb and Observe (P&O), Incremental Conductance (IC), Ripple correlation control (RCC) and Fractional Open- Circuit Voltage(FOCV). To find the static and dynamic efficiency of this four MPPT algorithms, the algorithms are simulated with both constant and variable irradiance. The temperature is kept constant in the simulations, since it is the effect of irradiance change that is studied. The dynamic efficiency is measured with two kind of irradiance profiles. One with a trapezoidal and one with a staircase irradiance profile. This simulation is done with the PV strings connected to a buck converter, which is connected in the submodules of the MMC. This approach makes it possible to study the behaviour of the MMC while the irradiance is chaining.

The MMC is a very promising topology for integrating PV into the grid. Some of the advantages that the MMC got is the generation of low Total Harmonic Distortion (THD) and possibility of individual MPPT for PV arrays connected in the submodules. Compared to a single- stage topology, the studied topology requires less complex control. The buck converter performs the MPPT for each PV string, while the MMC ensures that the different outputs of the PV inverter meets the grid requirements. The IC algorithm is the MPPT algorithm with highest static and dynamic efficiency of the four studied algorithms. It behaves well during both constant and when the irradiance is changing. The algorithm also responds quickly to irradiance changes.

Optimal use of resource flexibility in distribution systems

Student: **Fleur Dubarry**
Supervisor: **Olav Bjarte Fosso**

Summary

To cope with the increasing share of dispatchable renewable energy sources, the consumer needs to evolve from being a regular passive consumer, to being a prosumer. The prosumer produces energy through residential solar panels, and tries to adapt his loads to energy production. This is done by shifting flexible appliances, such as a dishwasher, washing machine, tumbler dyer or an electric vehicle charge. The Smart-Meter automatically triggers flexible appliances as a response to low price signals to reduce the user daily cost, and is modelled in this thesis. Three main pricing schemes were tested, to encourage the use of more renewable energy sources and reduce the consumer's expenses: constant pricing schemes, dynamic ones and a main grid fee. The best result was obtained from dynamic pricing schemes with main grid fee, encouraging the use of local renewable power and reducing the daily cost by 9% comparing to a regular passive consumer. Yet, improved performance and reduced cost could be obtained if more flexible appliances were taken into account, making the most of the dynamic pricing schemes.

Switching Performance Assessment of a 1.2 kV, 300 A, 175 °C All-SiC Half-Bridge Module Using Computer Tools

- Investigation of the Impact of Internal Stray Inductance on Switching Behavior

Student: **Joakim Leer Endalsvoll**

Supervisor: **Dimosthenis Peftitsis**
Contact: **Bijan Zahedi**
Collaboration with: **Siemens PEC**

Summary

One of the most attractive attributes of SiC MOSFETs is the fast switching capability. Increasing the switching speed can downsize passive components, filters and transformers and yield less costly and more efficient electric power conversion systems. Thus, this attribute can enable high-power converters with a power-density not currently possible with the Si IGBT technology. However, to unfold this capability, a more thorough attention to parasitic inductances is required. A low inductive arrangement of any bypass capacitors, bus bar connections as well as a low inductive design of the power module is required. A parallel array of individual film capacitors and a strip-line design of bus bar connections are widely accepted approaches for system designers, however, the design of power modules are fixed by manufacturers. This thesis investigates the inductive design of what is considered state-of-the-art in high-power SiC MOSFET module design today. The main contributors to internal module parasitic inductances and the impact the power loop inductance has on switching performance are studied. The entire investigation is conducted by using computer tools.

A half-bridge module rated at 1.2 kV, 300 A, 175 °C employing 16 SiC MOSFETs (CPM2-1200-0040B) and 12 SiC Schottky Diodes (CPW5-1200-Z050B) has been developed. The developed module emulated a commercial available SiC MOSFET half-bridge module from Cree (CAS300M12BM2). As a part of the design methodology, a literature review of packaging approach and trends specific to unfolding the properties of SiC MOSFETs was conducted and is provided for the reader in this thesis. The module was realized in SolidWorks. The 3D CAD model can be seen in Fig. 1.

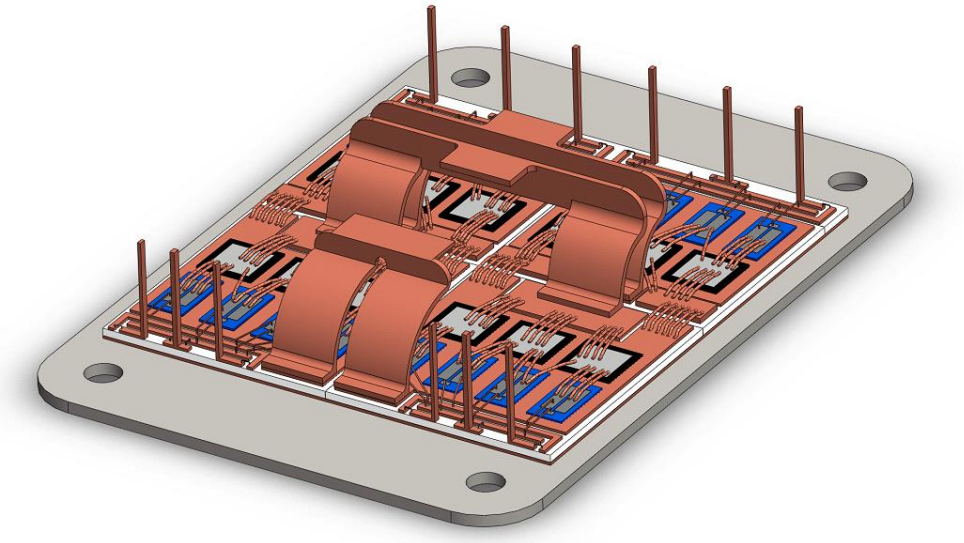


Figure 1: 3D CAD model of 1.2 kV, 300 A, 175 °C half-bridge module

The 3D CAD model was then imported into ANSYS Q3D to destine the partial self-inductances of the various parts of the geometry. The main contributors to the internal stray inductance were disclosed to be the bulky power terminals and the DBC substrate. The extracted parasitic inductances were then incorporated into a downscaled test circuit (800 V, 150 A) in LTSpice to assess the switching performance of the developed module. A pulse-test on the lower-side MOSFETs were conducted. The extracted parasitic and the SiC MOSFETs and SiC Schottky diode device parasitics made up the parasitic elements of the circuit. A gate driver circuit designed as per their datasheet were implemented. The SiC device LTSpice circuit models were provided by Cree. The turn-on and turn-off times were in the range of 25 to 50 ns, respectively, which is very fast compared to Si IBGTs for the same conditions (in the range of 200 ns). The study revealed that the power loop inductance gave a notch of 193.4 V (606.4 V) at turn-on and an overshoot of 137.2 V (937.2 V) at turn-off, as can be seen in Fig. 2. The current overshoot was due to the charging of the junction capacitance of the diode, which caused a displacement current adding to the load current. In addition, ringing in device waveforms were discussed and verified to being an effect of the power loop inductance resonating with the junction and output capacitances of the devices.

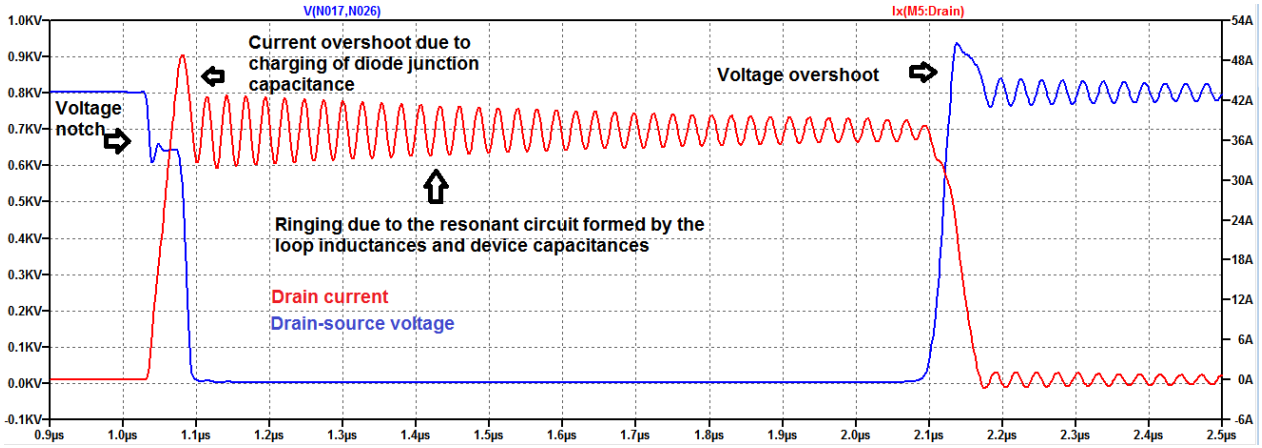


Figure 2: Simulated device voltage and current waveform

The developed module had a power loop inductance of 16.6 nH, yielding a mismatch of only 1.6 nH from the real Cree module. For the design of high-power conventional SiC MOSFET modules, a strip-line design of the power terminals (DC_+ and DC_-) were discussed to be the most viable approach for reducing the internal parasitic inductances at the time being. As the current rating of high-voltage SiC dies increases, the contribution from the DBC substrate is also anticipated to decrease.

The study validates the use of computer tools for investigating power module designs and advocates the usage as being a valuable part of a design methodology for cost- and time-efficient development cycles. The study also shows that using computer tools are a very valuable tool for understanding the performance of SiC MOSFET devices/modules for non-ideal conditions.

Voltage control for optimization of power transmission for a long subsea HVAC cable

Student: **Christen Paulov Engebretsen**
Supervisor: **Prof. Elisabetta Tedeschi**
Co-supervisor: **Gilbert Bergna**

Problem description

The objective of the thesis is to make a dynamic system representation of a long HVAC subsea cable, to investigate the use of controlling the operation voltage to optimize the active power transmission of the cable.

The task

The dynamic representation was based on the simplified model presented in *"Variable Transmission Voltage for Loss Minimization in Long Offshore Wind Farm AC Export Cables"* [1]. The paper is a static analysis investigating the potential of minimizing the losses for a long HVAC cable, by using either fixed or variable voltage control. The system presented in [1] consists of an offshore wind farm (OWF) connected to a grid onshore through an AC cable.

The analysis of the system only considers the cable side of the system by representing the OWF and the grid, with their respective transformers with on-line tap-changers (OLTC), as voltage sources, V1 and V2 respectively. This is made possible by assuming the transformers as ideal. The simplified system is presented in Fig. 1.

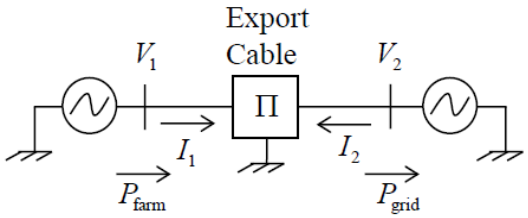


Fig. 1. Simplified system of [1].

Model

The dynamic representation of [1] made in the thesis, substitutes the transformers with OLTC, with back-to-back DC converters. The voltage regulation will then be faster. The dynamic representations for fixed and variable operation voltage were made in Simulink. The voltage source representing the OWF V1, was made as a voltage source with a voltage source converter (VSC) as a control loop to control the active power output of the voltage source. The voltage source representing the grid V2, was made as a voltage source with a fixed input for the fixed operation voltage model. The variable operation voltage model had a control loop, which adjusted the operation voltage based on the active power received at the grid side of the cable to create a more realistic model. It did not however continuously adjust the voltage scaling. The Simulink model of the system is presented in Fig. 2.

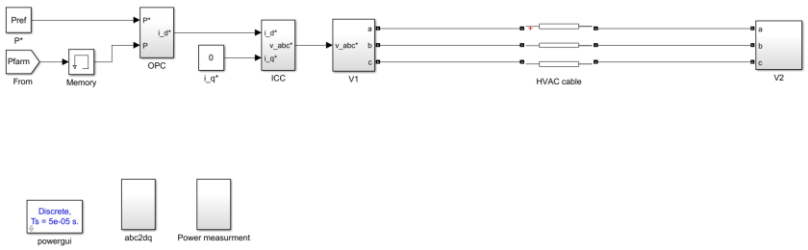


Fig. 2. Model of the HVAC system developed in Simulink.

The performance and viability of the system were investigated for several power production and fixed voltage levels. The performance was considered by calculating the cable efficiency. The viability of the system was considered by measuring the operation current and voltage to see if they were within the cable's operation limits.

Results

Most of the simulations were found to have exceeded the current limit of the cable, and none of the simulations had as high cable efficiency as in [1], Fig. 3 Fig. 4. The only simulations that did not exceed the current limit was the low production levels for variable operation voltage and low fixed operation voltage. The calculated cable efficiencies for the variable operation voltage model (Fig. 4) is found to be constant for all the production levels, 0.846.
The low fixed operation voltage simulations where found to have the highest operation area for power produced and the highest cable efficiency. The difference in results between the simulations in this Thesis and [1] can be explained by the high charging currents, which suggest that the cable selected for the simulations is not equal to the one in [1].

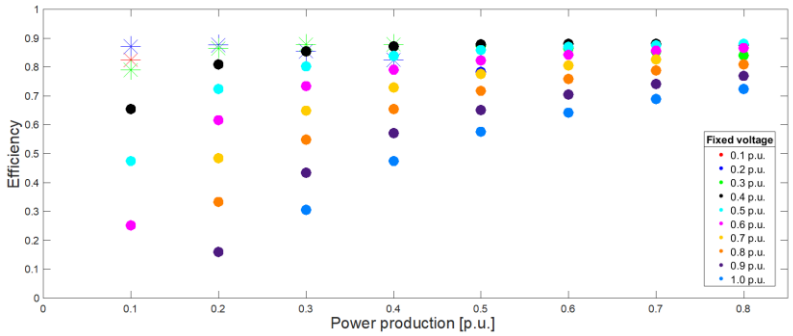


Fig. 3. 34. Calculated cable efficiencies for all the fixed operation voltage model simulations, within the efficiency area zero to 1. * and · denote that the operation current is within or exceeds the cable's current limit, respectively.

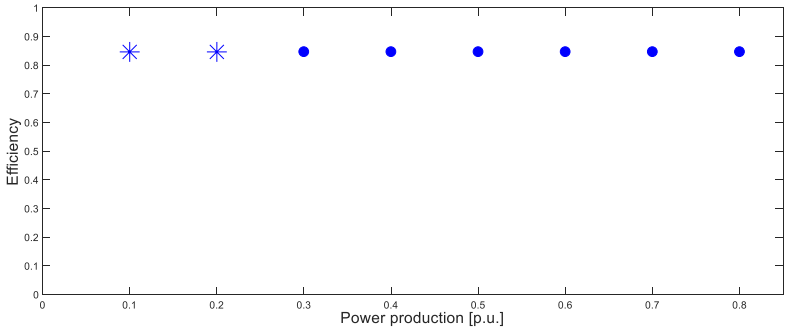


Fig. 4. Calculated cable efficiency for the variable operation voltage model simulation, within the efficiency area zero to 1. * and · denote that the operation current is within or exceeds the cable's current limit, respectively.

Conclusion

Even though the results of the simulations differed from the results found in [1], the use of voltage control to optimize the power transmission was however found to work as the simulations showed that low operation voltages gave the highest cable efficiency for low production and high operation voltage gave the highest cable efficiency for high production.

Stochastic Optimisation of Battery System Operation Strategy under different Utility Tariff Structures

Student: **Jørgen Sørgård Erdal**
Supervisor: **Magnus Korpås**

Problem description and modelling

This master thesis builds on the project work "En studie av økonomisk potensiale for PV-systemer og batterier i husstander for ulike nettleiestrukturer", and develops a stochastic optimisation software for household grid-connected batteries combined with PV-systems. The objective of the optimisation is to operate the battery system in order to minimise the costs of the consumer, and it was implemented in MATLAB using a self-written stochastic dynamic programming algorithm. Load was considered as a stochastic variable and modelled as a Markov Chain. Transition probabilities between time steps were calculated using historic load patterns from up to three previous years, exploiting the repetitive patterns of weekdays and weekends. PV-production was considered deterministic when included. The SDP-model was tested on data from Norwegian households for 2016, and the global optimum solution was used as a benchmark, as found using the dynamic programming model from the project work.

As Norwegian households were used as test cases, the Nordic power market Nord Pool Spot sat the scene for market transaction calculations. Day-ahead spot prices were used as market prices, meaning that the prices for the coming day was considered deterministic from noon the present day. The fixed 24-hour horizon optimisation was performed at midnight for each day, yielding an optimal wait-and-see operational policy for the battery system.

The optimisation was investigated under three different utility tariff (UT) structures: Energy based, time based and power based. The energy based UT is a fixed price per kWh, which is what is being used in today's market. The time based UT is a time-of-use tariff, which penalised use during peak demand hours 9-11 and 17-19 in weekdays. The power based UT increases linearly with the demand, designed to limit the power usage at any given time and day. While the energy based UT is what is being used as of today, the widespread roll-out of advanced metering systems (AMS) by 2019 in the Norwegian market will enable UT structures such as the time- and power based ones studied in this thesis.

Conclusion

The global optimal solution achieved 1.2 % (energy based UT), 14.2 % (time based UT) and 8.6 % (power based UT) of operational savings without a PV-system, illustrating the negligible potential for saving under the energy based UT. The developed SDP-model achieved 75-92 and 87-94 % of the global optimal savings without a PV-system under the energy- and time based utility tariff, respectively. This is increased to 92-99 % and 91-96 % with the PV-system installed. Under the power based utility tariff the model shows less promising results, scoring a maximum of 25-44 % of the global optimal solution without a PV-system, and 75-90 % with.

Gearing as a part of an Electric Machine Functionally

Student: **Johan Nicolai Fjellanger**
Supervisor: **Robert Nilsen**
Contact: **Eirik Mathias Husum**
Collaboration with: **Rolls-Royce Marine**

Several researchers groups in Europe claim magnetic gearboxes have significant potential as the replacement for mechanical gearboxes in various power conversion systems. One of the developments of magnetic gearing has been to integrate it as a functionally in an electric machine, thus leading to a new class of electric machines – pseudo-direct drives (PDD). It is believed that application of PDD in marine systems, e.g. propulsion units and deck machinery, can be beneficial. The task was to investigate and design such a machine for industrial application, given by Rolls-Royce Marine AS in Trondheim.

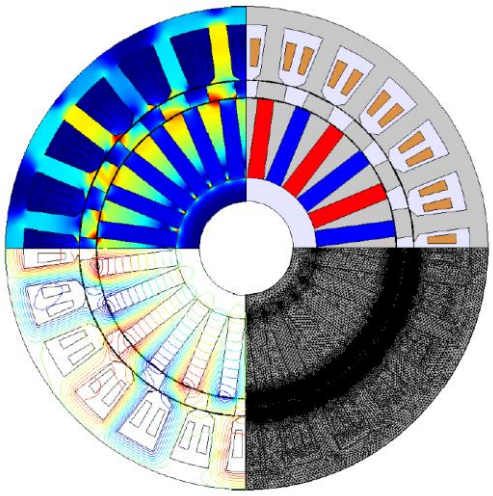


Fig. 1. Comsol PS-SFPM 24/20-machine model visual. Top left: Magnetic flux density. Top right: Geometry. Bottom left: Magnetic flux lines, where red and blue indicate direction. Bottom right: Mesh density overview.

Several integrated magnetic gear topologies was investigated, and Fig. 1 was the one showing the most promise. The machine is a partitioned stator switched flux permanent magnet machine(PS-SFPM). By partitioning the stator of the SFPM, the PMs are separated from the hot copper windings, and utilizes machine space more efficiently. While maintaining the flux focusing effect of the SFPM, this separation returns the conflict between PM, copper and iron back to the situation in a conventional brushless PM machine, where the air gap diameter determines the ratio of magnetic and electric loading. The main drawback is power factor, due to two air gaps instead of one.

Through use of Finite Element Analysis software COMSOL Multiphysics the machine was numerically investigated to determine different geometric parameter influences on machine performance. The machine was then soft optimized conclude whether it could meet the requested performance specifications of 200kNm and 4.2MW, at 200rpm, 1.2m diameter and 690V 3-phase, with no more than 2.4m machine length. The machine was found to be well within these criteria, but with low power factor of 0.52 and high cogging torque at 6.8%. Through shaping of the rotating modulating pole pieces, the cogging torque was reduced by 28.5%, at the cost of 11.2% torque reduction, and slightly lower power factor. The machine was found to be a very interesting concept that may be used for efficient low-speed high-torque application when lower power factor can be managed(i.e. power electronics).

Active Filter Capability of a Voltage Source Inverter in Marine Applications

Student: **Vegard Moritsgård Flatjord**
Supervisor: **Prof. Elisabetta Tedeschi NTNU**
Contact: **M.Sc. Hanne Rygg Siemens AS**
Collaboration with: **Siemens AS in Trondheim**

Problem description
In the marine and offshore business, an energy storage revolution is ongoing. Big energy storage solutions as Li-ion batteries are put onboard both vessels and rigs to increase robustness for blackouts and optimize the operation. DC main distribution allows easier integration of energy storage for these systems, which has resulted in a trend shift from AC to DC main distribution. However, the hotel loads and auxiliary loads, such as light, rectifiers and direct connected motors, are still AC loads. Thus, to be able to supply these loads, big static DC/AC converters (in the MW power level) are needed.
The goal of this project is to investigate the design requirement of these static DC/AC converters and involves: state of the art investigation of power distribution in onboard/offshore applications, understanding of technical requirements and constraints of these applications, power electronic design, regulator design and detailed simulation (in Matlab/Simulink) of the selected DC/AC converter. Implementation of an active filter will be performed with the aim of meeting the demands concerning the harmonic distortion.

This master thesis project will be done in co-operation with Siemens AS.

Abstract
This thesis is centered around the possibilities of utilizing the active filter capability of a Voltage Source Inverter (VSI) to mitigate harmonic distortion in a marine power system.

Hotel loads in marine vessels constitute an increasing part of the installed power onboard, as ships are increasingly electrified. Hotel loads represent the loads that are do not contribute to the propulsion of the vessel, e.g. lighting or cranes. The system studied in this thesis is presented in figure 1. The system consists of a power supply supplying hotel loads in the MW range. The power supply, which is connected to the internal DC-grids of the ship, consists of a VSI and a LCL-filter. The problem is related to the highly distorting hotel loads propagating harmonic distortion into the system. The harmonic distortion is mainly produced from the diode rectifier stages in Variable Frequency Drives (VFD). The VFDs are used to control AC-motor torque and speed by varying frequency and voltage at the motor terminals.

The main objective of this thesis is to ensure a voltage waveform at point B, see figure 1, within the requirements on Total Harmonic Distortion (THD) set by Det Norske Veritas (DNV). The worst-case THD obtained in the system exceeds the requirements. Measures must be taken in order to lower the harmonic content at point B and fulfill the requirements. An active harmonic filter integrated to the control of the VSI was developed in order to mitigate the harmonic distortion. Three cases have been simulated, with different degrees of harmonic filtering. The applied active filter features great performance and obtains a low THD well within the demands. However, it comes with a price in terms of increased power losses and the current rating of the components.
It was concluded that the active filter capability of the Voltage Source Inverter is sufficient to mitigate the harmonic distortion in the system. However, the results are strongly dependent on

the parameter data; further research should therefore put more efforts into gaining more precise estimations of these data.

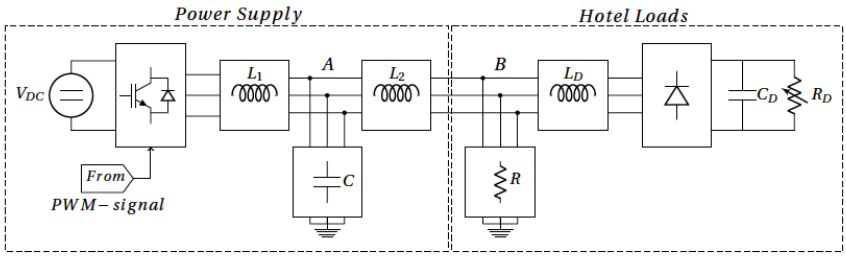


Figure 1: The system studied in this thesis.

Conclusion

A power supply in a marine power system has been investigated in this thesis. The power supply supplies highly distorting hotel loads onboard a marine vessel. The focus has been pointed towards the active filter capability of the power supply integrated Voltage Source Inverter. This section contains the most important conclusions that have been drawn.

The distorting hotel load, representing components driven by VFDs, was modelled in two different ways, both having a diode rectifier supplying a DC-load being either an ohmic resistance or a controllable current source. There were found negligible differences between the two models in terms of the THD. Therefore, it was concluded that the modelling of hotel loads is representative of the actual hotel loads located onboard marine vessels. A mathematical model of the system was built in order to investigate system properties in terms of voltage frequency and LCL-filter capacitor sizes. Due to the system properties found, it was decided only to focus on cancelling the 5th, 7th, 11th and the 13th harmonic orders. An Integrated Active Filter based on the selective harmonic mitigation method was developed in order to mitigate the harmonics dealt with. Three different cases were simulated, with various degree of harmonic mitigation.

Case 1 was simulated with the aim of totally cancelling the four harmonics dealt with. The IAF showed great performance with the ability to mitigate the relevant harmonics to negligible magnitudes. A satisfying worst-case THD of 3.44% was obtained, which is far better than the requirement of 8%. The worst-case power losses were at 3.58%, caused by increased system currents, which in this case were concluded to be too high.

Case 2 was simulated with the aim of fulfilling the THD requirements with a limited margin. Only the 5th and the 7th harmonics were dealt with in this case. Anti-windup of the PI-regulators made it possible to partly mitigate the harmonics dealt with and to reduce the size of the LCL-filter capacitor. This case shows small worst-case power losses of 1.94% caused by small system currents, which again are caused by the smaller capacitor and the limited degree of harmonic mitigation. Due to the limited harmonic mitigation, a worst-case THD of 7.18% was obtained.

Case 3 proposes a harmonic mitigation well within the THD requirements while still obtaining small power losses. This case is divided into two, simulating the system with a new and an old LCL-filter capacitor. When the the LCL-filter capacitor ages, the capacitance decreases. During aging, the THD increases and the power losses decrease. The decrease in power losses is brought on by a decreasing current when the capacitance gets smaller. An overall worst-case THD of 4.43% is obtained, with worst-case power losses of 2.27% of Sn. The active filter capability of the Voltage Source Inverter is sufficient to mitigate the systems harmonic distortion to magnitudes well within the requirements. If one is willing to increase the power losses by maximum 0.3% of Sn, the worst-case THD drops from 9.33% to 4.43% using the IAF setup in case 3.

Relay Protection of DG-units in Norway

Student: **Bendik Fossen**
Supervisor: **Hans Kristian Høidalen**
Collaboration with: **Sunnfjord Energi AS**

Summary
The relay protection monitors the electrical power system for abnormal situations. Its protection settings define whether a production unit should stay online or decouple during abnormal situations. Reviewing the current protective relay settings, used by the Norwegian industry, one sees that there is ground which suggests that the established settings are too conservative. This causes unnecessary decoupling of production units leading to financial losses. With an increasing number of production units in the distribution system, areas with a high production density could lose significant in-feed during abnormal situations. Decreasing the downtime of a production unit will not only have financial benefits, but could additionally improve the local stability of the power system.

This work investigates the current requirements for production units between 1-10 MW, the industrial use of these units, and the methodology for selecting the optimal settings. The methodology suggested concerns itself to meet the requirements of today, and builds a foundation on which to meet the requirements of the future. An actual distribution network from the collaboration company Sunnfjord Energi AS with two production units were analyzed
and modeled in the transient electromagnetic program PSCAD. To collect relevant data an on-site inspection was additionally conducted by this author.

The analyzed production units indicate conservative settings on production units built previous to 2011. Conservative protection settings limit the utilization of the fault-ride-through
capabilities of the production units. This in turn inhibits their use in providing local stability. Many existing production units were found to include insufficient or inadequate documentation, and in some cases lacked any all together. As of lately, there has been an increased focus on production units influence on the distribution system.

This analyze of an actual network resulted in new protection settings for one of the production units in question. The findings suggest specific improvements should be made to the current requirements to achieve a sustainable operation of production units in the distribution system.

Parallel Computing and Optimization with COMSOL Multiphysics

Student: **Sol Maja Bjørnsdotter Fossen**
Supervisor: **Robert Nilssen**

Summary

In this thesis the parallel capabilities of COMSOL Multiphysics are investigated. A description for how one can run COMSOL on a Linux cluster is presented. The speedup was found to be poor for medium-sized simulations with less than 10 million degrees of freedom. The speedup for parametric sweeps were found to be excellent. Particle swarm optimization (PSO) was implemented using LiveLink for Matlab, and run on the supercomputer at NTNU. It was found to perform very well without any tuning of the algorithm.

Wound Rotor Induction Machine – Laboratory Measurements of Stator Current Harmonics and Harmonic Propagation in the Distribution Grid Causing Power Quality Problem

Student: **Tone Følling**
Supervisor: **Trond Toftevaag**

A great deal of parameters effects the power system quality and harmonics is one of them. The origin of this thesis is a quality issue experienced by a customer in Norway, where troublesome flicker in the light equipment occurred periodically. Former investigations have found the cause of the problem to be fluctuation of, especially, the 7^{th} harmonic voltage. The reason for the fluctuation is the integer harmonic component and an interharmonic component, with frequency close to the integer, interfering with each other creating a beat frequency with approximately a frequency of 2 Hz. The quality problem coincided 100 % with a pump station located downstream in the distribution grid. The main objective of this thesis is to find if the wound-rotor induction machines (WRIM) in the pump station can be the only source of the interharmonic and harmonic components causing the flicker.

From the literature study about stator harmonic current it is found that the two components can arise in a WRIM. Where the origin of the harmonic 350 Hz component is saturation and the interharmonic component is due to a rotor-stator interaction. An equation is found to calculate the frequency of the interharmonic component which is dependent of the slip of the machine.

To verify the findings from the literature study, a laboratory test of a WRIM is performed at the Smart Grid laboratory at NTNU. The machine is connected to a controllable voltage supply, where both sinusoidal voltage and voltage containing harmonics is feed the machine to investigate the response in the current spectra with different supply condition. With results obtained from the analysis of data from the WRIM, a power system harmonic analysis is executed in the software Power System. Both a harmonic load flow and frequency sweep is carried out. This is done to investigate how the distribution grid will respond when a non-linear load (assuming the WRIMs are the only source of the power quality problem) is connected and to see how different parameters related to the simulation will affect a prospective resonance.

The stator current spectra of the WRIM in the laboratory displays both the harmonic and interharmonic component, which is in consistency with similar papers on the subject. The 7^{th} harmonic current is highly dependent on the voltage level as the component increases in the test where the voltage was increased above the machine's rated voltage. Adding harmonics in the supply voltage yields minor variations in the current spectra except the amplitude of the associated supply harmonics. In some of the tests, low resolution in the DFT gives consequential unusable data.

The power system harmonic analysis reveals that the harmonic currents from a non-linear load will propagate in the distribution grid, causing distortion of the supply grid. A worst case scenario, where only one load is connected and the resistance is set to be independent of the frequency, reveals a resonance close to 350 Hz when two shunts is connected to the bus where the harmonic current source is connected.

Short Circuit Current Contribution from Converters

Student: **Synne Garnås**
Supervisor: **Hans Kristian Høidalen**

Problem description

The implementation of converter connected distributed generation in the grid is increasing. The converter enables control of the renewable resources' intermittent nature, which leads to regulation of voltage, frequency, and power output characteristics. This makes converters a preferable interface for renewable resources. The implementation of these units introduces new challenges in the distribution grid. One being a bi-directional power flow. This could be problematic for the traditional protection scheme, because it is based on an one-directional flow. Another challenge, is that the units can impact the short circuit level.

The task

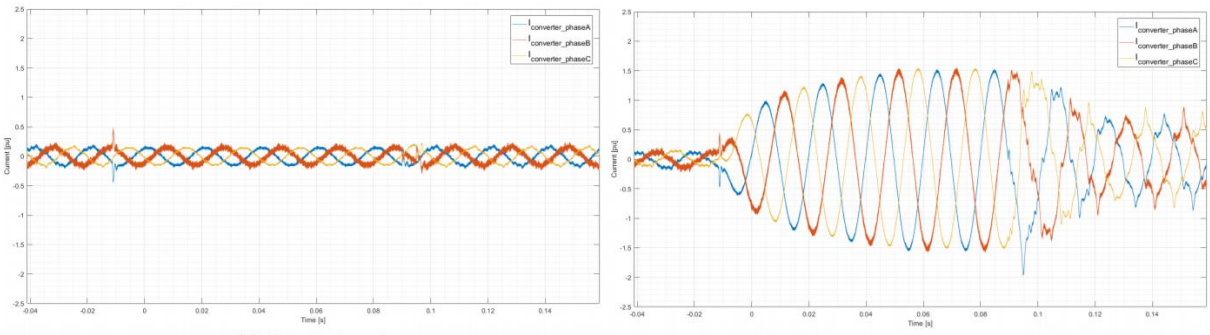
The scope of this master's thesis is investigating the short circuit current contribution from converters. Common practice today, is to operate with a rule of thumb saying that the short circuit current is one to two times the rated current. Therefore, the purpose of this thesis is to gain a deeper understanding of the converter short circuit behaviour, beyond the rule of thumb. The hypothesis of this thesis, is that the short circuit current contribution from a converter is negligible.

Model/ measurements

To investigate the hypothesis thoroughly, this thesis is divided into three parts. The first part, consists of a literature review. This review has two main goals: find research papers that have tested the short circuit contribution from converters either by simulations or by laboratory tests and to elaborated on the reasoning behind the rule of thumb. The second part, consists of simulations in Simulink. The purpose of these simulations, can be divided into two. Firstly, to predict the converter short circuit behaviour in the Smart Grid Laboratory. Secondly, to test aspects beyond the possibilities in the laboratory. The third part, includes laboratory tests. Short circuit tests will be performed on a voltage source converter in the Smart Grid Laboratory at NTNU.

Calculation

Two different control schemes were tested in the laboratory. Control scheme 1 was directly controlling the reactive and active current, while control scheme 2 supplied AC voltage support to the grid. Different external factors and internal control settings were changed, to investigate the impact on the converter short circuit contribution. The following settings were varied within one control scheme: the active current reference, the time of occurrence, the short circuit duration, the short circuit impedance, and the type of short circuit. Figure 1 illustrates the difference in the converter current contribution from the converter, when control scheme 1 and control scheme 2 is implemented.



(a) Control scheme 1.

(b) Control scheme 2.

Figure 1: $I_{converter}$ for a 100 ms three-phase short circuit with I_{active_ref} equal to 0.1 pu, T_{sync} equal to 9.8 ms and Z_{sc} equal to 2 mH.

Main Findings

- The implemented control scheme impacts the converter short circuit current contribution.
- The laboratory results show that a control scheme that operates as an AC voltage regulator, injects a larger current during short circuits than a control scheme directly controlling the current.
- The specific control settings and external factors could impact the converter short circuit current contribution. The extent of the impact depends on the implemented control scheme and the factor in questioning.
- The ratio between the current injected by the main supply and the converter, depends on the implemented control scheme.

Conclusion

The literature review corroborates the hypothesis to some extent. The review illustrates that the short circuit current contribution from a converter, is small. Some papers went as far as stating that the converter short circuit current contribution, is negligible. The results from the Simulink simulations showed that the short circuit contribution from one converter is small. However, this result is only accurate for the simplified control scheme implemented in the simulation model.

Some of the laboratory results also corroborate the hypothesis. Two different control schemes were tested in the laboratory. Results showed that the current contribution was largest with control scheme 2 implemented. However, even with this control scheme, the largest measured current was only 1.61 pu.

The findings in this Master's thesis, are not enough to make a general conclusion regarding the short circuit current contribution from a converter. To make such a conclusion, more research is needed. However, the findings have corroborated the hypothesis.

Power quality studies of a Stand-alone Wind-powered Water Injection System without Physical Inertia

Student: **Alexander Tufta Gaugstad**
Supervisor: **Elisabetta Tedeschi**

Problem description

The purpose of this thesis is to study the power quality in a stand-alone wind-powered water injection system for enhanced oil recovery. Water injection is crucial for boosting the recovery rate in mature oil reservoirs. The concept of a stand-alone wind-powered water injection system is to utilise a single wind turbine to solely power the water injection pump in an installation which is physically disconnected from the mother platform. The concept is possible due to recent technological developments within offshore floating wind power and advances within power electronic converters. The proposed electrical system is illustrated in fig. 1. The main objectives have been to develop a model in MATLAB/Simulink®, implement coordinated control systems and study the power quality during common, and important scenarios.

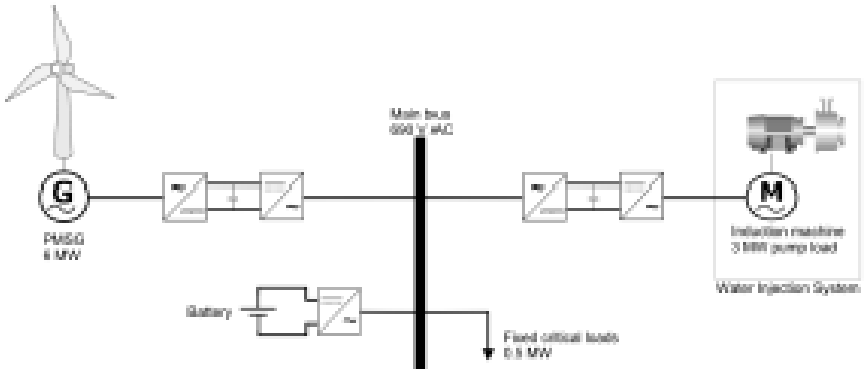


Figure 1: The proposed system studied in this thesis.

The system is powered by a 6 MW permanent magnet synchronous generator which is directly driven by the wind turbine. The generator is interfaced with the microgrid main bus through a 2-level back-to-back voltage source converter, in order to obtain variable speed operation of the turbine. The main load is the water injection system which is driven by a 3 MW induction machine with pump loading. The induction machine is also interfaced with the microgrid through a 2-level back-to-back voltage source converter for speed control. The battery storage is responsible for supplying the fixed critical loads during low wind conditions, and to control the main bus voltage magnitude and frequency.

The wind turbine is tested through several common wind scenarios. The performance is shown to be a trade-off between the ability to follow the optimal speed and fluctuations in

produced power. The turbine is further tested for fault ride-through capability and harmonic distortion.

Due to the slow pressurisation in hydrocarbon reservoirs, water is not required to be injected with a fixed rate. Thus, the water injection is performed only when there is wind power available. However, the wind is volatile, which makes it critical for the induction machine to be able to follow a rapidly fluctuating speed reference. This has been analysed in-depth. Another critical event of a microgrid is the capability of performing a black start. The battery has been tested and shown capable of establishing and maintaining the rated voltage and frequency of the microgrid.

The results obtained are thoroughly discussed throughout the thesis, simplifications and problems encountered have been highlighted.

Experimental Investigation of Operational Reliability of Silicon Carbide MOSFETs

Student: **Fredrik Tomas Bjørndalen Wergeland Göthner**
Supervisor: **Dimosthenis Peftitsis**
Contact: **Magnar Hernes**
Collaboration with: **SINTEF Energy**

Abstract

As the performance of silicon power semiconductors is close to the theoretical limit, other semiconductor materials are sought to improve power electronics system efficiency. Devices made with the wide bandgap material silicon carbide (SiC) are promising due to the possibility of significantly improved system efficiency and reduced system volume and weight. However, reliability is still a key issue to be dealt with before wide-spread use of the devices may take place.

In this thesis two of the largest reliability concerns of the SiC MOSFET are evaluated by investigating discrete devices. The issues are the threshold voltage instability and the reliability of packaging of the devices. Dedicated test benches were established to study the issues. The tested devices indicate that the drift of the threshold voltage is still an issue for SiC MOSFETs.

The methodology of performing power cycling tests was investigated. This accelerated life time stress test can be utilized to evaluate packaging reliability. The tests were performed by using the Vsd(T)-method to evaluate the junction temperature.

Several devices were tested, all of which indicated failure by bond-wire lift off. The results furthermore indicate that power cycling of SiC MOSFETs is affected by the threshold voltage instability. In particular, a reduction of the on-state voltage was observed at the beginning of almost all the tests, which was attributed to the instability of the threshold voltage. The results call for a discussion as to how power cycling of SiC MOSFETs ought to be performed, in order to reduce the influence of the threshold voltage drift. A suggestion for reducing the influence of the latter is also given.

Nettplanlegging i lys av timesmålinger fra AMS-målere og solcelleproduksjon

Student: Andreas Hammer
Veileder: Trond Toftevaag

Sammendrag
Nettplanlegging er et viktig område for alle nettselskap, og kartlegging av forventet kapasitetsbehov har blitt mer utfordrende med den økende andelen effektkrevende apparater og solcelleanlegg tilkoblet distribusjonsnettet. Dagens nettselskaper har ulike planleggingsmetodikker, og for nettplanlegging i NTE anvendes NetBAS. Verdiene for lastmodellene i NTE baserer seg på en rapport av belastningsundersøkelser utgitt i 1992. AMS-målerne som nå installeres hos alle norske strømkunder vil gi nettselskapene sanntidsinformasjon om belastningen i strømnettet. Smartere planlegging som utnytter slik informasjon vil være et viktig bidrag i utviklingen mot fremtidens smarte nett.

Målet med denne masteroppgaven gitt av NTE Nett, er å analysere forbruket til ulike sluttbrukergrupper. Dette gjøres for å avdekke forskjeller og likheter mellom målt forbruk hos kunder, og forventet forbruk gitt av dagens modeller for forbruk.

I denne oppgaven har forbruket til seks ulike sluttbrukergrupper blitt analysert ved å innhente timesmålinger for et utvalg kunder for en periode på opptil fire år. Gjennom analysen undersøkes variasjonen i forbruk mellom de ulike kundene. I tillegg vil nye modeller for forbruk og distribuert produksjon fra solceller utvikles, og modellene vil sammenlignes med dagens modeller. I denne oppgaven vil ikke modellene temperaturkorrigeres. Modellene vil testes på en case i NetBAS med formål om å undersøke hvordan de kan påvirke og eventuelt forbedre nettplanlegging.

I løpet av de fire årene som analysen omfatter viser analysen at maksimalt døgnforbruk til en kunde i gjennomsnitt vil inntreffe for et gitt tidspunkt i mindre enn 10% av dagene. I tillegg viser analysen at det er store variasjoner i forbruket til ulike sluttbrukergrupper, og tidspunktet for maksimalt døgnforbruk varierer.

En sammenligning viser at de nye produksjonsmodellene gir verdier som er lavere enn faktisk solcelleproduksjon i 7% av timene, mens for dagens modeller skjer tilsvarende i 35% av timene. De største forskjellene mellom modellert produksjon og faktisk produksjon er mindre enn 33% ved bruk av nye modeller.

Simuleringen i NetBAS viser at nye modeller for forbruk vil påvirke forskjellen i last og spenning i liten grad, mens forskjellen i årlig energitap er 19% lavere med nye modeller. Simulering med solceller viser derimot store forskjeller i årlig produksjon mellom modellene, og med nye modeller vil mengden innmatet effekt til samleskinnen reduseres med opptil 60% i en time sammenlignet med dagens modeller. Med dagens planlegging vil simulert last i nettet være 7% høyere enn målt maksimal last.

Dersom det i fremtiden kan planlegges med en risiko for overlast i noen timer i løpet av året, viser dette at størrelsen på transformator og forsyningskabler kan reduseres noe. Større usikkerhet i fremtidig belastning vil gi økt usikkerhet i planleggingen, noe som kan bety at dagens deterministiske planleggingsmetoder må erstattes av probabilistiske modeller, der de nye modellene for forbruk og solcelleproduksjon utviklet i denne masteroppgaven inngår.

Online Voltage Stability Monitoring in Distribution Networks

Student: **Hans Kristian Hansen**
Supervisor: **Kjetil Uhlen**

Power systems are often operated close to their stability limit. Line contingencies or other disturbances can cause the system to lose stability. If the power system loses stability counteractions have to be taken or else interruption in parts of, or in the whole system, occurs. In order to identify operational limits, the system operator needs the appropriate tools to make counteractions towards maintaining the security of operation.

Phasor measurement unit utilization has great potential for improved situational awareness in power system operation. This thesis assesses three indicators to monitor voltage stability in real time. All indicators are composed of changes in power with respect to changes in load. The indicators are based on local phasor measurements at the load bus, meaning no information about the topology is taken into account. In addition, two methods for estimating the Thevenin impedance and accordingly the maximum power transfer are reviewed. The methods and the indicators are suitable for online implementations to visualize the current state of the system and the distance to voltage instability.

Experiments realized through a laboratory power system consisted of a coil, a flexible line equivalent, a transformer and an adjustable resistive load. The scenarios the system was exposed to was an increase in load power demand and a line contingency. MATLAB simulations beforehand illustrate the theoretical behavior of the laboratory experiments.

As the indicators are able to detect the maximum power transfer limit, the trajectories visualizing the indicators will be of great benefit for the grid operators to identify the distance to the stability limit of the power system. As a large disturbance results in a severe change in power, the indicators need proper filtering depending on the desired monitoring. The estimation of the Thevenin impedance was validated and is corresponding with the calculated system impedance based on laboratory components. Nevertheless, the methods and indicators are viable for practical implementations in power systems to have an online voltage stability monitoring.

Analysis of Electromagnetic Behavior of Permanent Magnetized Electrical Machines in Fault Modes

Student: **Muhammad Usman Hassan**
Supervisor(s): **Robert Nilssen – NTNU**
Co-supervisor(s): **Henk Polinder – TU Delft, Astrid Røkke –Rolls Royce Marine AS**
Collaboration with: **TU Delft, Rolls Royce Marine AS**

Over the years, the use of PM machines has been increasing in the offshore wind industry and marine industry. The industries thrive on efficient function of the PM machines. These machines are prone to electro-mechanical faults due to environmental conditions and maintenance. Out of all these faults, stator internal faults are concerning as they can lead to insulation failures which may take around 30 seconds to expand and lead to a fire on ships, or on wind turbines. These types of faults develop gradually, which gives the opportunity to control the fault currents before they reach dangerous levels. Rolls Royce Marine AS is also working to tackle this problem for their hybrid propulsion shaft generator. DNVGL requires the generator to be made electrically dead during such event and the long-term propulsion should not be affected. During such conditions, WTs are either turned off or field weakening is used to develop a fault tolerant control (FTC) by the help of power electronics for the WT. FTC helps the machine not to be turned off completely, but less power is generated during fault conditions. An alternative efficient field weakening method using a Dual Rotor PMSM was suggested for both the applications. The DR-PMSM has two rotors instead of one, with identical surface mounted magnets on both rotors. One of these rotors has the capacity to rotate with respect to the other, to reduce the flux or completely short the flux path by misalignment of rotors. The machine stator is exactly like the conventional PMSM. The machine can reduce the induced emf to zero by field weakening.

In this thesis, a transient 3D finite element model is presented to test the credibility of the machine. A 2D FEM of a conventional PMSM was also built to check the validity of the machine. It is seen that torque is a function of the active length of the machine, and if a gap is introduced between the rotors then the total length of the machine must be increased. Also, axial flux component which induces eddy currents in the stator teeth was studied. By modeling anisotropy in the stator iron, certain hot spots could be seen in the middle part of the stator. The forces that were in the shifting mechanism were studied and it was concluded that machine cogging can be reduced to reduce the effect of these forces. A machine prototype was also built which confirms the field weakening capability of the machine.

The DR-PMSM works like a conventional PMSM but with flux weakening capabilities and can be implemented on marine and wind turbine applications for these type of fault conditions.

Analysis of CO2-emissions and power market consequences from electrification of offshore petroleum installations

Student: **Haavard Haugse**
Supervisor: **Magnus Korpås**

Problem description
The aim of this thesis is to analyze the power market consequences and CO_2 emissions related to electrification of Utsira using a GAMS model to simulate the future Nordic power system.

Main findings

- Electrification of Utsira will lead to an increase of nearly 7.3 million tonnes of CO_2 in the Nordic power system in the period 2020-2055. The net emission increase is lower than this, as the offshore emissions are not taken into account in this calculation. This number only represents the sum of yearly emissions on a five year basis and does therefore not represent the total emissions in the period 2020-2055. It does however give some idea of the general trend of emissions related to electrification.
- Emissions in 2055 will be near one third of what they are today, mostly as a result of increased installed wind capacity (and thus lower thermal production).
- An increase in installed wind capacity will result in less hydro power production.
- With an increasing CO_2 price as well as increased installed wind capacity, coal production, both lignite and hard coal, will decrease greatly.
- Being less emission intensive than coal production, gas power production will increase as the CO_2 price increases.
- The net import in Norway will increase towards 2030 as the power demand of Utsira increases. No extra power production is started to cover this load, resulting in everything having to be imported.
- Power prices will increase in the southern part of Norway as the power demand of Utsira increases and peaks around 2030. Power prices decrease slightly towards the last years of the simulated years. The model does not take into account the cost of new transmission cables, meaning the modelled power prices will be unaffected by these.

Hybrid HVDC Transmission for Large-Scale Offshore Wind Integration

Model-Based Control Design and Performance Assessment

Student: **Inga Haukaas**
Supervisor: **Prof. Olimpo Anaya-Lara**
Co-supervisor: **Dr. Raymundo Torres-Olguin**

Today, the world faces major challenges regarding our global environment. The most pressing challenge is global warming, and the scientific community is well aware of the catastrophic consequences an increase in global temperature will have. There is a global understanding that fossil fuels must be phased out as soon as possible, and renewable energy sources must replace them. Wind power is an important energy source which is mostly exploited onshore. Today, the number of offshore wind farms is increasing because they have some advantages over onshore installations like the high wind speeds and low turbulence. A challenge for offshore wind farm developers, are the transportation of power over long distances. HVDC-transmission technology is the preferred solution for offshore transportation, but it is dependent on an offshore converter station. It is expensive to install the converter station at deep water, therefore possible solutions for reducing the cost must be investigated.

This Master's thesis has investigated a hybrid converter topology which will reduce the power losses and the cost. The hybrid converter consists of a diode rectifier connected in series with a voltage source converter. The two converters complement each other in a way such that the power losses and the total cost are kept low. The hybrid solution has few active power devices and will therefore be a reliable and robust converter station. A model-based controller for the hybrid converter was proposed. The controller makes the solution flexible and adaptable to the system dynamics. The hybrid topology was compared with other converter topologies to see the benefits of using the hybrid solution.

The work on the hybrid converter began by reviewing proposals on alternative solutions for the converter platform. The control theory was studied to create a foundation of knowledge for the control design. The control objectives for the system was determined in the beginning because the objectives decide which parameters are to be controlled. Several control objectives make the controller more complex and difficult to implement. A model-based controller was developed by utilizing a procedure from the passivity-based control theory. A model of the system was implemented in the simulation program PSCAD/EMTDC and the control system was simulated.

Several approaches for the control design were tested before a final solution for a system with two control objectives was found. A dynamic performance assessment was performed on the final controller to validate that it performed well. A comparison between the different solutions showed that the hybrid topology has the advantages of lower losses and total cost. The hybrid topology showed promising results for further research and a detailed plan for future work was given in this thesis.

Dynamisk analyse fornettintegrasjon av småkraft

Student: **Vebjørn Vidarsson Haukaas**
Veileder: **Kjetil Uhlen**
Samarbeid med: **Siemens PTI og Voss Energi AS**

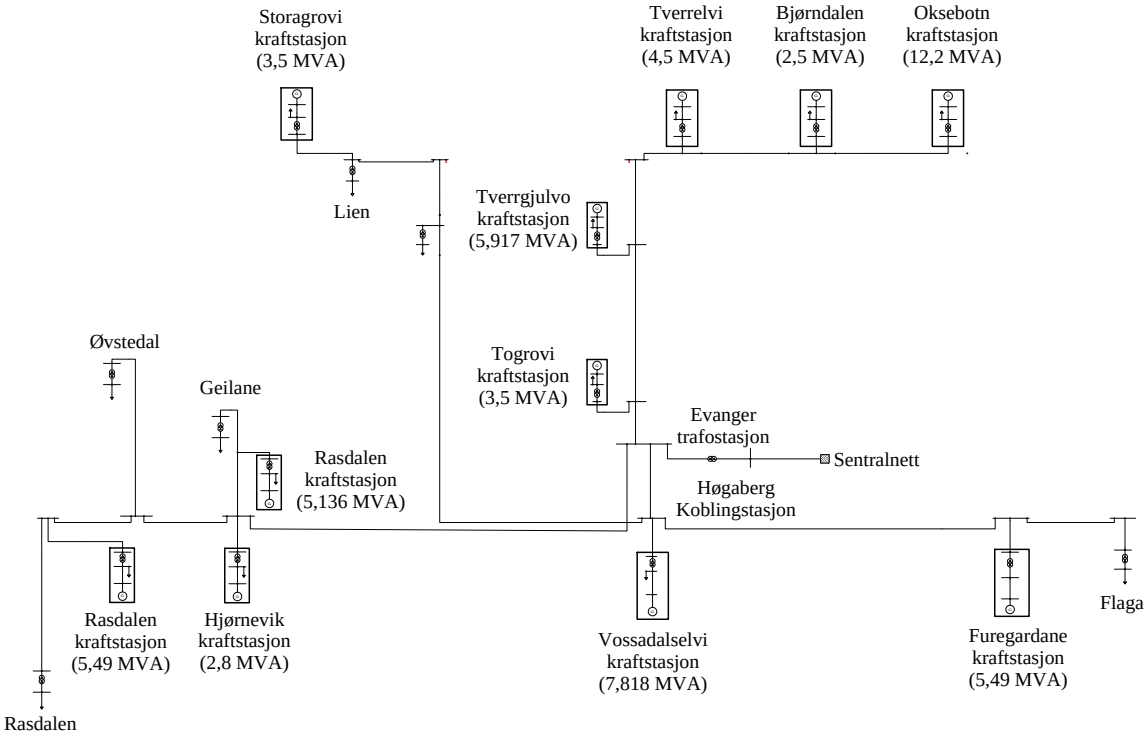
Et distribusjonsnett med mye lokal småkraftproduksjon kan gi stabilitetsutfordringer i nettet. Under Evanger trafostasjon er det i dag seks småkraftverk i drift. I tillegg er det fem småkraftverk som venter konsesjonsbehandling av NVE.

I denne oppgaven utføres det en dynamisk nettanalyse av nettet til netteier Voss Energi i område rundt Evanger. Dette innebærer kartlegging av transient og stasjonær stabilitet på eksisterende generatorer, samt sette krav for reaktanser og svingmasse på nye generatorer.

Nettanalysen viser at fire av eksisterende generatorer ikke transient stabile for feil med 20 % restspenning og varighet 200 ms i Evanger Transformatorstasjon. Tiltak som er diskutert på ustabile generatorer er øking av svingmasse og reduksjon av reaktiv effekt trukket fra nettet. Ved å studere egenverdiene til systemet, er alle generatorene å anse som stasjonær stabile. Krav til reaktanser og svingmasse på nye generatorer er riktig dimensjonert ut fra forutsetninger som settes til transient stabile generatorer.

Oppgaven vil ha høy fokus på utførelsen av slike nettanalyser. Det er blitt gjennomført en datainnsamling av 62 generatorer. 20 av disse ble brukt i et tobussystem for å undersøke hvor lenge de holder seg i synkronisme ved forskjellige spenningsdip. Videre ble påvirkningskraften til ulike parametre undersøkt på tre av disse generatorene. Dette for å kartlegge hvordan usikkerheter i slike parametre vil påvirke dynamiske nettanalyser, og hvilke forutsetninger som kan oppnå en konservativ nettanalyse. Slik kan man sikre at analysen ikke fører til feildimensjonering. Valg og diskusjoner i den dynamiske nettanalysen til Voss Energi, baseres på konklusjoner fra dette.

Alle dynamiske simuleringer ble gjort i PSS®SINCAL og PSS®NETOMAC.



Kontrollstrategier for lading og utlading av et batteri i samsvar med last og produksjon hos en plusskunde

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Faglærer: **Ole-Morten Midtgård**
Veileder: **Ole-Morten Midtgård, Henrik Kirkeby og Iromi Ranaweera**
Utføres i samarbeid med: **SINTEF Energi**

Sammendrag
Denne masteroppgaven har analysert funksjonaliteten til utviklede use cases ved å utføre forsøk i laboratoriet. Use casene har blitt utviklet for en batteripakke plassert i en husstand med PV produksjon tilknyttet strømnettet gjennom en plusskundeavtale. Use casene som har blitt testet og analysert er "Håndtering av plusskundens PV produksjon" og "Regulering av effekt trukket fra nettet".

Use case "Håndtering av plusskundens PV produksjon" har som mål å øke eget forbruk av sluttkundens PV produksjon ved bruk av en batteripakke. Use case "Regulering av effekt trukket fra nettet" har som mål å bruke batteripakken til å holde effekten trukket fra nettet under en bestemt effektgrense, slik at lastprofilen til husstanden er mer forutsigbar fra nettets perspektiv, uten de store svingningene.

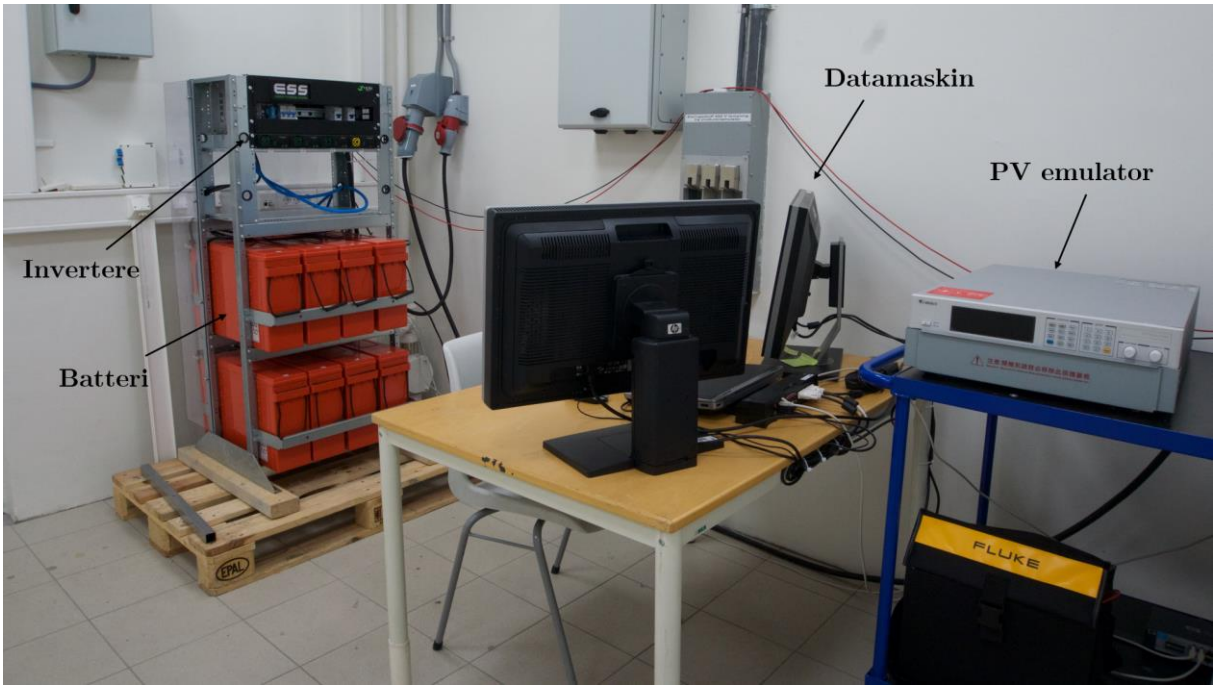
Det har blitt utviklet to modeller i NI LabVIEW, en for hvert use case. Laboratorieoppsettet hvor kodene har blitt testet i, består av et batterisystem levert av Eltek, kalt *Smart Storage Enabler*, og en PV emulator. Laboppsettet er avbildet i figur 1. PV emulatoren er brukt til å simulere et solcelleanlegg med PV produksjon. Smart Storage Enabler består av tre toveis-invertere, kalt *Ipack*, en DC-DC inverter som PV emulatoren er koblet til og åtte blybatterier. Hvert batteri har en nominell spenning på 12 V og nominell kapasitet på 190 Ah. Datagrunnlaget som har blitt brukt i forsøkene er timesverdier for last, solinnstråling og temperatur. Ved bruk av innebygde, matematiske modeller har PV emulatoren generert I-V og P-V kurver basert på solinnstråling og temperatur. I et videre studie, er det anbefalt å utføre forsøkene for et tidsintervall med høyere oppløsning, som 15-minuttsverdier eller 1-minuttsverdier, for å avdekke hvordan kodene og batteriet takler større fluktuasjoner i produksjon og forbruk.

Denne oppgaven har bidratt til at utstyret i laboratoriet er operativt, at utviklede use cases er implementert i NI LabVIEW til fungerende modeller og at inverterne i systemet kan svare på kommandoer og utføre spesifikke funksjoner fra NI LabVIEW via en CAN protokoll. Resultatene viser potensialet for forbrukerfleksibilitet hos en plusskunde med PV produksjon og energilagring. Gjennom utviklede use cases og forsøk i laboratoriet, har det også blitt demonstrert ulike måter fleksibiliteten til en batteripakke i samsvar med forbruk og produksjon kan utnyttes på.

For use case "Håndtering av plusskundens PV produksjon" kom det frem at det økonomiske potensialet basert på egenforbruket for testperioden, april til og med september 2015, er 2205.53 NOK uten bruk av batteri og 2291.97 NOK med bruk av batteri. Dette tilsvarer en økning på 4\%. Med andre ord, er installasjon av en batteripakke i systemet ikke lønnsomt med tanke på investeringskostnadene til batteriet. Imidlertid er det viktig å påpeke at batteriet kan gi andre nytteverdier, som å dekke effekttopper på vinteren og begrense innmatet effekt. Videre, ble det konkludert med at den totale energien matet inn i nettet synker med 33\% med bruk av batteri, fra 597.11 kWh til 397.49 kWh.

For use case "Regulering av effekt trukket fra nettet" kom det frem at det er hensiktsmessig å variere effektgrensene avhengig av hvilken årstid det er. Det ble også konkludert med at batteriet ikke klarer å kompensere for de største svingningene over effektgrensen. Ideelt sett skulle batteriet ha kompensert for all svingning over effektgrensen, slik at netto effekt trukket fra nettet ville vært lik effektgrensen og null over grensen. Ved effektgrensen på 1.2 kW, ble det trukket totalt 426.54 kWh fra nettet etter at effekten opp til effektgrensen, PV produksjonen og utlading av batteriet var blitt trukket ifra, mens for effektgrensen på 0.75 kW ble det trukket totalt 537.78 kWh fra nettet.

I tillegg til å ha denne rapporten som et resultat, har masteroppgaven resultert i to modeller i NI LabVIEW, med hver sin funksjonalitet som utforsker fleksibiliteten til et PV/batteri-system hos en plusskunde. Modellene gir derfor muligheter for videre forskning på forbrukerfleksibilitet hos sluttkunder. Det er også mange muligheter for videre arbeid med modellene, som å optimalisere kodene, utvikle kodene til å måle batteriets ladetilstand og dermed også bevare batteriets livssyklus. Det er også anbefalt, i et videre arbeid, å kombinere kodene som er utviklet, samt inkludere en parameter som teller måned og har tilgang til historisk forbruk og produksjon, slik at hvilken kode som skal kjøres bestemmes ut ifra dette.



Figur 1. Laboppsett.

Evaluation of a Medium-Voltage High-Power Bidirectional Dual Active Bridge DC/DC Converter for Marine Applications

Student: **Sindre Helland**
Supervisor: **Dimosthenis Peftitsis, NTNU**
Co-supervisor: **Eirik Elvestad, Rolls-Royce Marine Trondheim**

Due to an increased focus on the development of high-power marine microgrids, new vessels are being installed with large power systems including highly fluctuating loads operating at high efficiency and low emissions. The introduction of a battery energy storage system in a shipboard DC grid allows for operating the diesel gensets at variable speeds, not being locked to a fixed frequency or speed. The transient performance of the system can also be improved and an optimal load leveling of the different prime movers can be achieved by the proper implementation of a battery. Thus, the system can operate efficiently with highly fluctuating loads while keeping the fuel consumption low.

In order to integrate the batteries into the shipboard DC grid, high-power bidirectional DC/DC converters are needed. Many converter configurations are available, yielding different advantages and disadvantages. Thus, each different system should be evaluated in order to see which converter topology is best suited for that specific system. The stress levels on the switching devices are also higher than before, which can be seen as a result of the utilization of higher voltages and currents in the shipboard grids. Isolated bidirectional DC/DC converters for high power applications can provide the proper connection, but along with the increased loads comes higher requirements to component ratings as well as a more complex control system.

A high-power medium-voltage DC/DC converter suitable for implementing such a battery is analyzed in this thesis after explaining the shipboard electrical system. The converter has a rated power of 4MW with an equal input and output voltage of 1100V and with a high-frequency transformer providing galvanic isolation between the shipboard power grid and the battery. Its performance is evaluated by means of modeling it in Matlab/Simulink where the focus has been on the switch resonance components in order to achieve a high-performance, soft-switched converter.

A PI controller is also implemented in order regulate the output voltage of the converter for different load levels. As some of the converter requirements are a robust design, high operating efficiency and a fast response, the PI controller is tuned in order achieve this and it is seen that the converter responds fast with small deviations in parameter values for load variations of several megawatts. A gate signal generator is also made, where the output of the PI controller is used as input, delaying the gate signals to switches in either the primary or secondary side, depending on the power flow direction.

The model is used to analyze the current waveforms through the switches and the transformer, and by doing measurements and calculations based on the simulation results, the efficiency of the converter is calculated at different load steps ranging from 0 to 4MW. It is seen that the converter operates at an efficiency of 97.2% at an output power of 4MW with increasing efficiency for lower load levels due to the lower conduction losses. However, the high-frequency transformer is assumed ideal in this thesis and thus the efficiency will be somewhat lower with this included.

Use of Battery Energy Storage for Power Balancing in a Large-Scale HVDC Connected Wind Power Plant

Student: **Marta Naasen Hellesnes**
Supervisor: **Elisabetta Tedeschi, NTNU**
Co-Supervisors: **Kamran Sharifabadi, Statoil ASA**
Santiago Sanchez Acevedo, NTNU

Problem description

The increasing implementation of intermittent renewable energy sources into the power system brings challenges in terms of grid stability, power quality and security of supply. Traditionally, thermal power plants and rotating reserves based on fossil fuels have been used to provide balancing services in the grid, but due to an increased focus on sustainable solutions and increasingly demanding climate goals, more environmental friendly solutions must be considered. The main objective of this thesis is to study how battery energy storage can be used to provide the ancillary services of primary and secondary reserves to the grid, in order to help stabilize the grid and support integration of large scale offshore wind power.

Based on the literature review of available battery storage technologies, and DC/DC converter topologies, the project will focus on the analysis and simulation of the system including the wind farm feeding an HVDC transmission system and the battery interfaced to the HVDC-link by the selected DC/DC converter. When the onshore AC grid requires primary reserve support, the battery storage should provide the primary and preferably secondary reserves for limited time. The task includes defining the optimal system configuration, considering the battery storage feeding the HVDC-link on the DC-side, and analyzing different operating scenarios. Simulations will be implemented in MATLAB and Simulink.

Method

The system studied in this project consist of an offshore wind farm connected to the grid onshore via a high voltage direct current (HVDC) transmission system. Battery energy storage is connected through a DC/DC converter to the DC-link of the HVDC system, as shown in figure 1. The main focus of the work is related to the battery and the DC/DC converter. The battery consists of Li-ion battery cells and the DC/DC converter is a bidirectional galvanically isolated DC/DC converter which consists of a modular multilevel converter (MMC), a two-level voltage source converter (2L-VSC) and a medium frequency coupling transformer.

The scope of the thesis consists of two main parts; a design part and a simulation part. In the design part, the design of the different components of the system are discussed in terms of voltage levels, power ratings, number of components, type of components, size and cost. In the simulation part, simulation models of the different parts of the system are developed. The models are implemented in MATLAB and Simulink. The different parts are modeled and verified separately before the final system is created by connecting the different parts. Two simulation cases are performed.

In the first case, a simulation of the DC/DC converter and the battery is performed. The power flow is controlled to be both positive and negative to verify that the converter provides bidirectional power flow so that the battery can charge and discharge, depending on the state of charge (SOC). A battery SOC model has been included in the 2L-VSC model in order to verify that the battery is charging and discharging.

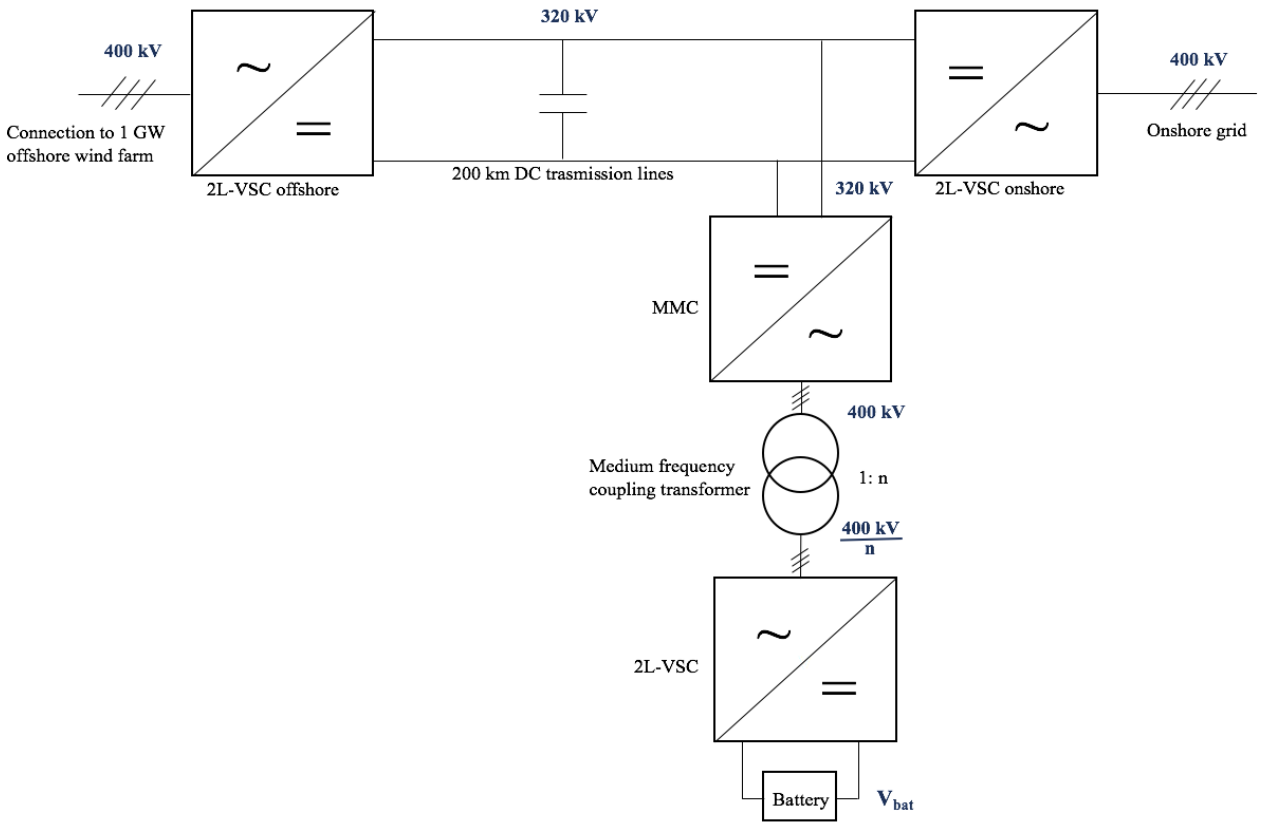


Figure 1: One-line diagram of the system

The second simulation case also includes the simulation model of the HVDC transmission system, the offshore wind farm and the grid onshore. In this case the power flow of the HVDC system and the DC/DC converter is controlled so that when the wind power generation increases above the constant power consumption onshore of 0.82 pu, the battery system must charge, and when it decreases below 0.82 pu, the battery system must discharge, in order to provide a constant power flow of 0.82 pu to the grid onshore. This is simulated to verify that the battery storage can provide ancillary services to the grid and provide balancing services in order to stabilize the grid and support integration of offshore wind power into the power system.

Results and conclusion

In the results of the design part of the thesis an optimal design of the system is proposed. Some of the main design results are provided here. The battery is designed based on ABB's EssPro™ Grid battery modules and the battery in this project consists of 273 such modules implying that it will be large, and regarding size and costs it is an advantage to place it onshore. In terms of semiconductor devices for the DC/DC converter, it is found that the insulated-gate bipolar transistor (IGBT) press-pack devices are preferred over the integrated gate-commutated thyristor (IGCT) for both the MMC and the 2L-VSC for the converter design in this project. It is also found that for the galvanic isolation of the DC/DC converter, the optimal choice is to have a medium frequency transformer with a frequency of 300 Hz and a turns ratio of 1:3.

The results of simulation case 1 are shown in figure 2 and they show that the battery can charge and discharge and that the proposed DC/DC converter provides bidirectional power flow.

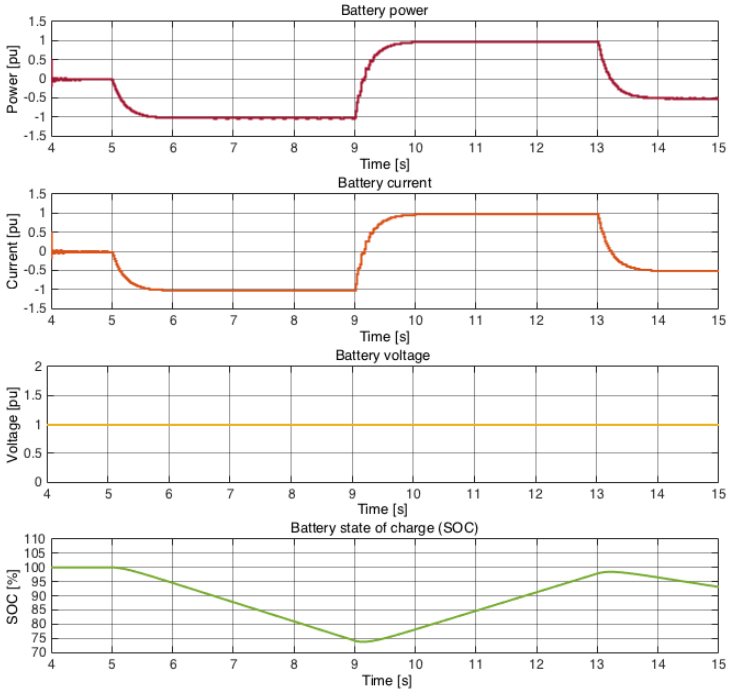


Figure 2: Results showing that the DC/DC converter provides bidirectional power flow and showing that the battery can charge and discharge

The results of simulation case 2 are shown in figure 3. They show that the battery helps stabilize the grid to provide constant power flow to the onshore grid by charging in times when the wind power generation is higher than the power consumption onshore, and by discharging in times when the wind power generation is lower than the consumption.

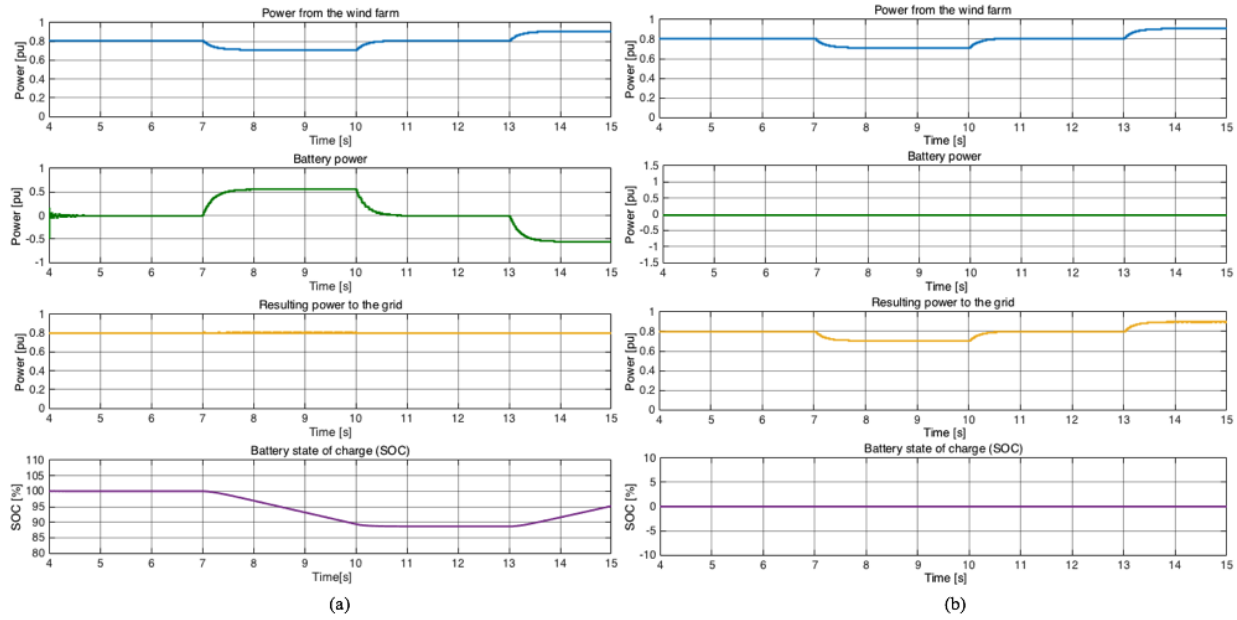


Figure 3 (a): Results when the battery storage system is not connected and the offshore wind power production is variable, resulting in variable resulting power fed to the grid onshore. (b): Results when the battery storage system is connected supporting the grid to provide a constant power flow to the grid onshore.

The main conclusion to the thesis is that battery energy storage can be used to provide ancillary services to the grid in order to help stabilize it and support integration of intermittent renewable energy sources. The conclusion is supported by the literature review and theoretical background in the thesis in addition to simulations that verify this.

Metodikk for identifisering av potensielle nettområder for mikronett i distribusjonsnett

Student: **Tomas Oskar Hellesø**

Faglærer: **Kjell Sand, IEL**
Veileder: **Arnt-Magnar Forseth, TrønderEnergi Nett AS**

Utføres i samarbeid med: **TrønderEnergi Nett AS**

Problemstilling

Oppgaven går ut på å lage en metodikk for identifisering av potensielle nettområder for mikronett i distribusjonsnett. Herunder besvare:

- Hvordan bør et nettselskap gå frem for å identifisere potensielle nettområder for mikronett?
- Hvilke kriterier bør vektlegges i en slik kartleggingsmetodikk for mikronett?
- Hva må ligge til grunn for at mikronett kan være et lønnsomt alternativ kontra tradisjonelle nettoppgraderinger?
    - Hvor mange og hvor store mikronett?
    - Hvilke analyser/simuleringer bør gjøres og hvordan?

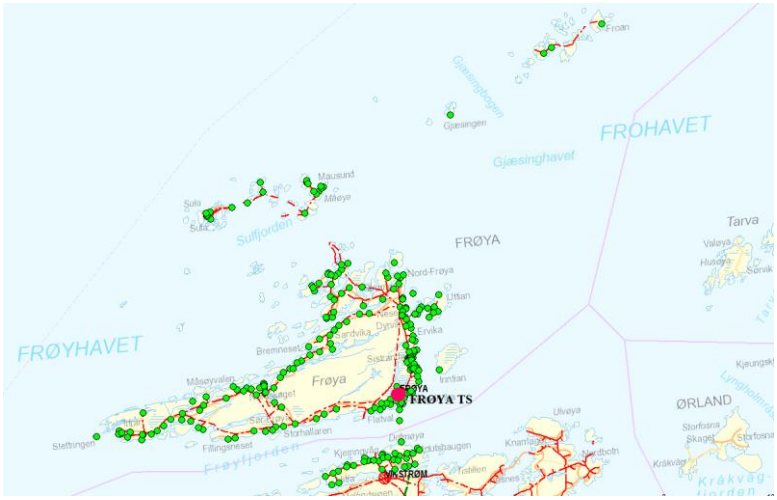
Oppgaven

Denne masteroppgaven presenterer en prototype til metodikk for identifisering av potensielle områder for mikronett i distribusjonsnettet til TrønderEnergi Nett AS. Med mikronett menes en egen kontrollerbar enhet i kraftnettet med last, distribuert energiproduksjon og energilagring som kan driftes både tilkoblet kraftnettet eller frakoblet i såkalt øydrift.

Metodikken benytter programmet Powel Netbas til å identifisere og hente ut nettdata til potensielle caser med svakt lavspentnett, deretter analyseres egnethet formikronett i casene med programmet Matlab. Avslutningsvis gjøres en kostnad-nytte-analyse for de fem best vurderte casene. Kostnadsanalysen gir en prisindikasjon om etablering av et mikronett i øydrift kan være samfunnsøkonomisk lønnsomt i hvert case. Rapporten tar i hovedsak for seg nettanalyse og vurdering av kriterier for å identifisere og vurdere potensielle mikronett-caser.

Modell/målinger

For å utarbeide metoden ble programmet Powel Netbas benyttet til å fremskaffe nettdata for potensielle mikronett-caser ved søkefunksjon og fra kartvinduet. Figuren her viser nettstasjoner (grønne prikker) supplert fra transformatorstasjon på Frøya (rød sirkel). Videre ble data for 50-100 potensielle caser eksportert og vurdert i Matlab.



Beregninger

I tabellen vises kostnadsberegninger for testcase «Fillan», der Olderøy Vest trekkes frem som eneste gunstige case for mikronett med kostnadsnivå over case-spesifikk grense på 4 kr/kWh. Casene er nettstasjoner med tilhørende svakt lavspentnett.

Tabell 9.2: Kostnader for Fillan inkl. hsp-lengder

Case nr.	Plassering	hsp-lengde [km]	Pris [kr/kWh]
1	22060 OLDERØY VEST	0	4.85
2	20650 KULVIK	0.488	2.47
3	21750 FAKSVÅG	0.134	1.53
4	21400 GJØSSØY	0.208	1.43
5	21900 HELGEBOSTAD	0.414	1.74

Konklusjon

Det ble konkludert med at en fungerende fire-trinnsmetodikk for mikronett i øydrift ble oppnådd. Metodikken ble utprøvd for to ulike testcaser i prosjektet. Styrken til metodikken er at den nyttiggjør seg av den store mengden nettdata et nettselskap besitter, og metodikken kan vurdere nettdata til flere hundre caser samtidig. Svakheten til metodikken er at den ikke automatisk identifiserer caser ytterst på radiell i distribusjonsnett (avgjørende faktor for grunnlag til å søke NVE om "Fritak for leveringsplikt"). I tillegg må lengden av høyspentledning for radiell ut til nettstasjon sjekkes manuelt i Netbas-kartet. For kriterier ble det konkludert, at de fire viktigste kriteriene for at mikronett kan være lønnsomt i et case er:

- Lavt energiforbruk [kWh]
- Svakt lavspentnett med behov for nettforsterkning,
- Nettstasjon ytterst på radiell i distribusjonsnett
- Nange høyspentlinjer for radiell ut til nettstasjon.

Fra resultater i testcasene ble det funnet et case: "22060 Olderøy Vest", som potensielt kan være lønnsomt for videre mikronett utredning.

Planlegging av mikronett

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Veileder: **Kjell Sand**
Utføres i samarbeid med: **Nordlandsnett**

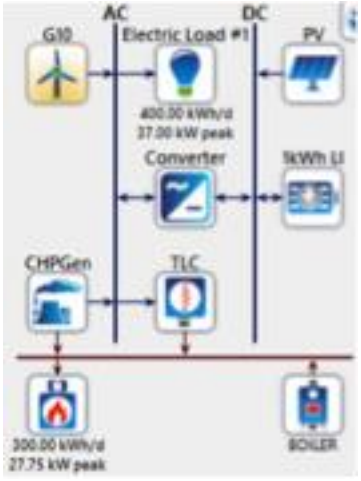
Problemstilling
Målsetningen med oppgaven er å belyse hvordan et mikronett generelt kan planlegges og designes på en best mulig måte.

Oppgaven
Oppgaven studerer planlegging av mikronett og har som målsetning å belyse hvordan et mikronett kan planlegges på en best mulig måte. Oppgaven er delt i to deler, hvor den første delen er et litteraturstudium og den andre delen er praktisk planlegging av et mikronett.

Litteraturstudiet inkluderer relevant teori for distribuerte generatorer, energilagringssystemer og laststyring. Og det er utarbeidet en systematikk for å planlegge et mikronett som er basert på SINTEF sin planleggingsbok for kraftnett og retningslinjer for planlegging av mikronett utarbeidet av IEC.

I den praktiske delen blir et mikronett for øyen Givær planlagt.

Modell
Mikronettet for Givær ble planlagt i planleggingsverktøyet Homer Energy. Det ble utarbeidet flere løsninger for mikronettet på Givær, og systemdesignet for den beste løsningen er vist i figuren under. Mikronettet inkluderer 50 kW vindturbiner, 14 kW solceller og et kombinert varme- og kraftverk driftet av biodrivstoff.



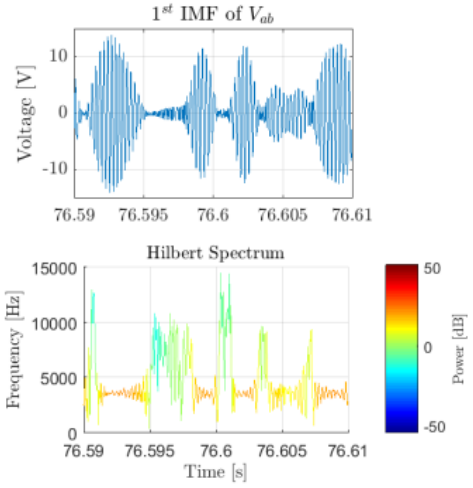
Konklusjon
For mikronettet på Givær ble den beste løsningen oppnådd når energibehovet til øyen ble sett på som en helhet og deler av elektrisitetsforbruket ble flyttet til termisk last. Dette gjorde det mulig å utnytte restvarmen i et kombinert varme- og kraftverk slik at energiressursene ble best mulig utnyttet. Planlegging av mikronett skiller seg vesentlig fra tradisjonell planlegging av kraftnett ved at det i må tas hensyn til flere faktorer.

Methodology for Detecting and Interpreting Instantaneous Frequencies in Stand-alone Microgrids

Student: **Benedikt Hillenbrand**
Supervisor: **Marta Molinas**
Contact: **NN**
Collaboration with: **NN**

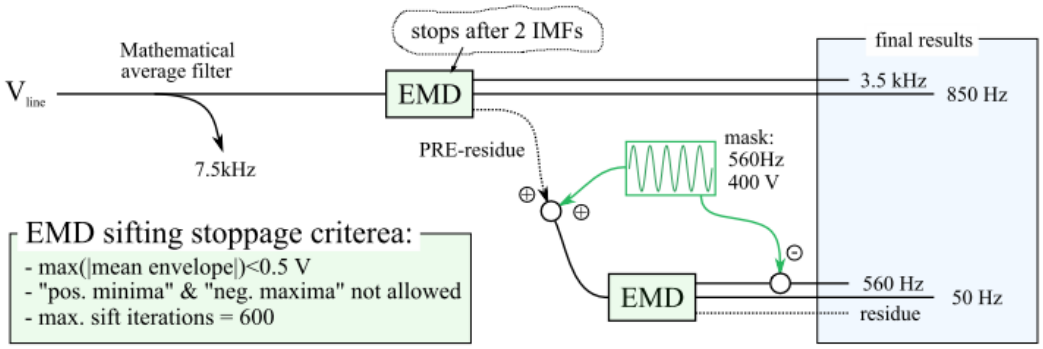
Problem description

The majority of measurement Equipment is not ably to show the truth about the signal that is measured in small remote microgrids. These microgirds, with a major share of power electronics in the generation-, or consumption, are susceptible to (fundamental) frequency variation as the stabilizing effect of the inertia from rotating machines is missing.
As most measurement equipment is based on Fast Fourier Transformation (FFT) to separate the fundamental frequency from low-, and high frequency components, and the FFT is based on the assumption of slow changing fundamental frequency variation (to adjust the measurement window), measurements can be inaccurate. Example cases are 3-phase electrical grids in developing countries, the electrical network in all electrical vessels or other 3-phase grids that operate in remote mode. The thesis focuses on deriving the analysis of electrical measurement from the basics and suggests to investigate in three stages. Starting at single phase-measurement, extending to 3-phase current and voltage representatives and ending with the analysis of instantaneous power. The results from the investigation on one of the three the line-voltage is shown in the following figure. Only the highest frequency mode is depicted.



The task

The Task is to tune the algorithm of the Empirical Mode Decomposition (EMD) and test it as a tool to replace the Fast Fourier Transformation. The EMD is a non-linear algorithm that shows possibilities to separate oscillation modes when the signal is non-linear and non-stationary. An example application is given in the following figure:



Model/ measurements

The data that is handled within this thesis is the voltage-, and current recording from an al-electric marine vessel during sea voyage, captured by Tomasz Tarasiuk from Gdynia Maritime University. The measurements are recorded with a sample-rate of 30 kHz. The ship comprises a 3-phase, 3-wire network and line-voltages and phase-currents are recorded.

Calculation

The work that has been done within this thesis can be split in two parts. At first, existing methods have been derived from scratch again, to be used in the later analysis. The major work is to find successful applications of the EMD on the measurement signal. The EMD is tuned and used at different stages in the conversions of the raw measurement signal.

Conclusion

The EMD shows promising results and has been proved to be able to extract the expected information on frequency variation. Further on a far deeper insight on the complete harmonic spectrum of the measurements has been obtained. However, the EMD-algorithm needs to be improved to increase the quality of the resulting data. This can be done by researching on publications or inventing own methods.

Feasibility Studies on a Stand-Alone Hybrid Wind-Diesel System for Fish Farming Applications

Student: **Marius Holt**
Veileder: **Kjetil Uhlen**
Utføres i samarbeid med: **NVES**

This thesis aims to explore feasibility related to implementing a Hybrid Wind-Diesel System for an offshore fish farm. The primary motivation behind this is to exploit the excellent wind resources along the Norwegian coast in order to reduce CO_2 emissions related to the operation of diesel generators (DGs). Thus, instead of diesel as the only source of electrical power, the hybrid system will utilise a wind turbine and battery system to reduce the diesel generator's operating time as much as possible. Additionally, excessive wind energy from the wind turbine could be used to run auxiliary equipment on the farm, such as oxygen production, washers for lice removal and freshwater production.

As a starting point, the thesis provides a clear and perspicuous overview of conventional offshore fish farms and Hybrid Wind-Diesel Systems in general. This constitutes the basis for building a suitable model from fundamental blocks in the MATLAB/Simulink environment. The purpose is assessing the system's dynamic performance when exposed to disturbances.

The hybrid system comprises a Permanent Magnet Synchronous Generator (PMSG) wind turbine, connected to a 400 V AC bus bar through a back-to-back Voltage Source Converter (VSC) and a step-down transformer. The purpose of the turbine VSC is to facilitate variable speed operation of the turbine and also enhance system control. The battery is of Lithium-ion type and incorporates a VSC for AC/DC conversion. The fish farm also contains an Electrically Excited Synchronous generator (EESG) associated with a diesel engine. This can be used for fast active and reactive power support if the wind and battery system fails to cover the load. The main load is a fixed, inductive load together with a variable-speed Induction Motor (IM), and the dump load consists of a variable inductive load and a directly connected IM.

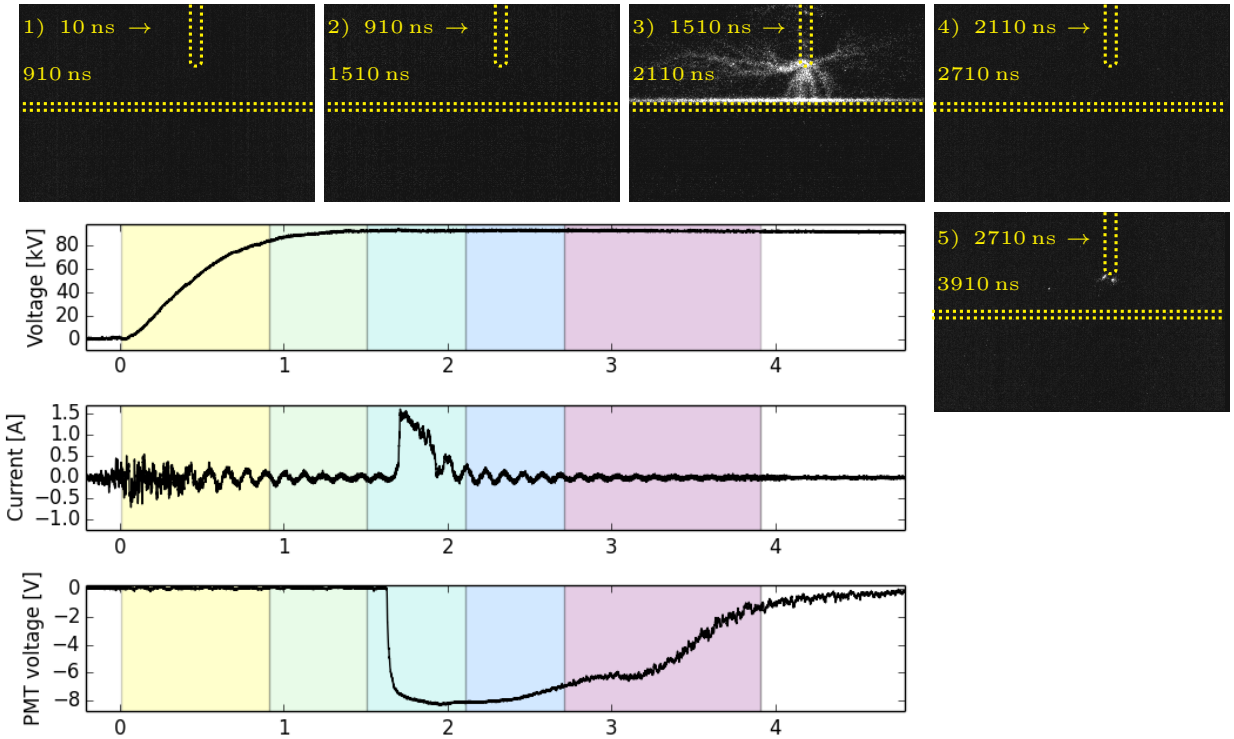
Three critical situations have been investigated. These represent some of the most frequent and severe situations that the system will have to endure on a day-to-day basis. Start-up of the directly connected IM proved to be the most critical scenario, due to the high initial reactive power requirement. If sufficient resources of reactive power are not present, this may lead to a permanent voltage collapse. Starting the DG during sudden shortfall of wind indicated redundancy. However, the importance of bringing it online in generator operation and not in motor operation was highlighted. Start and stop of the feed blowers induced little stress on the system, even at low wind speeds. Overall, the system shows promising performance during most of the investigated disturbances.

Streamer Charging of Dielectric Barriers in Inhomogeneous Air Gaps – Measurements of Surface Charge Depositions

Student: **Martine Husøy**
Supervisor: **Frank Mauseth, NTNU**
Co-supervisor: **Atle Pedersen, SINTEF**

Abstract

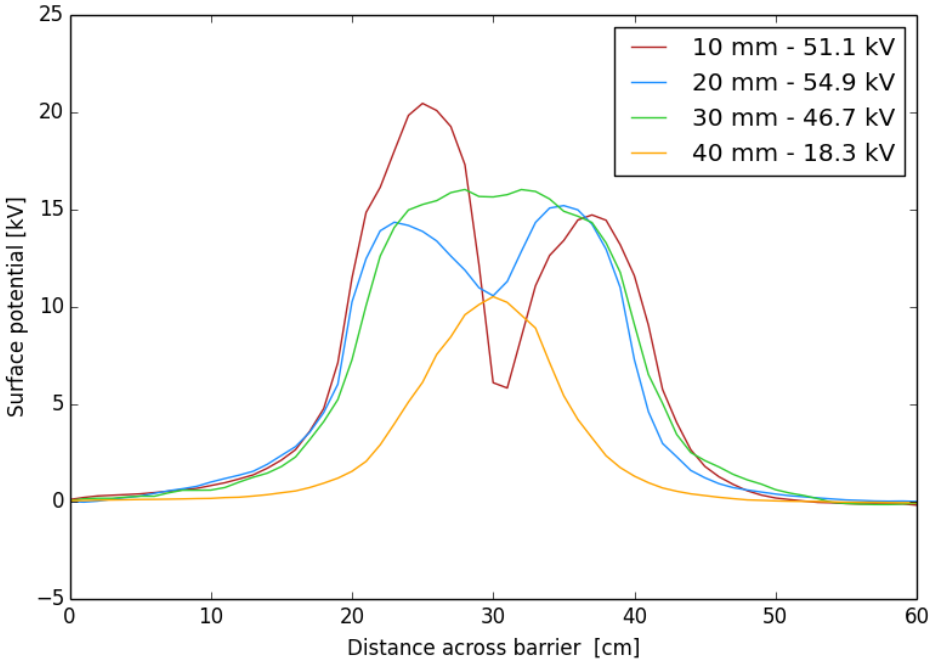
The purpose of this thesis is to conduct experiments on a rod-plane gap, with and without a dielectric barrier. The gap is connected to an impulse generator, which stresses the gap with a lightning impulse triggering streamers in the gap. The residual charge left by streamers can be measured with a nullifying probe. Two different laboratory set-ups are used. One with a grounded plane and the other upside-down with a grounded rod. Cameras able to take a trigger pulse was added to the grounded-rod set-up, but due to electric noise and other problems with the camera set-up, the camera ended up never working properly. The grounded-plane set-up on the other hand has a working camera and the possibility for measuring residual charge left on the barrier.



Gap with d = 60 mm and a = 20 mm. The barrier is not washed after the last streamer and is stressed with repetitive lightning impulses. The voltage is increased until a new streamer, presented here, occurred. The coloured slots in the graph represent the

The residual charge measured after streamers have shattered charged particles all over the barrier, shows that the shape of the residual charge curve was either bell- or saddle-shaped. If the residual charge is saddle-shaped, back-discharges are visible in the PMT-signal. The saddle-shape is present when the barrier is close to the rod and/or the applied voltage is high.

Pictures taken of streamer activity in the gap show that a bright channel sometimes ignites after a streamer has developed in the gap. The bright channel looks more like a leader than a streamer. The rod-plane gap where this leader-type channel is observed is 80 mm or shorter. Leaders are traditionally only observed in gaps longer than 1 m.



Residual charge from four different gap set-ups. Gap length d = 60 mm is constant, but the barrier is moved. The voltage at streamer inception is given. The a = 40 mm curve is from a very early streamer.

Modeling, Simulation, and On-line Detection of Rotor Fault in Hydrogenerators

Student: Kari Gjerde Jørstad

Supervisor: Arne Nysveen

Co-supervisor: Mostafa Valavi

Hydropower generator is a critical component in hydropower stations and is therefore subject to a preventive maintenance strategy to avoid failures of the generator's components. Fault detection techniques can be used to assess the technical condition of the generator either through on-line or off-line detection methods. Off-line measurements are carried out periodically during scheduled inspections and revisions, and require stop of the generator to perform the detection method. Available on-line detection methods require often installation of specific measurement equipment inside the generator. Therefore, non-invasive methods for continuous monitoring, with no need for installation of new measurement equipment, would be useful to continuously get information about the generator condition. By detecting a fault in early stages, problems can be improved at a lower cost and with a shorter downtime. The aim of condition monitoring is to offer the plant owners more information about the generators and provide a more effective production.

This master thesis investigates fault detection of hydro generator rotor winding turn-to-turn short circuits. In this report, a new method for fault detection and continuous monitoring has been developed and tested through modeling of Kalvedalen hydropower generator in the simulation software ANSYS Maxwell. The modeling of Kalvedalen generator is based on technical drawings and data from Eidsiva Energi. Various fault severity cases are modeled in the simulation software, to test the new proposed fault detection method. The simulations are carried out at no-load and full-load operation.

First an initial study was carried out, were RMS values of terminal voltages are used for fault detection. The model was simulated for the six fault cases and the induced voltage waveforms were plotted. It was observed that the short circuit faults reduce the output voltage. However, the changes in induced voltage are considered as too small to detect a fault at an early stage, although the method could be used to detect faults were large part of the windings are shorted.

A new method for fault detection of turn-to-turn short circuits in rotor windings is developed. The proposed fault detection method can not be described here due to confidentiality. Based on modeling and simulations in ANSYS Maxwell, it was concluded that the method could be used for detection of rotor winding short circuits and to determine the fault severity of these short circuits.

Power Supply for Down-hole Applications Based on Flow

Student: **Syed Ali Irtaza Kazmi**
Supervisor: **Lars Norum**

Summary

The main focus of this work is to develop a power supply for feeding power to the down-hole electronic devices such as, instrumentation and communication units. The traditional way of supplying power using long cables from the topside seems to be an expensive approach. So, the present work aims to validate an alternative technique of feeding power to these devices. Numerous types of energy sources are accessible in the process of oil and gas production. The source of kinetic energy from a flowing fluid or gas is one of the useful source of energy which contributes in the generation of electrical power for the down-hole devices.

This study mainly focuses on the modelling of a switched mode power supply for down-hole devices using MATLAB/Simulink. The design of the system model is based on the method of using a permanent magnet synchronous generator coupled to a specific type of turbine, which converts the kinetic energy of the flowing fluid into mechanical energy on the shaft. The PMSG converts the mechanical energy of the shaft into uncontrolled electrical power. The output power from the generator is rectified using a three-phase diode rectifier. Moreover, the rectified power is stabilized and supplied to the dc loads using a large filter capacitor and several types of dc-dc converters. The stability of the system for supplying stable power to the dc load is thoroughly investigated in this research work. Consequently, feedback control loops for the dc-dc converters are examined to make a stable power supply using a storage unit and a dump-load. Therefore, the principle objective of the feedback control loops is to regulate the dc link voltage across the filter capacitor. Controlling the power from the source side is not applicable in this method, therefore a pitch angle control is eliminated and not implemented in this thesis.

The feedback control loops have been simulated for different cases to investigate the behavior of the system for varying nature of input flow rates and variable load demands. Therefore, various simulation results have been presented to analyze the performance of the system regarding the dc link voltage across the filter capacitor. The system has been examined for three different methods, the first and the second method are inspected by having a storage unit and a dump-load. The third method is considered to analyze the stability of the system without having any storage unit, because rechargeable are batteries not available for very high temperatures.

Finally, the feed-back control loops of the system model have been modified by using embedded coder target library which can be implemented on a Texas Instrument microcontroller. The process of code generation and system with a digital controller is studied and simulated using MATLAB/Simulink in the last section of the thesis report.

The results show that the objective of regulating the dc link voltage across the filter capacitor and maintaining the power balance of the system is achieved for all the methods, irrespective of the input disturbances and varying load demands. The system model without having any battery bank has some certain operating limits. The inputs for this type of system configuration must be within a predefined limits of flow rates. Therefore, to supply minimum demanded power to the load the input flow speed for this configuration must be always higher than its minimum specified limit. Secondly the input flow rate must not exceed the maximum limit, which saturates the flow of excess power through the dump-load. The dc load is completely disconnected from the system when the SOC of the battery bank is less than minimum limit and the input flow rate is negligible.

Piloted Protection Solutions for Distribution Networks with Integrated Distributed Energy Resources

Student: **Syed Hamza Hasan Kazmi**
Supervisor: **Hans Kristian Hoidalen** (Professor, Dept. of Electric Power Engineering)
Collaboration with: **TU Delft & ABB**

Problem description

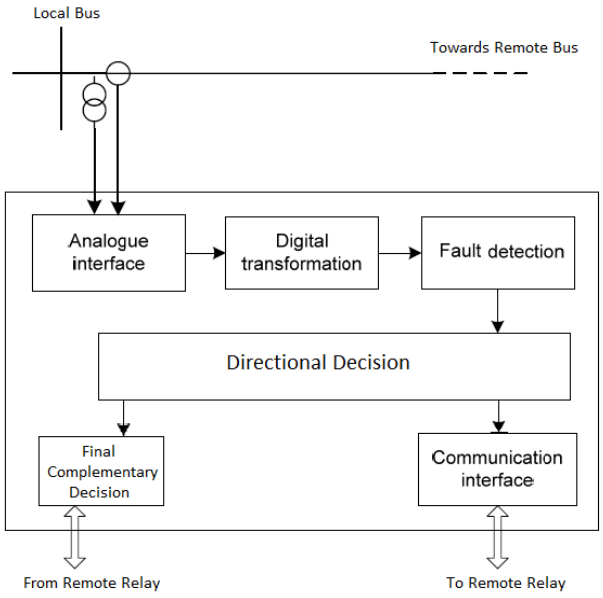
The wide scale integration of distributed energy resources (DERs) in the distribution networks (LV/MV) over the last few decades has resulted in new challenges for the protection system associated with overcurrent protection schemes, which are conventionally employed for distribution networks.

The task

This thesis work explores the possibility to overcome challenges associated with overcurrent protection schemes, which are conventionally employed for distribution networks, by utilizing communication-based protection techniques. These techniques include piloted directional protection techniques based on conventional methods and transient signals. Moreover, current-based line differential protection is also investigated.

Model/ measurements

The individual algorithms for all these protection schemes used by relay manufacturers (including ABB, Siemens and SEL) are developed and tested. The test network, system parameters and performance criteria are developed in the PSCAD/EMTDC environment, whereas the individual algorithms are developed in MATLAB/Simulink. The system and performance parameters are carefully designed to reciprocate the performance of the modern distribution networks with weak sources replicating the performance of DERs during faults. Up to this point, the fault clearing time has not been critical for these networks but the integration of DERs has resulted in the additional requirement to fulfill the critical clearing time of each generator, therefore relay operating time is also considered in this study. However, the impacts of some real world imperfections including harmonics, measurement inaccuracies, communication noise and data loss etc. are ignored.



Results

Practical Attributes	Directional		Line Differential
	Conventional	Transient-based	
Data Management & Synchronization			
Communication Channel			
Data Transmission Delay			
Parallel and Double Circuit Lines			
Series Compensated Lines			
High Impedance Faults			
Charging Current & In-Line Transformers			
CT Saturation			
Source Strength Coverage (DG Integration)			
System Grounding Coverage			
Practicality of Application (V & I Information)			

Conclusion

With the advent of communication methodologies over the last decade, these piloted schemes offer distinctive advantages over overcurrent protection with directional supervision.

However, as far as the directional protection is concerned, the conventional schemes would result in insecure operation if the faults are close to these distributed weak sources. Moreover, vulnerability of these methods to system frequency unbalance would also be a matter of concern.

In contrast, the tested transient-based directional algorithms base their decisions on fault components and the use of adaptive threshold for fault detection make these methods less susceptible to both these vulnerabilities. All the tested algorithms with the exception of positive sequence method offer high-speed performance, which allows the additional requirement of limited CCT to be met. The transient energy and replica impedance methods have already proven their worth in the transmission network, but the average window method is relatively new and seems to be more defenseless against high fault resistance and system frequency unbalance than its predecessors are. By combining both the conventional directional protection and transient-based direction protection, it is proved that a secure pilot protection system could be formulated with certain advantages. One important limitation that all the directional schemes face is the requirement of voltage information to determine fault direction, which can be practically irrelevant for distribution networks because of the involved costs.

Although the performance of the tested line differential protection relays has proven to be exemplary for modern distribution networks, the customary limitations associated with this technique including data synchronization and saturation of current transformers are the restricting factors for its wide scale implementation. Moreover, the costs and technology associated with laying a dedicated communication network also limit its application.

The transient-based directional protection scheme based on current information only would prove to be the ultimate solution for such networks because of its exceptional performance in weak networks and its autonomy over communication-based limitations associated with line differential protection.

Test av litium-ion batterier for transportmidler med høy belastning- og fokus på varmeutvikling

Student: **Eivind Klokkehaug**
Faglærer: **Trond Toftevaag**

Sammendrag

Revolve NTNU har de siste årene bygget en bil som både går fortere og er lettere. For at dette skal skje blir alle komponenter i racerbilen presset til sitt ytterste. Dette har medført at batteripakken, som er den tyngste og en av de mest sentrale delene i bilen, utvikler mye varme på grunn av mengden battericeller men og strømstyrke. Det er denne utfordringen som har vært inspirasjon til masteroppgaven. Den omhandler testing av battericeller og moduler med fokus på varmeutvikling.

Oppgaven er skrevet i samarbeid med NTNU Revolve. Det er batterier som er brukt i racerbilen Revolve- team 2017 som er benyttet i undersøkelsene. Enkeltceller, celler i parallell og en hel modul har blitt testet. I masteroppgaven er det blitt sett på nye type studier av battericeller ved bruk av elektrokjemisk impedans spektroskopi for å kunne få en enda mer detaljert forståelse av hvordan battericellene oppfører seg ved forskjellige temperaturer. En har også sett på nye metoder for kjøling av battericeller ved bruk av Phase-change material som er ikke-elektrisk ledene. Dette gjør at du kan ha de i direkte kontakt med battericellene. Eskalering av testingen for å se på en hel modul har og blitt gjort, for å få et mer realistisk blide av hvordan forholdene er i batteripakken i en racerbil og for å få en bedre forståelse av hvordan cellen blir påvirket av hverandre ved stor påkjenning av strøm og høye omgivelsestemperaturer. Det er og blitt sett på forskjellige kjølemetoder, i situasjoner som simulerer forholdene i racerbilen.

Resultatene av modultestingen har vist at differansen på temperaturen på utsiden av modulen sammenlignet med innsiden er på hele 13.7C. Resultatene har og vist at det er rundt senter cellene er varmest mens de blir kaldere jo nærmer ytterkant av modulen de kommer. En ser og at temperaturen er høyere i midten av cellene sammenlignet med lengre nede når strøm er påsatt. Når modultestene har kjørt rene opp og utladningsstrømmer har det vist seg at strømretningen påvirker og varmeutviklingen i modulen. Ved kjøling ved hjelp av vind har det vist seg at parallell kjøling er det som gir best resultater for varmeutvikling. Det har og blitt sett på entropieffekten i en modul. Det har vist seg at ved 2C ladningmed 36C omgivelsestemperatur har den kaldeste temperaturen i modulen vært på 34C. Testing av PCM har vist at nok volum av denne væsken vil gi en bra kjøleeffekt. Ved elektromagnetisk impedans spektroskopi har det vist seg at impedans i battericellene er avhengig av både SOC og temperatur. Det har vist seg at lavere en 30% SOC øker impedansen i batteriet betraktelig, mens for temperaturen ned mot 5C gjelder dette for 60% SOC.

Alle testene som er blitt gjort i denne masteroppgaven har blitt gjennomfør ved batterilabben ved institutt for energiteknikk med god hjelp av Preben Vie. Alle testene er testet i temperatur regulerende kammer der mesteparten av testene har blitt kjørt på 36 grader Celsius.

Comparing the Surface- and Interior Permanent Magnet Machine with Concentrated windings for High Dynamic Application

Student: **Lasse Kløvstad**
Supervisor: **Robert Nilssen**
Collaboration with: **Rolls Royce Marine AS**

Problem description

Investigate and design of a permanent magnet synchronous machine (PMSM) for a high dynamic application. PMSM for a high dynamic application should have high torque density and have good field weakening abilities. The machine should also have good efficiency over all speed ranges, hence low machine loss.

The task

Firstly a thorough investigation of optimal field weakening was done. This reviled that fractional slot concentrated winding (FSCW) machines where best suited because of their high inductance caused by their sub harmonic stator MMF. Traditionally surface permanent magnet machines (SPM) were said to achieve good field weakening. However not much studies were done on the interior permanent magnet machine (IPM) with FSCW.

Therefor the thesis's focused on comparing the IPM and SPM with FSCW for high dynamic applications. Were two different IPM designs where designed and tested against the SPM. The two rotor designs are shown in figure 23 and 28.

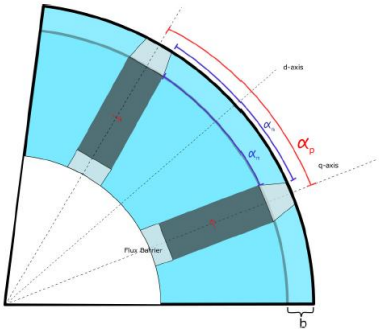


Fig. 28: I-Shaped IPM Layout.

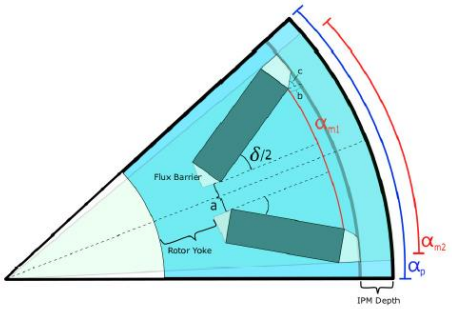


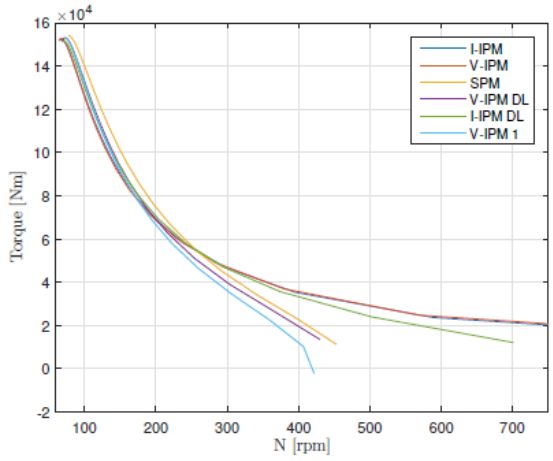
Fig. 23: V-Shaped IPM Layout.

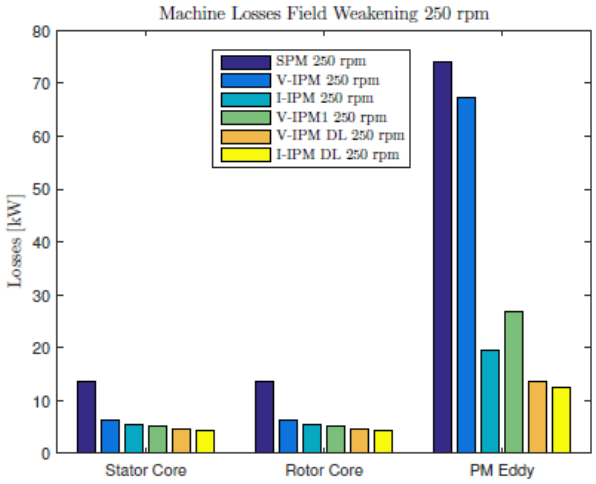
Model/ measurements

COMSOL 5.2 was used to model and simulate the machines. Additionally a loss algorithm was developed with Livelink Matlab feature COMSOL includes. The loss algorithm fetches the mesh data from the results done after a time simulation in COMSOL and estimates the losses. This is illustrated in figure 19.

Calculation

The results are shown in the figures below for two types of V-shaped IPM and one type of I-shaped IPM. It is also included double layer (DL) winding configuration.





Conclusion

The results show that the IPM machines are much better suited for field weakening then SPM. The V-shaped IPM design is difficult to optimize and had a high torque ripple. However the I-shaped IPM showed the best results concerning core loss and PM eddy current loss. All other performance factors as torque ripple and THD were lower than the SPM. One drawback was the power factor.

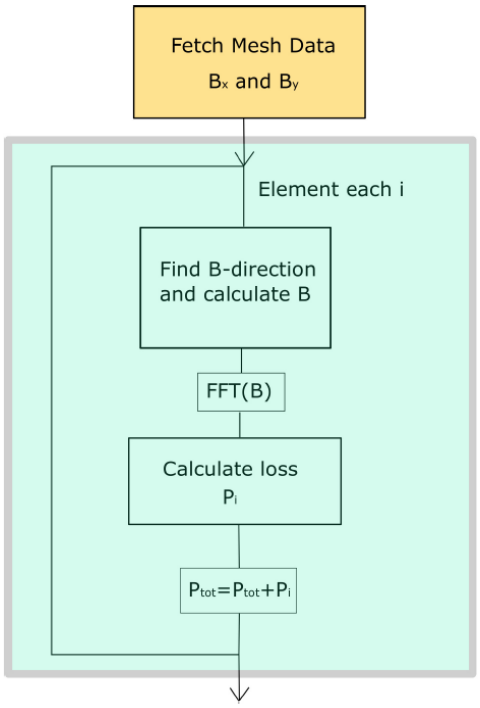


Fig. 19: Block diagram illustrating the steps to calculating total losses from the mesh data

Reliability-based Derating Approach for Interconnectors

Student: **Kjetil Koldingsnes**
Supervisor: **Associate Professor Vijay Venu Vadlamudi**

This Masters project work has its genesis in the preliminary findings of a research collaboration in 2016 between the Department of Electric Power Engineering, NTNU, and Statnett (the Norwegian Transmission System Operator). As its overarching goal, the research proposition centred on developing a foundation for a suitable theoretical framework for one issue related to cross-border capacity auctions: interconnector adequacy. The motivation itself for such an undertaking stemmed from the divergent recommended approaches of estimating the capacity that the prospective UK-Norway interconnector (North-Sea Link) is allowed to bid into the UK Capacity Market.

Capacity made available through an interconnector for an area with a capacity mechanism in place, should be eligible to participate in the auctions to prevent market distortion and to ensure that correct investment signals are sent. There is also a need for a transparent and robust method to calculate the proportion of the rated interconnector capacity allowed to participate in market auctions. Such a methodology should consider and remunerate the interconnector's contribution to improved system adequacy in the importing area. In the NTNU-Statnett project, a unique reliability metric – Interconnector Effective Load Carrying Capability (IELCC) was conceptualized for the purpose of probabilistic interconnector de-rating; preliminary results were demonstrated on a very simple interconnected test system with a simple load profile. IELCC was founded on Loss of Load Expectation (LOLE) quantification in the interconnected system, addressing the need for a reliability-based de-rating procedure, as opposed to other proposed approaches that focuses on empirical considerations such as price differentials.

This thesis examines the NTNU-Statnett project claim that obtaining the de-rated interconnector capacity using a probabilistic reliability framework is a well-argued approach. To corroborate the effectiveness of the IELCC metric, larger interconnected test systems (Roy Billinton Test Systems and IEEE Reliability Test Systems) with detailed load profiles have been deployed, and relevant sensitivity analyses have been conducted. Further, a new variant of IELCC, founded on Expected Energy Not Served (EENS) quantification in the interconnected system is posited, the results demonstrated on the aforementioned test systems and the implications investigated.

In a report by The Joint Research Centre of the European Commission from 2016, appropriate generation and system adequacy standards for the internal electricity market were identified. One of the recommendations of the study was to '…establish EENS as a preferred metric as it alone proves appropriate for the calculation of socially optimal levels of reserve'. In light of this, the proposed EENS-based IELCC in this thesis is deemed to have significant application potential in cross-border capacity markets.

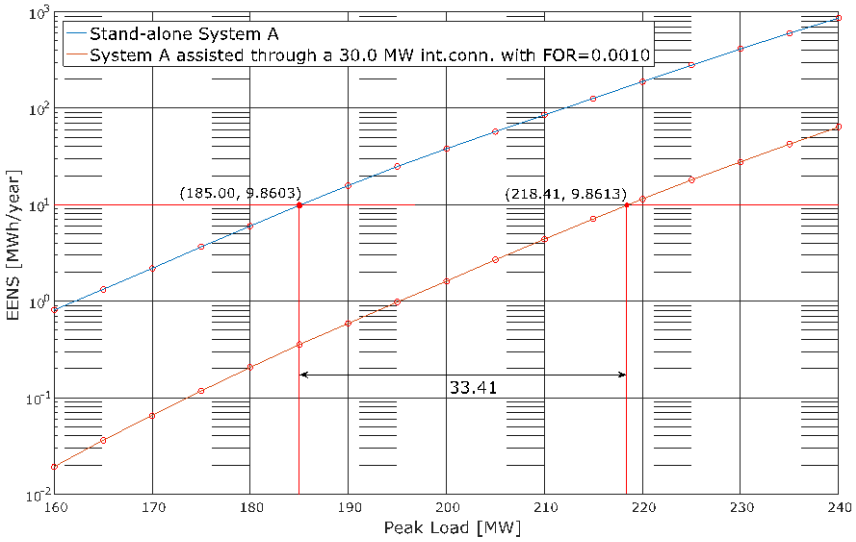


Figure 1: Plot showing peak load vs. LOLE curves for the interconnection of two Roy Billinton Test Systems.

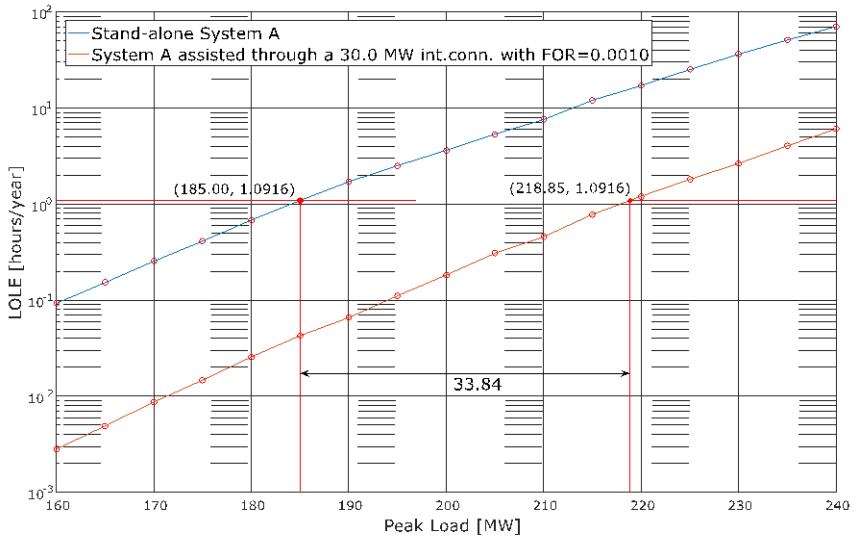


Figure 2: Plot showing peak load vs. EENS curves for the interconnection of two Roy Billinton Test Systems.

Figures 1-2 show the IELCC using LOLE and EENS as guiding adequacy metrics, respectively, for the interconnection of two identical Roy Billinton Test Systems through a 30MW interconnector. The results indicate that System A, which is assisted through the interconnector by System B, will be able to supply an additional 33.41MW/33.84MW of peak load while the reliability level (LOLE/EENS) in System A is maintained at the same level as before the interconnection.

Verdien av fleksibilitet ved prioritering av rehabiliterings- og reinvesteringsprosjekter innen vannkraft

Student: **Lena Krogh**
Veileder: **Solvang, Eivind**

Sammendrag

En beslutning som handler om rehabilitering og reinvestering innen vannkraft kan være en komplisert affære. Det er mange hensyn som må tas, og forutsetningene for videre drift kan være usikre. Av den grunn er det viktig å danne et godt beslutningsgrunnlag. Målet med denne rapporten har vært å undersøke om og hvordan verdi på fleksibilitet i rehabiliterings- og reinvesteringsprosjekter i innen vannkraft kan fastsettes.

Litteraturstudiet med fokus på realopsjon, flermåls beslutningsanalyse og porteføljestyring er gjennomført og for å finne sammenhengen og hvordan teoriene kan bidra til å finne og sette verdi på fleksibilitet i prosjekter. Koblingen som er funnet mellom de ulike begrepene kan sammenfattes til at flermåls beslutningsanalyse danner grunnlaget for kravet til informasjonen om prosjektene og at det er alternativene som gir fleksibilitet. Videre er det realopsjonsteorien som danner et grunnlag for å beregne verdien av fleksibiliteten. Ved bruke av porteføljestyring får man oversikt og kan utnytte fleksibiliteten som blir skapt gjennom alternativene på best mulig måte.

For å viser hvordan teoriene kan brukes er det blitt gjort analyser på ulike eksempler som illustrer aktuelle problemstillinger innen vannkraft. For et kraftverk vil en revisjon innebære en kostnad og det er ønskelig at det er de tiltakene som er beste for helheten i kraftverket som blir gjennomført. Ved å ha fleksibilitet i prosjektene kan kraftverket reagere basert på ny informasjon og endringer i forutsetninger.

Denne rapporten viser at det kan settes verdi på fleksibilitet gjennom eksemplene som er konstruert. Men da det er konstruerte eksempler har rapporten den svakheten at det er usikkerhet i hvorvidt de kan realiseres. For å verifisere at teorien og metodene kan brukes må det gjøres ytterligere analyser av virkelige prosjekter, men denne rapporten gir en et grunnlag for metodene og teoriene som kan brukes videre.

Evaluation of Possible PV System Solutions for Streetlight´s Care Center in Tagpuro, Philippines

Student:	**Ida Langvik Flåten and Frøydis Østtveit Kvinen**
Supervisor:	**Lars Norum**
Co-supervisor:	**Helene Moen (Norconsult AS)**
Collaboration with:	**Streetlight, Engineers Without Borders (IUG), Norconsult AS**

This thesis has evaluated different photovoltaic (PV) system solutions applicable for Streetlight in Tagpuro. The evaluation has consisted of on-grid and off-grid system designs. Streetlight operates a care center in Tacloban and Tagpuro, on the island Leyte in the Philippines. The Philippines is located at one of earth´s most exposed and vulnerable areas considering earthquakes, volcanic eruptions and typhoons. Socio-economic challenges are products of the environmental challenges in the area.

The local energy situation is characterised by frequent power outages and voltage drops - blackouts and brownouts. This is a challenge for Streetlight´s operation, and a more reliable electricity supply is desired. According to the local grid operator, the situation will improve in the future due to implementation of a new sub-station in the area. However, there is projected a power deficit in the coming years for the region.

The Philippines has the highest electricity tariff compared to their neighbouring countries and Streetlight wishes to evaluate whether it is feasible to invest in a PV system to reduce energy costs. Further Streetlight wishes to be self-sufficient with renewable energy as the energy source.

The solar potential in the Philippines is high and there are several governmental instruments providing benefits for investors in solar energy. The benefits include net-metering, feed-in tariff, tax and fiscal incentives. However, feed-in tariff is not yet implemented in Tacloban or Tagpuro.

The annual load demand of Streetlight Tagpuro was theoretically estimated to 54.94 MWh and annual critical load demand was estimated to 32.22 MWh. This is based on daily load profiles for Monday-Friday, Saturday and Sunday. The daily profiles illustrate a peak power demand during day-time 08:00-17:00 and lower power demand during the night. The power demand at night is related to outside lighting which is categorised as a critical load regarding safety concerns.

The on-grid cases evaluated PV modules located at all buildings (Office, Study Center and Orphanage), two buildings (Office and Study Center) and one building (Office), separately. The off-grid case evaluated PV modules at all buildings with different battery capacity and a maximised roof area. The on-grid an off-grid cases provides different possibilities and limitations, and the most feasible solution will depend on which factors Streetlight highlights.

A Levelized Cost of Energy (LCOE) analysis was conducted for all the cases, emphasising the sensitivity of the input parameters discount rate, battery price and net-metering rate. With a discount rate of 10 %, the PV system with modules at the Office at 7.71 PhP/kWh proved to be profitable compared to today´s situation with energy from utility at 7.93 PhP/kWh. Further, when utilising all buildings the LCOE was 8.79 PhP/kWh for the on-grid system compared to 30.32 PhP/kWh for the off-grid system.

Design and Performance Analysis of an Electric Motor Drive utilizing Silicon Carbide MOSFETs

Student: **Jostein Danielsen Kvitvang**
Supervisor: **Ole-Morten Midtgård**
Co-supervisor: **Richard Lund**
Collaboration with: Rolls-Royce Marine AS Trondheim

Abstract

The recent commercialization SiC technology, has made it desirable to use SiC in electrical motor drives for marine applications, due to the superior material qualities of SiC compared to conventional Si based technology. This Master thesis will present an analysis of the switching performance of a SiC MOSFET module from ROHM Semiconductor, and an accompanying investigation of how a high performance SiC based motor drive can be realized.

As part of the thesis work, the many critical components of an electrical motor drive system was investigated, and this will be described in this thesis. Two printed circuit boards were produced to enable the SiC modules to be operated using a motor controller. In addition, a low inductive three phase DC-bus was designed, produced and tested.

The three phase DC-bus design will be described through theoretical considerations, before an experimental analysis of the stray inductance of the DC-bus is presented. It will be shown that a low inductive design can be realized through the use of planar copper conductors, and the DC-bus design has good inductive capabilities compared with a single half-bridge DC-bus which was used in the experimental SiC characterization.

The SiC module performance characterization was conducted by performing double-pulse testing, both in simulations and in laboratory experiment. It was shown that the presence of stray inductive elements in the circuit causes voltage overshoots up to 110 V over the nominal voltage of 600 V and long lasting ringing. The switching characteristics calculated from these tests will be presented, and the circuit dynamics giving rise to these effects discussed. A comparison between the simulation results and experimental results was made, and it will be shown that while the simulation model captures some switching characteristics well, it fails to model the large voltage overshoots observed in laboratory experiments.

Further more, it was investigated if switching performance could be improved through the introduction of snubber circuits, in particular RC turn-off snubbers and DC-snubbers. Both the simulation results and the experimental results showed that the RC turn-off snubbers failed to remove the overvoltages completely, but was able to reduce it to 35 V with a snubber damping constant of 0.4. This comes at the cost of increased switching losses however, and it is clear that a trade off must be made.

COST BENEFIT ANALYSIS OF DIFFERET OFFSHORE GRID TOPOLOGIES IN THE NORTH

Student: Amaia Larrañaga Arregui

Supervisor: Hossein Farahmand

Collaboration with: Sintef Energy Research and Delft University of Technology

European Countries are showing their willingness to reduce their greenhouse gases emissions in the coming years. For example, the Paris agreement within the United Nations Framework Convention on Climate Change (UNFCCC) is one of the most crucial steps that countries have signed recently. The aim is to cause a lower global temperature increase, and thus, to reduce the resulting climate risks.

North-Sea Countries are working on a greener future in a national level, as well; and these are in fact, the countries which are the most concerned about the climate change globally. Moreover, these are affluent in terms of opportunities for using greener energy sources, due to their climatic and geographic conditions. Clear examples are hydropower plants in the Nordic region or offshore-wind in the North-Sea.

Nevertheless, these countries need also of infrastructure to achieve their objectives, such as a Power System which will enable to integrate green generation sources properly and to satisfy the societies' energy needs successfully. Power Systems are in fact, needed key enablers of this energy transition.

The topic of this Master Thesis is transmission expansion planning in the North-Sea for the year 2030. PowerGIM and PowerGAMA are used. The objective is to find the socio-economically beneficial grid design which will help achieve these future ambitions that the North-Sea countries have and at the same time, which will be robust w.r.t. renewable energy sources' development uncertainty. The main finding of this Master Thesis is that Dogger Bank Hub is obtained as part of the most socio-economically beneficial offshore-grid layout for the year 2030, in all implemented scenarios. Each scenario refers to one implemented ENTSO-E Vision (Visions 1-4) with some additional assumptions.

In short, in this Master Thesis, four different offshore-grid layouts are obtained, one per each implemented scenario; and all of them have the same core. The core is Dogger Bank Hub's interconnection with Great Britain, Belgium, Germany, Netherlands, Norway and Denmark. Nevertheless, there are some variations which depend on the implemented scenario and on the implemented assumptions. Overall, the obtained Dogger Bank Hub could also integrate between 13-32 GW offshore-wind in the North Sea.

Then, a reference grid layout is created, as well. This design embraces the previously mentioned four grid layouts in a conservative way, i.e. the repeated lines in all four obtained grid layouts are taken with the lowest capacity value among all four designs.

The efficiency of investment of each grid layout is calculated w.r.t. the reference case's grid layout by the return on investment value (ROI). It is calculated by the following equation:

$$ROI = \frac{Operating\ cost\ saving\ (€) - Investment\ cost\ Increase(€)}{Investment\ cost\ Increase(€)} \quad (1)$$

The obtained results are shown in the next graph, figure 1.

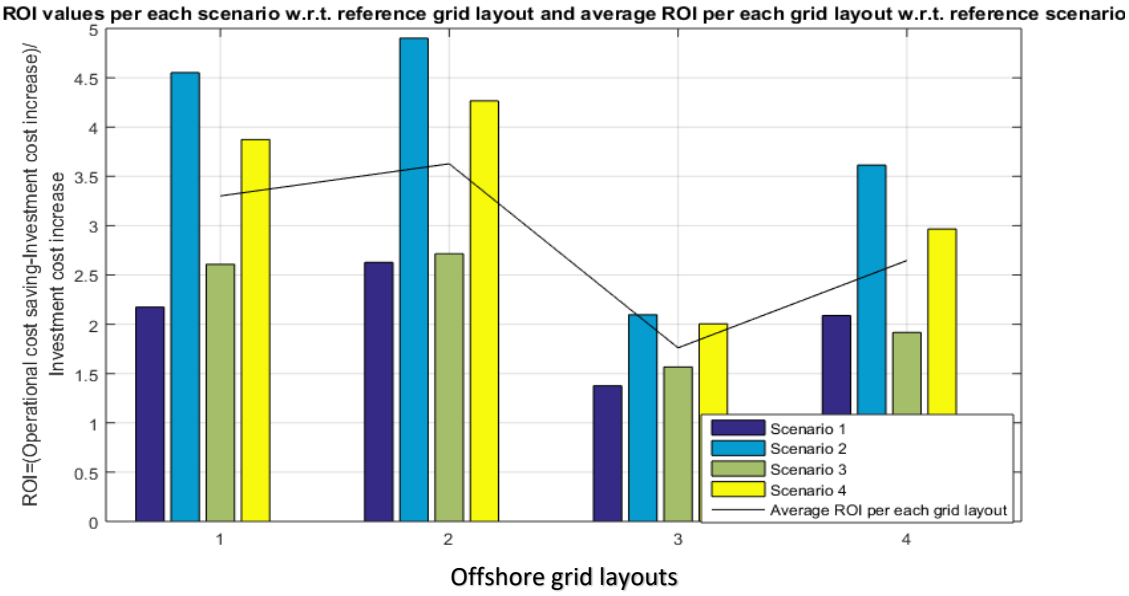


Figure 1. Obtained ROI per each grid layout and per each scenario and average ROI.

The grid layout obtained after the implementation of the second scenario is the most robust grid layout w.r.t. different future energy prospects. Its operational cost saving throughout the lifetime of 30 years w.r.t. the reference grid layout is of 20-33 bn €, depending on the implemented future scenario; and the investment cost increase is of 5.5 bn € w.r.t. the reference grid layout. As a result, it has the highest average ROI value, which is of 3.62. The offshore grid layout is shown below.

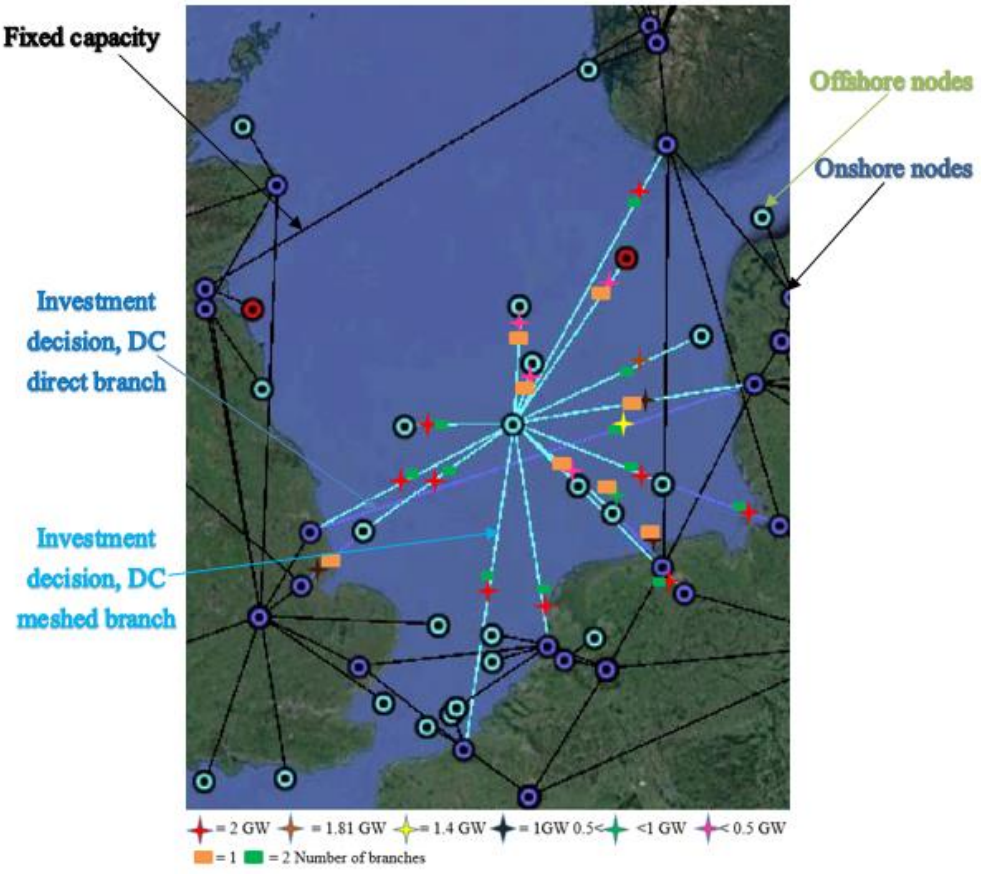


Figure 2. The most robust grid layout w.r.t. future energy scenarios.

Ground Fault Protection of Transmission Lines

Student: **Mari Lauglo**
Supervisor: **Hans Kristian Høidalen**
Cooperation with: **Statnett**

Summary
The ever more electrified and energy-intensive society increases the need for a secure power grid and energy service. The transmission system is the backbone of the electrical power infrastructure, to have a well-functioning protection system of this is therefore crucial. The most common type of faults in the power grid are ground faults on overhead lines, which makes it important to be sure about how the relays will measure such a fault. Distance protection is the preferred protection scheme for the transmission grid, thus it is of importance to determine how the performance of these depends on parameters like presence of ground wires, ground conductivity, system neutral earthing, different types of faults and size of fault resistance.

This masters thesis investigates the impact that presence of ground wires has on the ability of the distance relay to detect single phase-to-ground faults in a grid with solid earthed neutral. In compensated earthed networks it is investigated whether the distance relays are able to distinguish two single phase-to-ground faults at two different phases occurring at the same time but at distant locations from a single ground fault. To investigate these scenarios, models of a transmission line and a section of a transmission grid were implemented in the simulation programme ATPDraw. The models were used for testing of various fault scenarios in combination with different system neutral earthing methods, line design and ground conductivity.

It was found that presence of overhead ground wires does not have decisive impact on whether the distance relays are able to detect a single ground fault in a solid earthed grid. However, estimated fault location was severely improved for lines with ground wires compared to those without. Fault resistance was found to be the factor deciding whether a ground fault was detected. For a solid earthed grid lacking ground wires, high earth potential rise at fault location during a ground fault is a concern. The distance relays are displaying a clear difference in measured impedance for one ground fault versus two ground faults. Thus, in theory, it should be possible to implement more advanced protection zones that will only trip the relay for double faults and persistent single faults. However, this subject needs further analysis before a general conclusion applicable to all possible fault scenarios can be stated.

Kapasitivt indusert ladning i høyspentmast fra nærliggende kraftledning

Student: **Jon Lytskjold**
Faglærer: **Arne Nysveen**
Medveileder: **Anders Dall'Osso Teigset, Statnett**
Utføres i samarbeid med: **Statnett**

Sammendrag

Oppgaven har forsøkt å beregne kapasitivt indusert ladning i en høyspentmast i stål, plassert i nærheten av en spenningssatt 420 kV kraftledning. Beregningene ble gjort for varierende avstand til kraftledning og for varierende mastestørrelse. Videre ble beregninger gjort for varierende kapasitiv kobling mellom mast og jord.

Store deler av oppgaven går ut på å lage en pålitelig 3D-modell av problemet i COMSOL. Modellen kan forenkles da den bare skal ivareta de kapasitive koblingene. Forenklingene gjøres på bakgrunn av et teoretisk forarbeide, og numerisk testing av modellen. Forenklingene består i at kraftledningen kun modelleres som tre faseleder og at fagverket i høyspentmasten forenkles til stålplater med samme romlige utstrekning. En enkel jordmodell velges, der endring i kapasitiv kobling mellom høyspentmast og jord bestemmes av tykkelsen på et luftlag dem imellom.

Beregninger av kapasitivt indusert ladning i høyspentmasten beregnes i form av spenning før og etter den berøres av et menneske. I tillegg beregnes forventet strøm og utladningsenergi ved berøring. Resultatene viser at høyest spenning, strøm og utladningsenergi inntre˙er for minste avstand til kraftledning og for største mastegeometri. Dette fordi de kapasitive koblingene mellom kraftledning og høyspentmast her er på sitt sterkeste. I tillegg gir den korte avstanden større forskjell mellom kapasitiv kobling til hver individuelle faseleder, hvilket resulterer i at indusert spenning øker. Det viser seg videre at svakere kobling mellom høyspentmast og jord gir høyere indusert spenning.

Når et menneske berører masten, viser resultatene at styrken på strømmen kun avhenger av kapasitive koblinger til kraftledning og menneskets impedans til jord. Dette fordi impedansen til mastens kapasitive kobling til jord er langt høyere enn kroppens impedans, og derfor ikke påvirker strømforløpet. Største beregnede strøm ble 8.5mA, hvilket er under grensen for hva som regnes som farlig.

Utladningsenergi ved berøring blir også beregnet. Beregningene viser at utladningsenergien, aldri blir større enn 0.2 Joule, hvilket er langt under farlig styrke. Det viser seg at utladnings-energien er proporsjonalt avhengig av den indusert spenningen i masta, til tross for at den induserte spenningen er størst for svakere kapasitiv kobling mellom mast og jord.

Balancing Market Integration in Northern European System – A 2020 Case Study

Student: **Ingrid Tjellaug Løvstad**
Supervisor: **Hossein Farahmand**

The Nordic power system is a complex and interconnected system in the sense that all the Nordic countries are closely tied together when it comes to electricity trading, both in the important day-ahead market, where the majority of all electricity are purchased/sold, and the balancing market, where reserve capacity is procured and activated for balancing reasons. Sharing of power and electricity offers many advantages and great flexibility. Earlier studies show that an integrated Northern European balancing market provides huge economic gains and cost savings, both because the integrated countries can use the cheapest and most available resource, but also because the requirements for balancing reserves are folded down (imbalance netting). The achievements in the Nordic countries have been noted elsewhere in Europe and in the world, and other countries are now trying to get started similar agreements on a close electricity cooperation. In the future, the power system will consist of more unpredictable energy resources such as wind and solar, providing increased need for balancing reserves.

The purpose of this research work is to look at the impact of balancing market integration in Northern Europe. This is assessed considering simulations of an optimization model addressing reserve procurement in form of procurement per country and per balancing region, and FRR reservation on HVDC-lines. The optimization model for the integrated system is simulated in a 2020 scenario, which has been the case study of this thesis. The model used has earlier been formulated and simulated in a PhD for a 2010 scenario case study. A study of the balancing energy market is not included in this master's thesis.

Investigation of integrated balancing market using an already refined and developed optimization model is performed through a 2020 case study. The 2020 case study is considered by creating a realistic energy system that will be similar to what we have in 2020. This involves more RES and less thermal energy, and larger HVDC-line capacities. It should be mentioned that much of the input data used in the 2010 case study is also used for 2020, and that this does not necessarily match 100% with reality.

The objective of the optimization model is to minimize the total system operating costs, meaning costs related to both day-ahead market and reserve procurement market. In this case study, the cost related to day-ahead market is much higher than the cost related to reserve procurement market. The optimization model is formulated for optimal scheduling of country-vise and region-vise FRR procurement, and to optimally allocate the reservation for FRR exchange on transmission lines.

The main results obtained in this master's thesis are:

- The Nordic balancing market is a well-functioning market structure with great results compared to a non-integrated Nordic system.
- Given a considerably increased capacity, the HVDC-lines between the Nordic countries, Germany and the Netherlands are well utilized.

- The procurement of reserves (FRR) for balancing purpose per country increases overall sharply from 2010 to 2020. This comes as a natural response to a greater amount of unpredictable energy sources in the system.
- The procurement of FRR per balancing region increases as well. Throughout the year, most are procured from the Nordic region, except in early spring when the water reservoirs are empty. The procurement in the German balancing region follows an opposite curve of the Nordic region, where most of the FRR is procured in early spring.
- The total costs, including day-ahead and reserve procurement costs, increase when comparing the 2020 scenario (case 2) with 2010 scenario (case 1). The increase is highest in the day-ahead market. The total costs, compared with two reference cases from 2010 representing no-reservation of balancing reserves and sequential market clearance option, decrease with 3 and 1 million.

Innovative power system event-detection and synchronous plant emulation technique for large wind power plant

Student: **Ryan McGill**
Supervisor: **Olimpo Anaya-Lara**
Raymundo Torres-Olguin
Collaboration with: **SINTEF Energy Research**

Problem description
In the event of power system frequency excursions synchronous plants naturally provide inertia and other frequency support services through governor action. In order to do this they rely on direct measurements of the power system frequency, which would be prone to high noise and lack of accuracy. Contrary to this typical approach this MSc project will investigate an innovative method where a fully instrumented small/medium synchronous generator is installed at the wind farm power plant point of connection with the power grid. The small synchronous generator will be able to provide all ancillary services (assuming it has a Power System Stabilizer (PSS) and Automatic Voltage Regulator (AVR), inertia, governor droop control, reactive power, reserve, and curtailment functionality). Then the challenge of this project is to design a wind farm controller that emulates and amplifies the response of this small generator. The project will develop good knowledge of power system operation and wind farm control.

The task
The subject matter of this thesis report investigates a synthetic inertia and dynamic stability technique for grid inter-connection of large VSC-HVDC connected offshore windfarms. Assuming traditional load frequency control on the AC grid for the short-term reallocation of power generation resources due to load disturbances, this technique ties the dynamic response of the windfarm to the dynamic response of a small synchronous generator at a point of common coupling.

Model/ measurements
The report uses electromagnetic transient simulation to show that the windfarm can be made to react to onshore frequency events similar to any other synchronous generation source participating in power-frequency regulation. Simulation is also used to show that the windfarm can actively contribute to the frequency stability of the onshore AC grid. Simulation in PSCAD/EMT according to Figures 1 and 2 was used to solve the problem.

Calculation
Various scenarios were explored. The communicationless channel was used to implement the primary response feature of the method. The fiber-optic channel was used to implement the inertial response feature of the method. Strong frequency and weak frequency onshore AC grid scenarios were used to demonstrate the methods influence on AC system frequency stiffness and frequency strength respectively.

Conclusion
The design solution is intended to outline the design possibilities available with communication channels that can function independently of each other. For example, simulation has been used to show that manipulating inertial response information, before combining with primary response, may be beneficial to onshore AC system dynamic stability. This effect may be quantified as an inertia constant but the time rate of change of the kinetic

energy associated with that inertia constant may be more meaningful in this case. Simulation has also been used to show that the primary response feature contributes to steady state frequency regulation as power injection is adjusted based on this frequency. The method is therefore contributing to the AC system frequency stiffness. It should be emphasized that this study uses the simplifying assumption of manual excitation from all contributing synchronous machines.

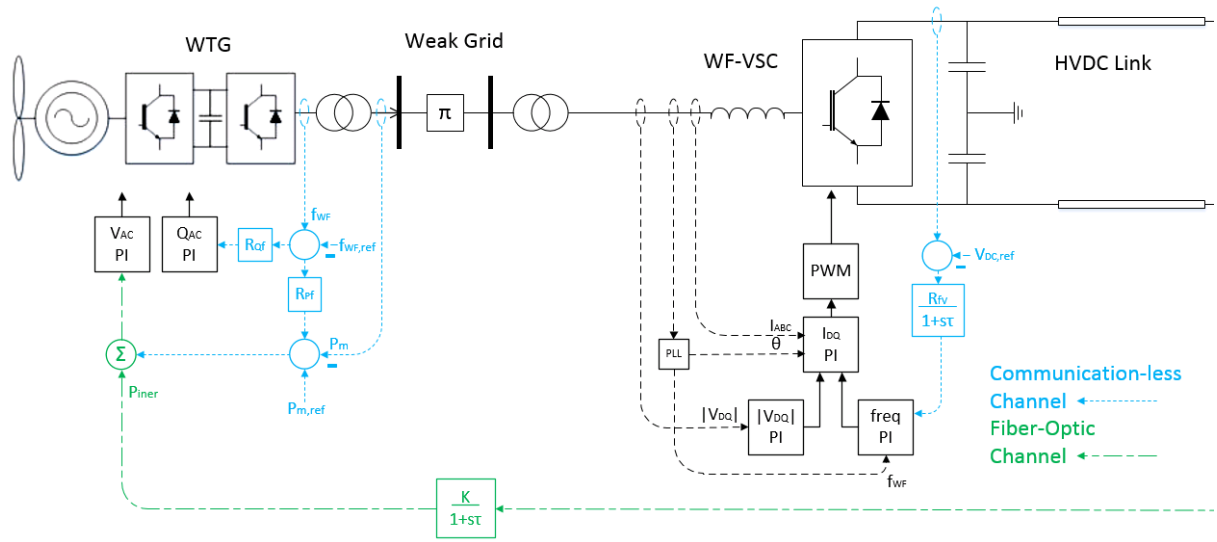


Figure 1: Offshore Reference Circuit

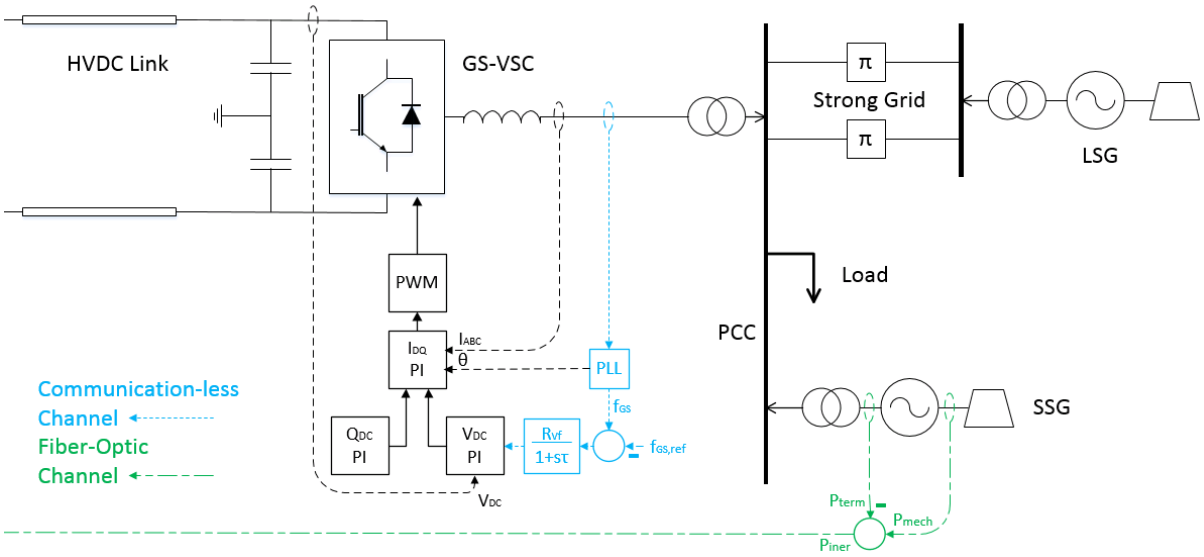


Figure 2: Onshore Reference Circuit

Experimental Determination of Losses in MgB_2 Superconductors for Wind Turbine Applications

Student: **Lars-Erik Moslått**
Supervisor: **Arne Nysveen**
Co-supervisor: **Niklas Magnusson**
Collaboration with: **SINTEF Energy Research**

Problem description

Superconducting rotor windings are considered for large offshore wind turbine generators to reduce weight, size and cost. Superconductors carry DC currents loss-free, when cooled down to low temperatures, and their current densities are about 100 times higher than in copper conductors. However, when exposed to an AC magnetic field, the superconductor exhibit energy losses. Although the rotor windings of a generator are operated with DC current, there will inevitably be a ripple AC magnetic field superimposed on the large DC magnetic field. The level of the losses appearing under these conditions will partly determine both the capacity and the design of the cooling system.

The task

- Develop a calorimetric system for measurement of AC losses due to low AC magnetic fields on a bias DC magnetic field.
- Perform measurements of AC losses.

The DC magnetic field in the 0.5 – 1 T range will be generated by a superconducting coil developed in previous projects. The AC circuit and the measurement equipment are to be designed, built and incorporated in the existing cooling system.

Model

A DC field winding is used to set up a strong background field and an AC coil sets up a magnetic field ripple. The magnetic field exposed to the wire sample is given by the superposition of these two fields. The AC ripple and the background field are aligned in parallel, perpendicular to the MgB_2 superconducting wire sample (Figure 1).

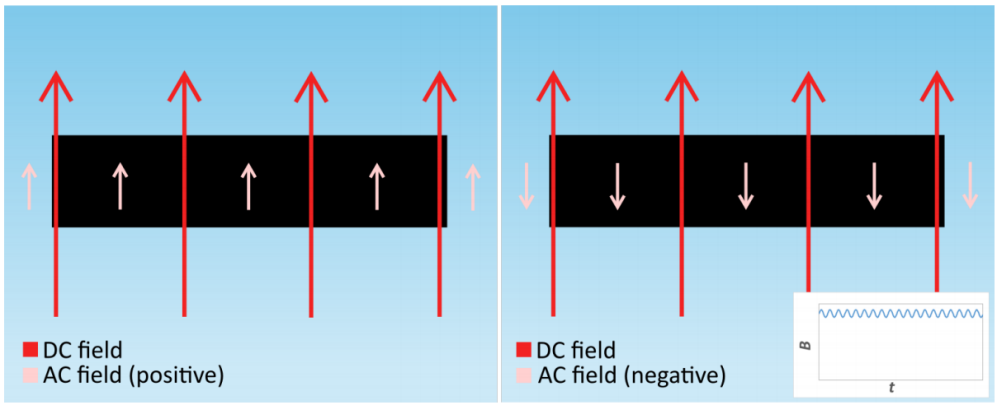


Figure 1: Illustration of the magnetic field in the cross-section of the MgB_2 wire sample

Results

Losses are measured for different AC magnetic fields up to 21 mT peak, with different background DC fields up to 0.35 T. The AC losses in the superconductor sample was found to increase with the 2nd power of the AC magnetic field applied. This pattern was similar for all DC background fields applied, but the magnitude of the losses was different for different background fields (Figure 2).

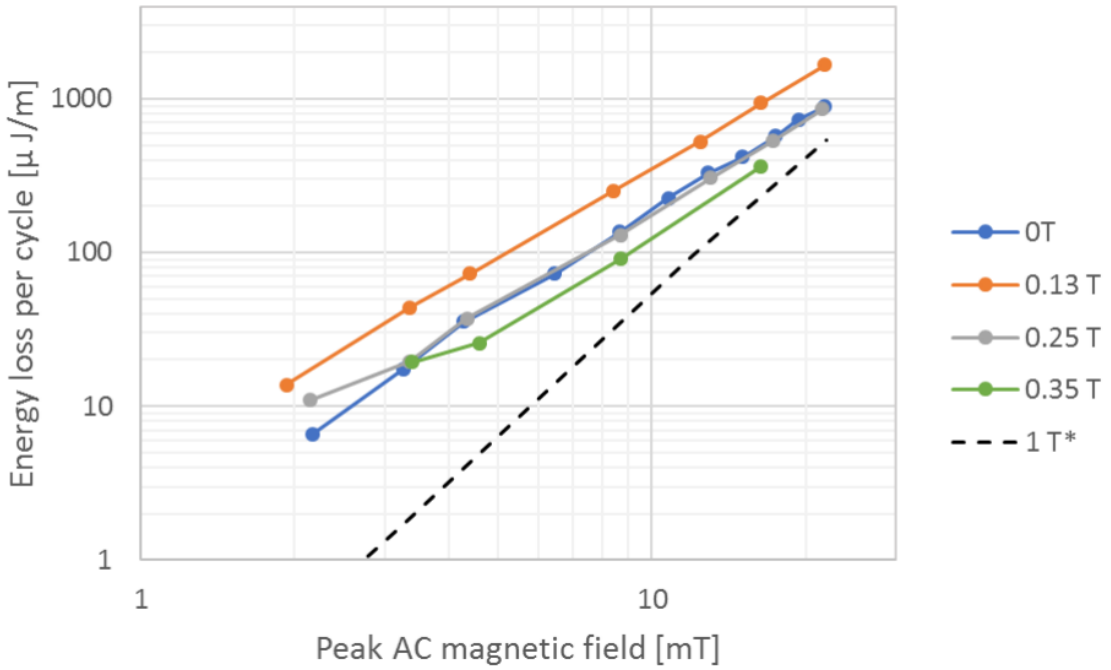


Figure 2: Measured AC power losses as function of the AC magnetic field applied, for different DC background fields. * Modelled superconductor losses.

Conclusion

Hardware for experimental testing of AC losses in a sample of an MgB_2 superconducting wire have been designed, produced and tested. The calorimetric measurement system installed was proven capable of measuring the AC losses in the 10-cm wire sample in the range of 150 μW to 10 mW.

The AC losses measured in the superconducting wire sample increased as an exponential function of the AC magnetic field applied with an exponent of 2. Considering the magnitude and the loss patterns, it is assumed that the losses at the tested field strengths are dominated by eddy current losses and hysteresis losses in the copper and the nickel in the superconducting wire, not superconductor losses in the MgB_2.

It was not obtained a background field of 0.5 T as planned in the testing. However, the results could be relevant to determine AC losses in a superconducting field winding in sections subject to weaker background fields. The losses measured for up to 0.35 T background field were significantly higher than the modelled superconductor AC losses. Hence, losses from sections with lower background fields in a field winding could strongly impact the total losses.

Modelling of future demand profiles and response

Student: Astrid Musæus
Supervisors: Gerard Doorman
Ivar Husevåg Døskeland
Collaboration with: Statnett

Abstract
The installation of smart metering systems to all electricity consumers in Norway, commissioned by NVE, is predicted to enable more active power consumers, due to a two-way communication of price and consumption information. A behavioral change in consumption is therefore expected, through the facilitation of Demand Response (DR).

The EFI's Multi-area Power-market Simulator (the EMPS model), is an important tool in Statnett's long-term market analysis, know for its ability to model and handle hydropower production. This thesis aims to evaluate ways to model DR within general consumption in the EMPS model. As the most straightforward way proved to be a change in the input demand profiles, new profiles were created for 2030. These were collected from another model, the Leopard model, a tool developed for Statnett to project future consumption and its annual distribution. Here, the demand profiles for residential consumption are optimized to even out daily consumption, thus imitating DR. The primary sector and the service sector were provided with non-flexible demand profiles.

Five cases have been developed and evaluated to test the new profiles, differing in their way of modelling firm demand. Three cases were provided with the new profiles, in addition to the new, projected consumption volumes applied in all cases. In the analysis, the three Leopard cases were compared to the original, non-flexible modeling of the 2030 power system, based on their change in consumption, prices, cross-border power exchange, socioeconomic benefits and profitability to the consumer. Even though all cases showed overall reductions in peak hour consumption and average prices, only one case yielded positive economical results to the consumer and to society. In this case, a finer resolution of general consumption was introduced, in addition to the extraction of non-temperature dependent flexible household demand, namely heating of water and charging of electrical vehicles. This way of modeling, combined with the change in temperature dependency proved to be the most beneficial in regards to demand response.

Even though positive results were seen in one of the cases, more thorough ways of modelling demand response should be evaluated, with a price based optimization. Additionally, all segments within consumption should be evaluated, as the potential for DR is not exclusively isolated in the residential sector. However, with a more active power consumer, a need for more frequent updates of the demand profiles might evolve. Therefore, Statnett should consider the implementation of demand profiles projected in the Leopard model, in addition to the projected annual consumption quantities.

Lokalisering av kortslutninger i høyspent distribusjonsnett

Student: **Ingrid Myhr**
Hovedveileder: **Gerd Kjølle**
Medveileder: **Kjell Anders Tutvedt**
Utføres i samarbeid med: **Hafslund Nett**

Innledning/ problemstilling

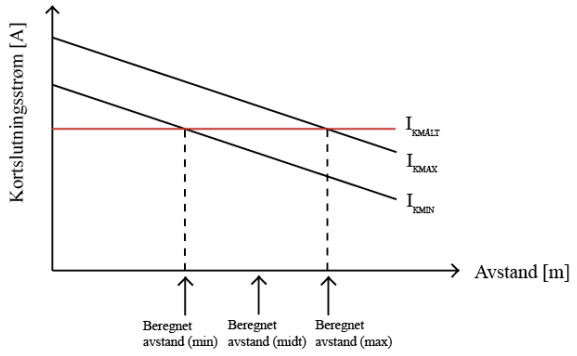
Ved varige feil i kraftforsyningen er det ønskelig å lokalisere feilens plassering så raskt og nøyaktig som mulig. På den måten kan feilstedet isoleres og øvrig forsyning gjenopprettes. Samtidig kan mannskapet som skal gjennomføre korrigerende vedlikehold reise direkte til feilstedet. En rekke metoder som kan beregne avstanden til en feil i nettet er foreslått i litteraturen. Den vanligste typen metoder kalles impedansbasert feillokalisering (Impedance-based fault location). Her benyttes måleverdier av strøm og spenning i feiløyeblikket til å finne en ekvivalent impedans mellom målepunktet og feilstedet.

Implementasjon av slike metoder krever som regel installasjon av nye måleinstrumenter og beregningsverktøy. De utgjør derfor en betydelig investeringskostnad for nettselskapene. Spørsmålet er om også enklere metoder, som benytter færre måleverdier, kan utføre samme oppgave på en tilfredsstillende måte. I denne oppgaven vil derfor en feillokaliseringsmetode som benytter allerede installerte måleinstrumenter og analyseverktøy hos nettselskapet Hafslund Nett bli presentert og testet.

Metode

Den foreslåtte metoden baserer seg på kortslutningsstrømmer som eneste måleverdi og tradisjonelle kortslutningsberegninger etter IEC norm 60909. Metoden sammenlikner den målte kortslutningsstrømmen, $I_{k\text{-målt}}$, med den beregnede feilstrømmen for alle punkt langs den aktuelle avgangen. Punktet med lavest avvik bestemmes som punktet nærmest feilstedet. Beregningene er gjennomført i Powel NetBas, og dette er illustrert i figur 1.

Gjennom IEC norm 60909 kan både en minimal og maksimal kortslutningsstrøm beregnes. Derfor vil det for hvert punkt i nettet kunne beregnes to feilstrømmer, som illustrert i figur 1. Den foreslåtte metoden sammenlikner den målte kortslutningsstrømmen, $I_{k\text{-målt}}$, med begge disse beregningene, og finner derfor to feilsteder. Det antas at det faktiske feilstedet i de fleste tilfeller befinner seg mellom disse to estimatene, derfor er også midtpunktet (i meter) mellom disse punktene beregnet.

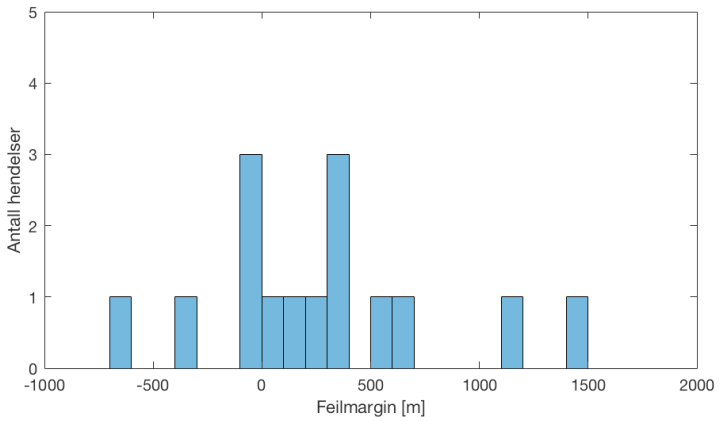


Figur 1: Illustrasjon av kortslutningsberegninger i Powel Netbas.

Resultater

Gjennom en uttesting av metoden som omfattet 20 historiske kortslutningshendelser ble det funnet en gjennomsnittlig feilmargin på 410 meter og 6 %. Prosentvis feilmargin er funnet som feilmarginen (i meter) delt på avgangens lengde. Her er beregnet feilsted (midt) benyttet, da dette ga lavest gjennomsnittlig feilmargin for disse hendelsene. Fordelingen var noe forskjøvet i positiv retning, det vil si at beregnet avstand til feil i de fleste tilfeller var større enn den faktiske avstanden. Et histogram over denne fordelingen er gitt i figur 2.

For 5 av disse hendelsene havnet beregnet feilsted utenfor avgangens rekkevidde, og disse er ikke inkludert i den gjennomsnittlige feilmarginen. Fordi uttestingen omfattet såpass få hendelser har det ikke vært mulig å vurdere hvordan forhold som feiltype, avstand til feil eller type nett har påvirket feilmarginen.



Figur 2: Histogram over feilmargin for de 15 hendelsene der beregnet avstand til feil havnet innenfor avgangens rekkevidde. Feilmarginen er beregnet som feilmargin [m] = $l_{beregnet}$ [m] – $l_{faktisk}$ [m].

Konklusjon

I uttestingen av den foreslåtte feillokaliseringsmetoden ble det funnet en høyere feilmargin enn det som er rapportert for et utvalg eksisterende algoritmer. Dette var som forventet, da de eksisterende algoritmene ble vurdert som mer avanserte. I et kostnad-nytte-perspektiv er det likevel gunstig at den foreslåtte metoden kun krever strømmålinger og at beregningene er relativt enkle. En eventuell videreutvikling av metoden bør fokusere på økt grad av automasjon i beregningene og mer omfattende modellering av feilmarginen. Det bør også vurderes nærmere hvordan impedansbasert feillokalisering kan benyttes i kombinasjon med andre teknologier i et fremtidig smart distribusjonsnett.

Reliability Analysis of the Nordic44 Model and modelling of corrective Actions in OPAL

Student: **Sindre Winsnes Nordhagen**
Supervisor: **Gerd Kjølle**

The power systems primary function is to supply electrical energy to costumers in a cost-effective way with satisfactory quality and continuity. Today's society is demanding continuously available electrical energy, which pushes the power system towards its limit. Continuous availability is not possible to accomplish, as the power system will experience component failures outside the control of the operators. As a result, the system designers, planners and operators will be fronted with a dilemma; how to best invest their money to operate the system within economic, reliability and operational constraints.
This thesis will look into the reliability analysis of power systems; an analysis which uses probabilistic techniques to evaluate the severity of a state of which the power system might exist. Thus obtaining a prediction of the power systems likely future behavior, which can point out unreliable parts of the system where investments are needed. In this thesis a reliability assessment of the Nordic44 model is implemented, which is an aggregated model of the Nordic power system. The reliability analysis is carried out using the OPAL methodology, developed at SINTEF Energy Research. The methodology consists of a consequence analysis where the severity of different system states is assessed, pursued by the accumulation of reliability indices, which can be used in decision-making processes for long-term planning purposes. The results revealed that the Nordic44 model was an unreliable model, with several issues providing adequate supply.
In the consequence analysis, the system operators may apply different strategies, as to minimize customers load shedding. These strategies can be disconnection of transmission lines, generator rescheduling or reactive compensation. Correct modelling of these strategies is important in the methodology used, and they should be implemented as close to the corrective actions used in real power system operation. This thesis will further develop the corrective action by reactive compensation. Finally, the benefits of activating different corrective action options in the consequence analysis will be considered for the Nordic44 model under different system states, and their performance will be compared to foregoing studies. Results affirmed the corrective actions applicability for larger power systems, and that reactive compensation is beneficial for adequate supply when assessing reliability of the Nordic44.

Sammenligning av feilstatistikk hos nettselskaper – Med utgangspunkt i kostnadsnormen og bruk av GIS

Student: **Magnus Holm Nygaard**
Faglærer: **Gerd Kjølle**
Veileder: **Jørn Heggset**
Utføres i samarbeid med: **Statnett**

Sammendrag

Distribusjonsnettet i Norge er delt inn i 139 konsesjonærområder. Hver av disse er pålagt av NVE å rapportere data om feil og avbrudd. På grunn av rivende utvikling innenfor datateknologi knyttet til "det digitale skiftet" åpner det seg nye muligheter for anvendelse av kartfestede data.

Formålet med denne oppgaven har vært å undersøke mulighetene til å benytte geografiske informasjonssystemer (GIS) for å presentere feilstatistikk. Måten distribusjonsnettet er strukturert på gjør det mulig å sammenligne feilstatistikk mellom nettselskap. I denne oppgaven er det undersøkt om geografiske data kan brukes som grunnlag for en slik sammenligning.

En bakgrunnsstudie av feilanalyse og en praktisk utforming av verktøyet "dashbord" med påfølgende vurdering utgjør kjernen i oppgaven.

Bakgrunnsstudiet gir en oversikt over dagens rapporteringssystem for feil og avbrudd i kraftsystemet (FASIT), som lagrer store mengder nyttig informasjon om nettselskapene. TrønderEnergi ble kontaktet og brukt som modell i arbeidet. Oppgaven fokuserer på kart som medium og bruk av geografiske data NVE har om nettselskapene i dag.

I motsetning til tradisjonell feilstatistikk som tar for seg alle nettselskaper samlet sett, vil et dashbord kunne gi rom for å analysere individuelle forskjeller mellom nettselskap. Den praktiske utformingen av dashbordet ble begrenset av mangelfull programmeringserfaring med GIS som er tidkrevende og komplisert, samt mangel på kartfestede data.

Erfaringen med dashbordet viser at man kan sammenligne feilstatistikk fra ulike nettselskap. For feilstatistikkens del ble det slått fast at koordinatfesting av feil er en forutsetning for å kunne gjøre inngående sammenligninger. Vurderingen avdekker også at flere forhold i feilrapporteringen og kilden til anleggsdata (eRapp) bør forbedres for å effektivt kunne produsere god feilstatistikk for nettselskapene. Oppgaven belyser også muligheter for videreutvikling og gir eksempler på andre kartkilder knyttet til geografiske, topografiske eller klimatiske faktorer som kan brukes i feilanalyse.

Hovedkonklusjonen for oppgaven er at det er et behov i nettselskapene til å kunne nyttiggjøre seg av egen feilstatistikk og sammenligne seg med andre selskap. Økt bruk av GIS vil styrke arbeidet med feilanalyse, sårbarhetsanalyse og risikoanalyse og dermed bidra til økt leveringssikkerhet for framtiden.

Air flow and arc cooling in load break switch

Student: **Olav Nyhus**
Supervisor: **Kaveh Niayesh**
Co-supervisor: **Erik Jonsson**

Current interruption is a complex process, and optimizing the design of a medium voltage load-break switch is difficult. The dominating technology for load-break switches in medium voltage switchgear is using SF6 as interruption medium. SF6 is classified as a potent greenhouse gas with very high global warming potential. Thus, the industry has begun looking at other technologies. One interesting option is to quench the arc using air. When using air instead of SF6, optimization with regard to size is important since larger equipment will not fit in many existing installation sites. Due to the superior properties of SF6, little research has been done with air as an interrupting medium in load-break switches.

The thesis addresses medium-voltage load current interruption in air. The project work has focused on determining how the air flow should be designed to obtain the best interruption performance in a load-break switch. A simplified experimental setup based on steady-state air flow and with an electrically heated wolfram wire, simulating the arc, was used. Two different air flow designs were made and tested in the laboratory: axial and radial flow.
With the axial design, the air flow was blown straight on the wire. With the radial design, the air flow was blown 90° onto the wire. Two different wire diameters for the simulated arc were tested to simulate the arc, 0.15 and 0.38 mm. The radial design proved to be 35 % more efficient with a starting temperature of 570°C over the heated were. Laboratory experiments showed that the difference between the axial and radial design increased with temperature. With the radial design, a higher velocity of the air flow was created towards the center of the nozzle. The results show the importance of the angle when air flow is blown on an arc.

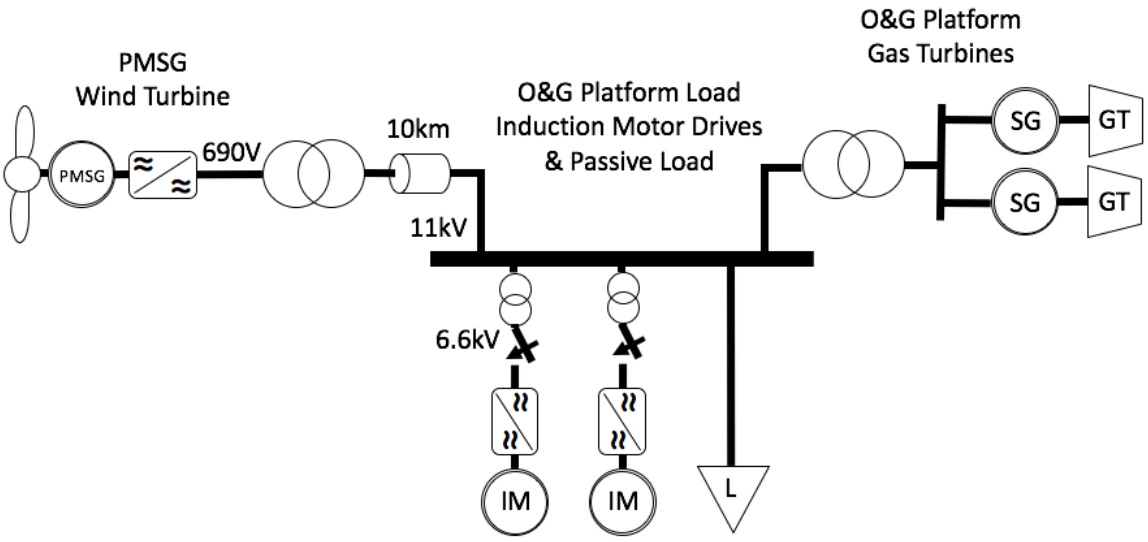
By heat distribution measurements, calculations of the convection loss over the heated wire during the cooling process were done. The convection loss increased with stepwise air flow and proved to be dependent on the air flow. The results verified the validation of the model. Hence, the convection loss can describe the efficiency of the cooling for the setup.

Simulations in COMSOL Multiphysics proved to be a good comparison to the laboratory experiments and a deeper picture of the heat distribution was analyzed. A good simulation model of the axial flow was obtained. Making a simulation model of the radial flow turned out to be more complex, but some results indicate the creation of turbulent flow with the radial design.

Electrical Grid Study of Using Offshore Wind Power for Oil & Gas Offshore Installations

Student: **Jonas Frium Opedal**
Supervisor: **Elisabetta Tedeschi**
Contact: **Wei He**
Collaboration with: **Statoil ASA**

The purpose of this thesis is to investigate the performance of a wind integrated oil & gas offshore installation. The motivation behind this is to reduce emissions of CO_2 and other greenhouse gases from offshore installations that utilize natural gas turbines. A model of the wind integrated oil & gas installation is built and implemented in Matlab/Simulink. The figure shows a schematic of the model. The simulations are focused on investigating the performance of the system for transient contingency conditions.



Wind Integrated Oil & Gas Offshore Installation

Two subsystems are investigated separately. The wind energy system is implemented as a $6MW$ direct-driven permanent magnet synchronous generator. The generator connects to the oil & gas installation by a 2-level back-to-back voltage source converter. An extensive control system allows for variable-speed operation to optimize power production. The configuration is found advantageous for use with oil & gas installations as the generator is decoupled from the platform transients by a DC-link. The oil & gas offshore installation is implemented as a $46MVA$ gas turbine synchronous generator, two $8MVA$ induction motor drives and a passive load of $16MW$. The gas turbine is shown to have a fast response in handling transients, and the induction motor drive is shown to have excellent speed and torque control.

The wind integrated oil & gas offshore installation combines the two subsystems through a transmission line. The complete system is simulated for both varying wind speed operation

and selected contingency events. The loss of passive load is found to give the biggest voltage transient. The biggest frequency transient is seen for the loss of one of the two gas turbines. All results are compared with the transient limits found in the NORSOK/IEC standards, and found to be within the requirements. The wind turbine is allowed to produce at maximum throughout the simulations, while the gas turbine is seen to balance the system to maintain the system frequency.

The conclusion of the thesis is that integration of a wind turbine with an oil & gas offshore installation is feasible within the NORSOK/IEC standards. This is true for all scenarios and contingencies tested in this thesis. The results are discussed further in the thesis, with challenges and suggested further work pointed out.

Analyses of Reserve Procurement Costs using the EMPS Model

Student: **Tale Marie Astad Paulshus**
Supervisor: **Hossein Farahmand**
Co-supervisor: **Arild Helseth**
Collaboration with: **SINTEF Energy**

Europe is moving towards an energy transition including increasing the share of power produced from renewable energy sources and an increase of the CO2 price in order to reduce the climate changes and curtail the damaged caused by emissions. A shift towards a larger share of power generation from renewable sources results in greater variations in power outputs and thus a greater need for reserve power to balance the power system. The Norwegian hydro power holds characteristics that make it fit to provide reserve power and is the motivation for the master project. The goal of the master project is to quantify and perform sensitivity analysis on reserve procurement costs in a simplified model of the Norwegian power system using the EMPS model as a modelling- and simulation tool for scenarios representing Norway and Europe in 2050. The EMPS model simulates the power market and handles hydro power in a detailed matter, including water value calculations to determine the value of water in reservoirs.

The master thesis is divided into three subsections: The first section present the theory, including modelling and solution principles, optimization problems, cost of reserves, setting reserve requirements, the project used to extract data for the scenarios, the e-Highway2050 project, and a presentation of the EMPS model.

The second subsections review the process of developing the scenarios by presenting the initial data set, the assumptions, the implementation process and the modified data sets, the scenarios.

The analysis takes part in the third subsection. The analysis is assembled by two cases, Case I and Case II. Case I has the objective to quantify the theoretical reserve requirements for the scenarios and to quantify the cost of introducing the reserve requirements in the three scenarios by the dual value of the reserve restriction included in the optimization problem, the difference in socioeconomic surplus and the effect on the power prices. The simulations showed that Norway has a large surplus of power and hence low prices of power in all of the scenarios. Introducing the reserve requirements in the data sets had a price and a cost, represented by the values listed, for all scenarios, but differs in extent. Case II has the objective to perform sensitivity analysis on the scenarios by investigating the trends of reserve prices (dual values), total socioeconomic surplus and power prices when increasing the reserve requirements with 2, 3,4 and 10 of the theoretical reserve requirements calculated in Case I to be able to handle dimension fault in the Norwegian power system. The findings in all of the scenarios coincided: The reserve prices increases with increasing reserve requirements, the difference in socioeconomic surplus increased with increased reserve requirements, the power prices in the time periods with initially high power prices were increased and the time period with prices near zero decreased with increasing reserve requirements.

Smart Power Control in Supermarket Applications

Student: **Håkon Person**
Supervisor: **Ole-Morten Midtgård**

Summary

In this study, smart power control system strategies for Norwegian supermarket applications are investi-gated. The relevance of smart power control systems is supported by trends in the market and the political environment. Examples include political goals regarding increased penetration of renewable electricity in the grid, economic incentives found in electricity pricing schemes, an increased number of Norwegian pro-sumers, technical challenges opposed on utility companies and new available technologies.

The stated power control goals are to increase the degree of self-sufficiency by local PV generation and to decrease yearly electricity costs. The means of mitigating electricity costs are peak shaving and load shifting from high price to low price periods, principles which are graphically described in Figure 6. The supermarket KIWI Dalgård, which is under construction and located in Trondheim, is selected as the case study. It is used as a common thread for discussing alternative solutions and making design choices for the various subsystems and strategies which compose the suggested power control systems.

To make a basis for a realistic power control design, load data are gathered as historical data with hourly values for a full year. Applied electricity cost elements are real data from Nord Pool Spot and the local utility company Trønderenergi, for the investigated period May 2016 to May 2017. Insight into load data has been obtained by granted access to the energy monitoring database of KIWI, along with conversations with key KIWI personnel. To form a basis for power control design for a full year and to assess the internal flexibility of the loads, the load data has been studied with a daily, seasonal and yearly perspective as well as distributed on load types. A detailed model of the PV system planned at KIWI Dalgård has also been built in the simulation software PVsyst. Based on the load and generation curves of KIWI Dalgård, an evaluation of convenient storage technologies has been made, of which a thermal PCM storage solution was decided to be included in the case study simulations.

A study of global research publications has been used to identify suggested smart power control strategies which are to be evaluated in a case study context. To support understanding and relevance of the discussed systems, technical theory is generally supported with system examples and available solutions in the market when found. Included in the scope is the power control system context, which forms an important part of the decision basis. The basic architecture of a building automation system (BAS) is described as it forms the system to which the smart power control is to be adapted. Different stakeholders and their goals are discussed, as it forms a basis for how the system should be set up. A potential saving assessment for the case study is included as it gives guidelines of which equipment and complexity which can be justified when designing a power control system. After an overall assessment, a real time fuzzy logic control system and an optimized scheduling system have been chosen as alternatives to be further investigated for the case study. A full year of hourly simulations has been conducted, and results are compared for the suggested control schemes.

Additionally, a sensitivity and scenario analysis is conducted to evaluate control system performance in different situations.

The proposed power control strategies of fuzzy logic real time control and optimized dispatch performed technically well according to the stated control objectives, however it proved difficult to generate economic revenue. The best performing control structure was the optimized scheduling system, which mitigated yearly electricity costs by 3.5 % and obtained a degree of self-consumption of 99.3 %. The largest savings were obtained by peak shaving. The main reason for the low savings obtained was the small potential for smart power control found in the case study, which was recognized by low consumption, flat load curves and 97 % direct self-consumption of PV electricity by the loads before smart power control was applied. For such a case, no control or a simple real time control structure requiring a minimum level of set-up time and installations seems to be most economically viable. Other constraints were market based, such as low energy grid tariffs and low variation in the hourly spot price. Still, the technical performance of smart power control systems was demonstrated, and the systems are believed to be attractive in more suitable applications. The relevance of smart power control increases with large grid tariffs, excess of distributed generation, sharp peak loads, large variation of electricity prices, and the number of synergies which can be integrated so that alternative cost components may be reduced.

Hydrogen Production from Wind and Solar Power in Weak Grids in Norway

Student: **Dimitri Pinel**
Supervisor: **Magnus Korpås**
Contact:
Collaboration with:

Problem description

Norway has a strong potential for developing wind power. However the needs of electricity of the country are already met by the hydro production that accounts for more than 95% of the electrical production. Moreover, the stronger potential is located in the north of Norway, in Finnmark, which happens to also be an area where the grid is weak, limiting the possibility to export this energy. Different alternatives are possible in order to still take advantage of this strong potential. One possibility would be to increase the local load, for example by implementing electricity hungry industries such as the aluminum industry or the paper industry. Another one would be to increase the capacity of the lines to allow for more exportations of energy.

Another way to increase the local load and to take advantage of the wind potential is to produce hydrogen. Hydrogen production can be performed through gas reforming using fossil fuels and through water electrolysis. In both case a liquefaction process is needed and requires a lot of energy. The electrolysis method has the advantage of producing a «clean» hydrogen, without emitting greenhouse gases, unlike reforming,

The hydrogen that would be produced could then be used as a fuel for vehicles such as cars, buses, or ferries.

The task

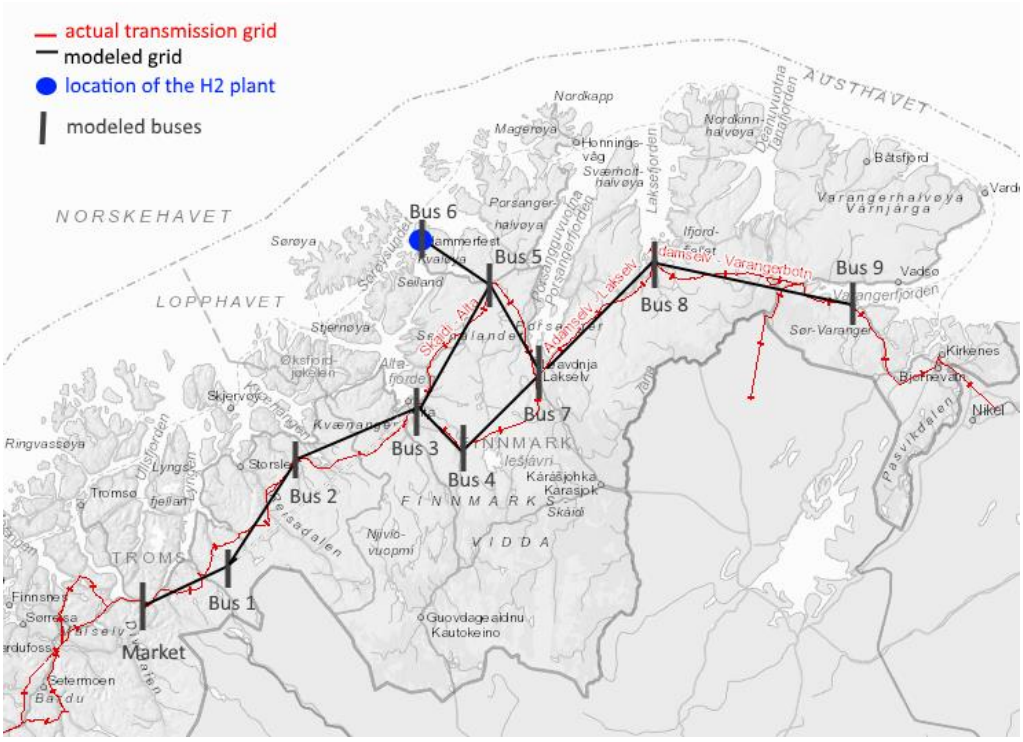
In this context, it is interesting to study how the production of hydrogen with electrolysis would affect the electrical system and how much investment would then be optimal in wind power and in the electrolyzer and hydrogen storage size. The opportunity for solar is also studied to see if some seasonal effect can make it viable despite low insolation on average. Different solar prices are studied and the ideal grid size is discussed. The modifications that happens in the hydro system are also studied.

Model/ measurements

The north of Norway is modelled with its lanes and buses at the transmission level. The area can be seen on the figure below. It also contains the loads, the existing wind farms, the aggregated hydro power plants and a connection to the market.

An optimization is then performed by linear programming over a year with hourly time steps. The objective function is the following :

$$max\Bigg\{ -\frac{T}{8760}\left[\sum_{i\in\mathcal{W}} C_i^w w_i^{exp} + \sum_{i\in\mathcal{H}_2} C_i^e e_i^{max} + \sum_{i\in\mathcal{H}_2} C_i^s h_i^{exp} + \sum_{i\in\mathcal{N}} C_i^{sol} s_i^{exp}\right] + \sum_{t\in\mathcal{T}}\left[\lambda^s p_{t,0}^{imp} - (\lambda^s+\delta) p_{t,0}^{exp} - \sum_{i\in\mathcal{N}} C^r r_{t,i} - \sum_{i\in\mathcal{H}_2} C^i h_{t,i}^i\right] - \sum_{i\in\mathcal{H}}(C^{v+} v_i^+ + C^{v-} v_i^-)\Bigg\}$$



Calculation

The main results were that the investment in wind power was mainly at bus 9 and 8 and that even if the electrolyzer size increased approximately linearly, the storage size on the other hand does not and increase greatly after the case 40%.

The possibility of investing in solar was then added to the model at a price of 3,8$/Wp and it turned out to not be profitable at this price before the case 50\%. It was however found that the addition of solar power yields a positive impact on the size of the storage needed due to advantageous seasonal effects.

The next step was to study different prices in order to find when solar becomes profitable. The resulting value for the case 10\% was around 0.4$/Wp much lower than the current price of 1,6$/Wp but also reasonable in a longer term as suggested by some other studies.

The next study was to account for the cost of the grid expansion in different cases to see if only limiting rationing is a good criteria. The simulation was used again with different grids and it appears that limiting the rationing was often giving the cheapest result even though upgrading the grid further do not result in a big increase in cost due to a trade off between operations cost and investment cost.

The last study was focused on the behavior of the hydro system during the previous simulation cases and it highlighted some interesting seasonal effect of the different technology.

Conclusion

As of now, solar power does not appear to be a good solution for the case of 10% of the total hydrogen coming from electrolysis due to its cost. Wind power appears to be a preferable solution even if the investment is not large and thus does no take fully advantage of the resources of the north of Norway. In the end it seems that even by having a bigger load and solar, upgrading the lines is necessary for not having rationing in the system.

Studying if relaxing the constraint on the hydrogen production could lead to reduction in the needed storage size and line size could bring important insights.

Design of a Circuit for Making Test for Load Break Switches

Student: **Alejandro Nahum Prieto Almanza**
Supervisor: **Kaveh Niayesh**

Problem description

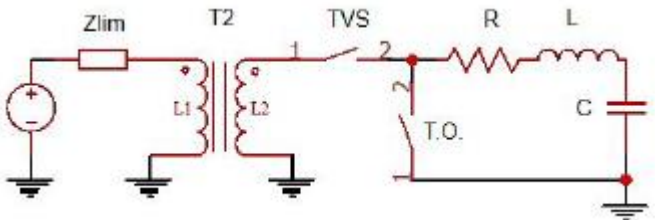
A load break switch is a type of switching device extensively used in medium-voltage applications at distribution systems. For that reason, it is of great importance that it works properly, and for this to happen, it needs to pass several types of tests. This thesis focuses on one of the most important tests designed for load break switches and that is the so-called *making test*. A making test for load break switches needs to be performed with the help of a circuit known as a *synthetic circuit* due to laboratory capability limitations. This master thesis explains what a synthetic circuit is and the impact that its components have on the correct performance of the making test.

The task

The main objective is to design a synthetic circuit to perform a making test of load break switches in a laboratory environment by selecting the most appropriate parameter of resistance, inductance, and capacitance that successfully permits the applying of a high-current according to the IEC Standard limitations and requirements. This task needs to be done by taking into account all components of the synthetic circuit and their respective voltage drops, losses, time delays, and other relevant considerations to obtain more realistic results. A deep study about important components of the making switch is also expounded due to its great importance on the making operation, more specifically, a study of the voltage drop across the making switch and across the load break switch is performed. The making switch is the component in charge of applying current at the desired moment during the test to the load break switch, which is the test object. The study of the making switch was done in a laboratory environment while the study of the load break switch was fully simulation based.

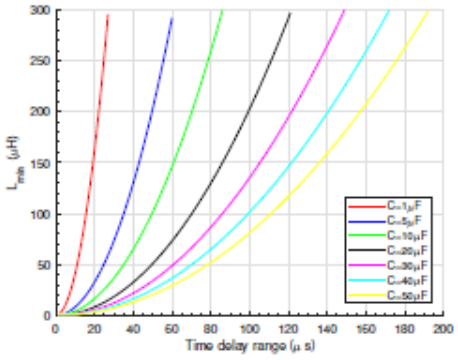
Model/ measurements

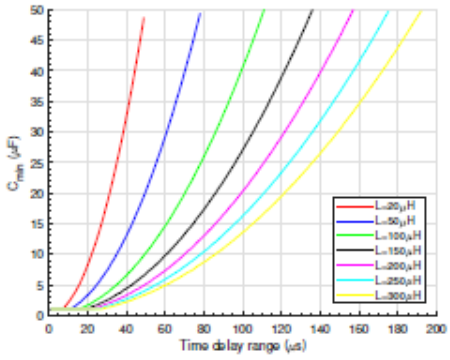
The actual circuit that is going to be used is shown below. To perform simulations, Matlab and a well-known Electromagnetic Transient Program (EMTP), ATPDraw, were used. The study of the voltage drop across the making switch was done at the high-voltage laboratory at NTNU.



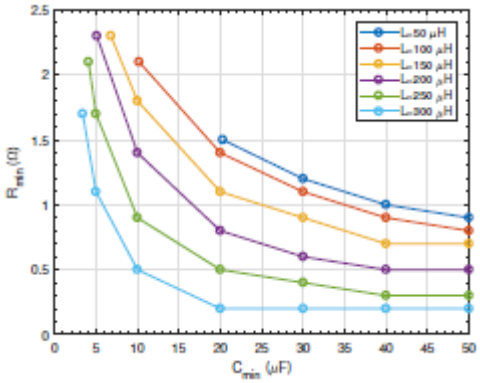
Calculation

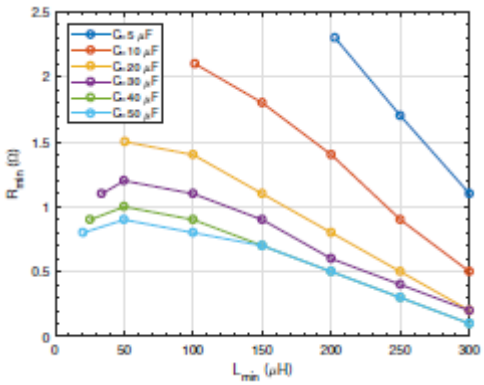
By having proper values for voltage drops it was possible to find several appropriate combinations of minimum values of resistance, inductance, and capacitance that make a satisfactory making operation possible.



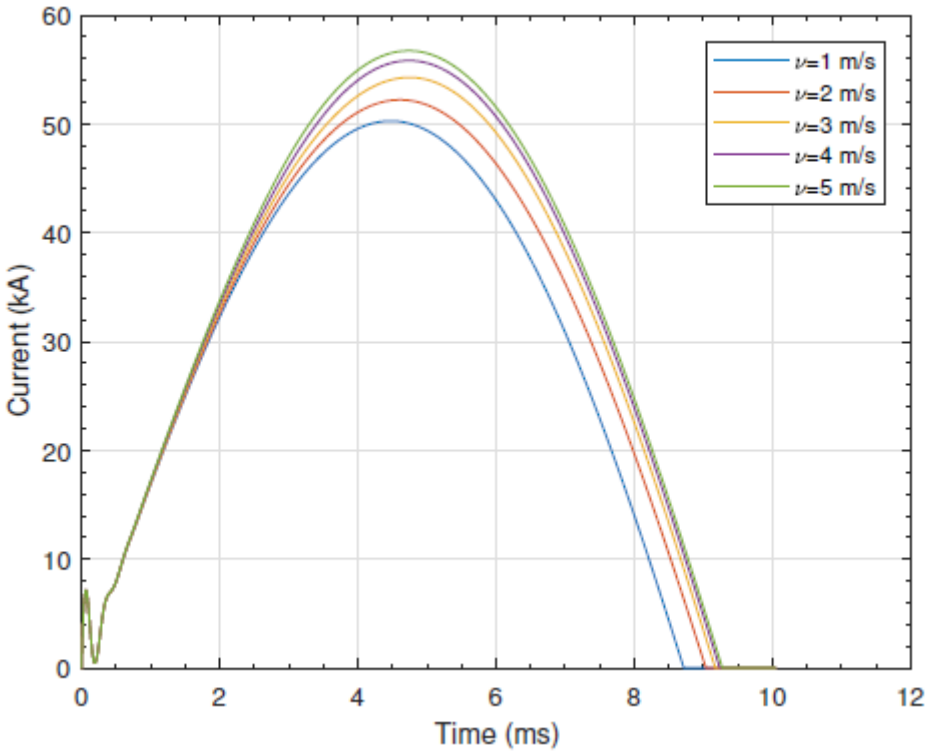


Conclusion





By choosing the right resistance, inductance, and capacitance values on the voltage-circuit it is possible to guarantee a good performance of the current appliance and, therefore, having a making current without current-zero point. The ending results were positive and showed that the making operation was made correctly for a load break switch rated for 24 kV with closing velocity from 1 to 5 ms and a triggered vacuum switch with time delay of 50 microseconds. The making current was in the range of 50 to 60 kA without any high-frequency crossing-zero points as expected.



Battery Energy Storage System connected to a Three-Phase 50-Hz Grid

Student: **Ida Pria Reite**
Supervisor: **Dimosthenis Peftitsis**
Contact: **Kamran Sharifabadi**
Collaboration with: **Statoil ASA**

Battery energy storage systems (BESS) employing secondary battery technology may offer the greatest potential for large-scale integration of renewable energy sources (RES), and is considered a key element for enabling smart grids for future power systems. The two main components of a BESS are the power conversion system (PCS) and the battery management system (BMS). When selecting a PCS topology, the most important characteristics are the reliability and efficiency of the converter. The converter technologies commonly used for PCS' have been the conventional two- and three-level voltage source converters (VSCs), however the PCS topology chosen for the BESS in this thesis is the modular multilevel converter (MMC).

The MMC offers several advantages over the conventional VSCs, such as modularity and scalability, low total harmonic distortion (THD), excellent efficiency and reliability. The battery technology chosen for the BESS is based on the lithium-ion battery technology. Lithium-ion offers desirable characteristics such as high efficiency, good response time, reasonably high charge and discharge rates, small dimensions and/or low weight and little maintenance requirements. All of the abovementioned converter and battery characteristics imply that the full MMC-BESS scheme will become highly efficient and reliable with a high round trip efficiency, well-suited for large-scale BESS applications.

The system in which the MMC-BESS is investigated, comprises of an offshore wind farm, a two-level VSC-based HVDC transmission system and the AC grid on land. Based on the investigated cases, this thesis can be divided into two main parts: design of the MMC-BESS, and modeling and simulation of the MMC-BESS. The design-part is mainly focusing on a more realistic approach of the MMC-BESS configuration by performing various calculations regarding both battery and converter requirements. The initial MMC-BESS configuration was the conventional, half-bridge MMC with centralized batteries connected to the common DC-link. This approach may offer the simplest solution to implement, however it negatively affects the reliability and efficiency of the full scheme.

Furthermore, to mitigate the drawbacks of the centralized battery-approach, an MMC-BESS configuration based on distributed batteries was proposed. This approach utilizes the MMC's modular structure, as well as improving both the reliability and efficiency. Moreover, by placing bidirectional DC-DC converters, base on the dual active bridge (DAB) topology, in the interface between the converter submodules and the batteries, a galvanic isolation of the batteries could further improve both the safety and reliability of the scheme.

Finally, a proposed approach with the main purpose of reducing space, components and cost, was to replace the two-level VSC stations of the HVDC transmission system with the MMC-BESS based on distributed batteries employing DAB converters. This solution offers the possibility to also improve the performance of the HVDC system. However, more effort should be made in verifying these assumptions.

The modeling and simulation-part analyzed the initially proposed MMC-BESS configuration in the design-part. The MMC was modeled as a simplified MMC, with an AC-side and DC-side representation and a power balance equation coupling the two sides together. The modeling approach was based on the scientific paper draft presented in \cite{santiago}, as well as the paper presented in \cite{7310477}. The centralized battery was modeled according to the linear battery model with a small equivalent series resistance (ESR). A state-of-charge (SoC) measurement system was modeled as a part of the BMS, to monitor the charging and discharging processes of the centralized battery. Furthermore, the HVDC transmission system was provided by Prof. Tedeschi and Post.doc. Sanchez Acevedo at the Department of Electric Power Engineering, NTNU. Moreover, the offshore wind farm and the AC grid on land where implemented as ideal AC voltage sources.

The simulation verified the MMC's ability to provide a controlled bidirectional power exchange with the centralized battery. The results showed the MMC operating satisfactorily with an active power flow in the range of 1.0 and -1.0 pu, and well-tuned current and energy controllers. The SoC measurements further verified the charging and discharging processes of the battery, where the battery SoC varied between 100\% and 73\% SoC. The MMC-BESS ability to provide grid support for variable wind power delivered to the AC grid was also investigated. The results showed the MMC-BESS was able to inject active power to the AC grid, as well as absorb active power from the wind farm. The SoC varied between 100\% and 85\% throughout the simulation. The last case to be investigated, was a comparison between the MMC-BESS presented in this thesis, where the scheme was connected to the AC-grid, and a BESS solution connected to the HVDC-link of the transmission system. The latter solution is based on the master's thesis of Marta N. Hellesnes, in \cite{marta}. Both solutions where able to support the AC grid by smoothing the varying wind power from the offshore wind farm.

Digital design and validation of GC-VSI control for Photovoltaic(PV) systems

Student: **Jie Ren**
Supervisor: **Lars Einar Norum**

Summary

Solar power is one of the most promising renewable energy in future. Nevertheless,the increasing PV penetration rates could lead to many problems. For example, when the local PV generation is higher than the demand in distribution systems, power will flow to higher voltage levels, which will cause the increase of voltage. Also, the fluctuating generation brings challenge to the stability of the grid.

To deal with the above mentioned challenges, power electronics equipment have been increasingly employed in the electric grid worldwide. More accurate modeling and digital design of the control systems for PV systems is necessary.

This thesis is structured as the follows: In the first chapter, the background of PV generation, the structure of PV systems and its working principles are introduced. Back ground knowledge of converters are introduced in Chapter2. Common used 3 phase in-verter control strategies and the coordinate transformation method for single phase systems are detailed. Based on a typical PV systems structure, the grid side, the DC bus, the PV side mathematical models are built in synchronous frame respectively in Chapter3. Chap-ter4 focuses on the control design principle. The Grid Synchronization problem is roughly discussed and a concept of Multiple Maximum Power Point Tracking(MMPPT) is came up. Conclusion and future work are stated in the last chapter.

Key words: PV systems, MPPT, Grid Connected Voltage Source Inverter, Nonlinear Con-trol, MMPPT

Nettmessige konsekvenser ved økt grad av elbillading i distribusjonsnettet

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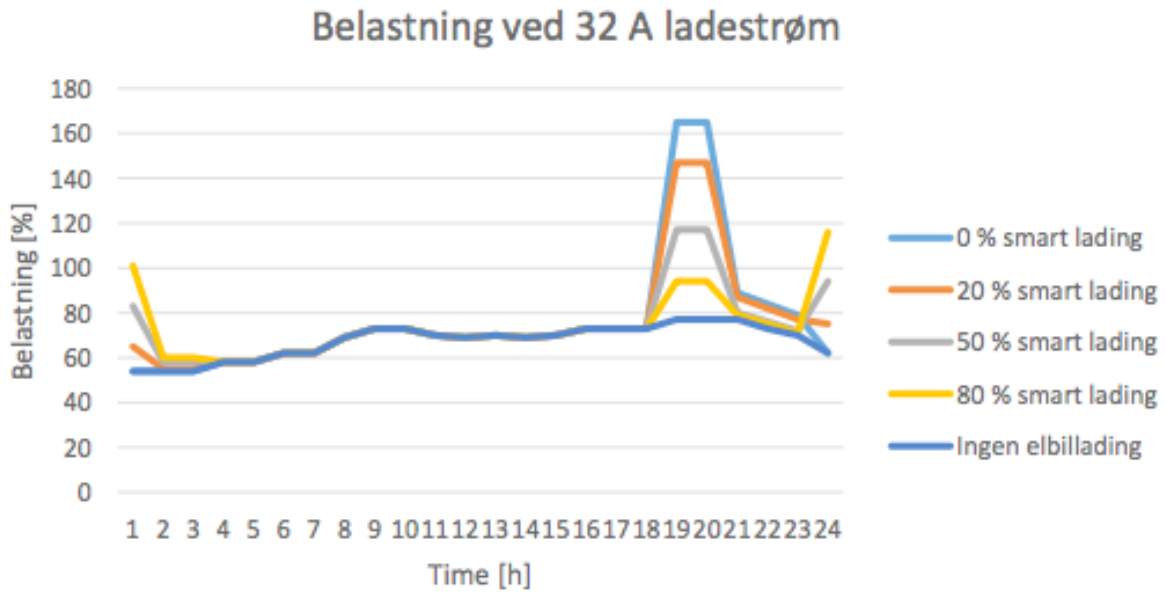
Faglærer: **Trond Toftevaag**
Veileder: **Rune Paulsen, Jan A. Foosnæs**
Utføres i samarbeid med: **NTE**

Denne masteroppgaven er et studie om nettmessige konsekvenser ved økt grad av elbillading i distribusjonsnettet. Det er utført simuleringer i programmene Netbas og DigSilent PowerFactory. Simuleringene baserer seg på to ulike ladestrømmer for elbillading – 16 A og 32 A. I case 1 er det utført simuleringer i Netbas på et bestemt nettområde som NTE eier og drifter. Her er det sett på hvordan belastning av transformatorer og spenning blir påvirket ved de to ladestrømmene og ved ulike ladestrategier – normal lading og smart lading. I case 2 er det studert spenningsusymmetri og spenningsfall ved ulike penetrasjonsgrader av elbillading i et IT-nett og i et TN-nett ved hjelp av simuleringer i DigSilent PowerFactory.

Det er i dag ingen insentiver til å forskyve ladingen til tider av døgnet hvor lasten er lav (smart lading). Dette vil være avgjørende for at nettet skal tåle høy penetrasjonsgrad av elbillading. Nettet som er studert i case 1 består av 1320 kunder. Det er antatt at 70 % av kundene lader elbilen sin hjemme, hvor 60 % lader elbilen hver dag og de resterende 40 % lader den når State of Charge er på en gitt verdi. Simuleringene er utført klokken 19 på en relativ kald vinterdag. Resultatet for 100 % penetrasjonsgrad av elbiler (1 per kunde) viser at ingen transformatorer i nettet blir overbelastet hvis ca. 50 % av ladingen er smart lading og det lades med 16 A ladestrøm. Høy penetrasjonsgrad av 32 A hjemmelading anbefales ikke da en slik ladestrøm fører til overbelastning av flere transformatorer, selv med 50 % smart lading.



Figur 1: Belastning av en transformator ved ulike ladestrategier og 32 A ladestrøm

I case 2 er det analysert et IT-nett og et TN-nett med 16 kunder hver. Resultatet viser at høy ladestrøm og høy penetrasjonsgrad av kunder som benytter hjemmelading av elbil vil føre til at forskriftens grenser for spenningsfall og spenningsusymmetri blir brutt, dette gjelder både for TN-nett og IT-nett.

Ved 16 A enfaselading er kravet for maksimalt tillatt spenningsfall begrensende ved penetrasjonsgrad på 25 % og 50 %, mens både kravet for maksimal spenningsusymmetri (2 %) og spenningsfall er begrensende ved 100 % penetrasjonsgrad. Lengdene på kabler og linjer har blitt justert for å studere hva kortslutningsytelsen har å si for spenning og usymmetri. Ved 100 % penetrasjonsgrad og 16 A lading vil det være tilstrekkelig med en kortslutningsytelse i nettets svakeste punkt på I_{kmin} = 900 A for IT-nettet og I_{kmin} = 800 A for TN-nettet ved fordelt last. Ved økt ubalanse av last mellom fasene og økt last vil spenningsnivå minke og maksimal spenningsusymmetri øke. Det er derfor viktig at lasten blir mest mulig fordelt mellom fasene på den aktuelle avgangen.

Enfase 32 A lading krever kortslutningsytelse I_{kmin} =1900 og I_{kmin} =1500 i nettets svakeste punkt for henholdsvis IT-nettet og TN-nettet ved fordelt last. Ettersom det i store deler av det norske distribusjonsnettet er lav kortslutningsytelse (40 % kundene har kortslutningsytelse < 1000 A) vil høy penetrasjonsgrad av 32 A enfaselading kreve dyre nettoppgraderinger. 32 A lading bør derfor kun utføres som trefaselading hos kunder med sterkt nett.

Tabell 1: Minste nødvendige kortslutningsytelse for IT-nett og TN-nett ved 16 A og 32 A ladestrøm

	I_{kmin} [kA] IT-nett		**I_{kmin} [kA] TN-nett**	
Lastfordeling (L1, L2, L3)	**16 A**	**32 A**	**16 A**	**32 A**
Symmetrisk	0,90	1,34	0,78	1,17
100%, 0%, 0%	3,12	5,62	2,71	7,75
50 %, 25 %, 25%	0,92	1,86	0,82	1,52

On-Line Voltage Stability Assessment

Combining Model Based and Measurement Based Indicators

Student: **Vilde Rye-Holmboe**
Supervisor: **Professor Kjetil Uhlen**

Summary
This master thesis has examined the possibility of combining measurement and model based methods for on-line voltage stability assessment in the power system. Voltage instability may lead to voltage collapse and blackout of total or parts of the system. To avoid severe damage to equipment, disconnection of customers and the resulting economic costs it is significant to know how far the system is from the stability limit. It is desirable that the system operator is warned as soon as possible when the system approaches the stability limit so that he/she has time to initiate countermeasures.

The maximum loadability of the transmission grid has been found to be a good indicator of voltage stability. A proposed method combining *Continuation Power Flow* (CPF) and *the S-Z Sensitivity Indicator (S-ZI)* has been presented and implemented in a case study where a power system approaches voltage collapse, through a series of consecutive disturbances. The CPF is based on a system model and requires measurements from the whole system (provided by the State Estimator (SE)). It finds a continuum of power flow solutions at the load bus to find the maximal loadability, which makes it computational demanding to carry through. Since it uses a model of the whole system, it is possible to simulate potential outages in the system, to study the steady-state stability after contingencies. The S-ZI uses measurements from the Phasor Measurement Unit (PMU), placed at the load bus. The S-ZI needs few measurements, is easy to compute and can, therefore, be conducted more frequently than the CPF.

The master thesis proposes a new method that aims to combine the accuracy of the CPF, with the frequency of the S-ZI. By combining the resulting maximum loadability estimated by the S-ZI (computed every 40 ms), which is then corrected by the CPF (computed every 5 minutes), the proposed method finds a new maximum loadability of the system, $P_{MAX,REAL}$.

The proposed method was able to detect that the system had moved into the alert state after the system had been subjected to a contingency. Based on the results of the case study, it is not, however, possible to conclude that the actual maximum loadability of the system have been found by the proposed method.

Both the S-ZI and the CPF were found to overestimate the maximum loadability of the system. Particularly the maximum loadability estimated by the S-ZI was found to vary a lot, overestimating the maximum loadability limit by as much as 2-3 times compared to the actual limit at some time steps. The variation in the resulting $P_{MAX,S\text{-}ZI}$ is too big to give any real information about the change in the maximum loadability between every time the CPF is solved. The results of the case study show that the proposed method can, at best, provide an indication of where the system is headed. Further study is needed to find a more appropriate monitoring of the actual variation of the maximum loading limit in the system.

Cost-Benefit Analysis of Maintenance Measures for Power Transformers

Student: **Tobias Rønneberg**
Supervisor: **Eivind Solvang**
Co-Supervisor: **Jørn Foros and Maren Istad**
Collaboration with: **SINTEF Energy Research**

Summary:
The work described in this thesis was conducted in cooperation with SINTEF Energy Research and their collaborating partners in the research project "Trafotiltak". The objective of the project is to develop a decision-making tool, based on both economic and technical data, to support asset management maintenance decisions on Norwegian power transformers.

Deciding when to perform reinvestments and finding the right type of maintenance action that creates the most benefit is challenging. Therefore, this thesis explores the different maintenance measures available for improving the condition of mineral oil within the transformer. To analyse the performance of different measures, service data from power transformers owned by Norwegian companies, collaborating in the project, were collected. The condition of each transformer was calculated by using a health index score, shorted HI-score. This score allows the asset manager to quickly compare power transformers against each other and find the transformers with the greatest need of improvements. This data acquisition of the condition improvements from previous cases helps create a statistical overview on benefits gained from different measures, and could be used as the input in a cost-benefit analysis between different maintenance measures.

The thesis has determined the estimated improvements for a standard reclamation of oil through the data acquisition, where also some of the other measures described in this thesis are included in the process. Due to lack of data from stand-alone measures e.g. recondition, oil change and drying of oil/paper it was not possible to make a corresponding statistical summary of expected improvements for other measures than reclamation of oil.

To test the performance of the proposed "Trafotiltak" model and especially the cost-benefit model included in "Trafotiltak", it was applied to two real power transformers in the need of condition improvements. By doing this it could calculate when maintenance was most beneficial and if reclamation of oil was a better alternative than to reinvest in a new transformer. The estimated improvements from reclamation found in this thesis are used as the benefit for the reclamation process in the model. The results from the case studies show that the model could give reasonable suggestions on which measure to choose and when measures should be performed. Even though the cost estimates and HI-scores that have been used are a little rough, they are still reliable and an indication that the model could be used in the industry to examine different maintenance alternatives.

Samanlikning av ulike anmeldingsmetodikkar i spotmarkedet

Student: **Anders Schjølberg**
Faglærar: **Prof. Magnus Korpås, NTNU**
Rettleiar: **Dr.ing Tellef J. Larsen, Statkraft**
Utførast i samarbeid med: **Statkraft**

Problem
Norske kraftprodusenter leverer kvar dag inn bud til NordPool, i form av budmatriser. Desse fortel kor mykje produsenten er viljug til å produsere på ulike prisnivå. Alle produsentene må levere buda sine før kl 12. Etter dette balanserer NordPool tilbud og etterpørsel, og reknar ut ein systempris og områdeprisar. Innleveringa av bud skjer 12-36 timar før vatnet renn gjennom turbinen. Optimaliseringa må derfor skje med ei viss usikkerheit i både pris og tilsig. Fig.1 viser noko av utfordringane kraftprodusentane står ovanfor, nemleg svingingar i pris. Når prisane er høge ynskjer alle produsentane å produsere mest mogleg, mens når dei er låge ynskjer dei å spare vatnet til seinare bruk.

Statkraft ynskjer å evaluere både interne rutiner og alment kjente metodikkar for å rekne ut desse buda. Simuleringane har vorte utført i produksjonsoptimaliseringsverktøyet SHOP, som kan modellere vassdrag av alle størrelser og inkludere alle komponenter i eit vassdrag. SHOP blir brukt som beslutningsstøtte i anmeldingsprosessen av dei fleste store kraftprodusentar i Norge.

Kraftmarkedet i 2017
Analyseområdet er avgrensa til Statkraft sine vassdrag i NO4, kor Rana-, Røssåga- og Svartisen-vassdraget er dominerande vassdrag. Ei utfordring i 2017 har vore den seine våren. Som vist i fig. 2 ligg fyllingsgraden i veke 22 (28.mai) 15.5 prosentpoeng under medianen. Dette har ført til at prisane i mai har lege opp mot 10 EUR/MWh høgare enn for same tidspunkt i 2015 og 2016. Mot sluttena av analyseperioden ser ein at 2017-prisen går ned, mens 2016-prisen går opp. Dette skuldast nok i stor grad auka temperatur og tilsig i 2017, noko som førte til nedgang produksjonsnedgang. Pristoppen for 2016 skuldast i større grad lite snølager og mindre nedbør.

Arbeid
Hovudarbeidsoppgåva i dette prosjektet har vore gjennomføring av anmeldingssimuleringar i SHOP. Ut frå anmeldingane er det notert nytteverdiar, lastforpliktelser, prognosert pris, realisert pris og reknetid. Desse resultata er systematisert, og dei ulike anmeldingsscenario er analyserte med vekt på samanhengen mellom budmønster og prisprofil.

Framgangsmåte
Simuleringane i SHOP resulterer i ein objektfunksjon som er eit mål på inntekten generert i analyseperioden, i tillegg til verdien på det vatnet som ligg att. Det blir rekna ut ein lastforpliktelse, som representerer budkurva til kvar anmeldingsmetodikk.
Anmeldingsmetodikkane er samanlikna med perfekt anmelding, som er den maksimale objektfunksjonen du kan oppnå med kjent pris og tilsig. Her har det, i tillegg til nytte og lastforpliktelser, vorte analysert reknetider.

Anmelding
Anmeldingsmetodene som er analysert består av både stokastiske og deterministiske optimaliseringsmetoder. Prisen er ein stokastisk parameter fram til NordPool utfører markedsklarering mellom kl 12-13 dagen før produksjonen. Tilsiget er usikkert heilt fram til produksjonstimen. Tilsiget vil derfor bli ein stokastisk parameter uansett kva for anmeldingsmetoder du brukar.

Budmatrise
Fig. 3 viser eit eksempel på 3D-framstilling av ei budmatrise. Her er prisnivåa [EUR/MWh] sorterte på y-aksen, timane [h] på x-aksen og buda [MW] på z-aksen. Eksemplet viser at buda er stigande for stigande pris. Ved stokastiske anmelding brukar ein den realiserte prisen på y-aksen til å linearisere eit bud for kvar time i det gitte prisintervallet.

Simulering
Simuleringsprosessen har gått ut på å rekne ut ei anmelding i Elspot-markedet kor prisen er ein ukjent parameter, for så å rekne ut ein nytteverdi av denne anmeldinga i Elbas, etter at NordPool har rekna ut områdeprisar og lastforpliktelser.

Resultatanalyse
Eit eksempel på analysegrunnlaget er vist i fig. 4. (Denne anmeldinga inneheld fiktive tal.) Her er budvolumet i MW framstilt på venstre vertikalakse og prisnivået på i EUR/MWh på høgre vertikalakse. Horisontalaksen inneheld timane i døgnet. Dei stipla linjene representerer prisserier, mens dei heiltrukne linjen representer budkurver.
Analysene har basert seg på å samanlikne korleis budmønsteret blir for ulike prisprofilar og –nivå. Anmeldingsmetodikkane er samanlikna med referansemetodikken perfekt anmelding (grå kurve), som er eit tal på den maksimale nytteverdien det er mogleg å oppnå med kjent pris og tilsig. Nokre anmeldingsmetoder skårar bra på prisnivå, mens andre treffer betre på prisprofil.

Sia dette er ei bedriftsoppgåve, som er underlagt konfidensialitet, er det ikkje publisert noko resultat eller konklusjon i denne oppgåva.

Conductivity Measurement in Switching Arcs using Electric Probes

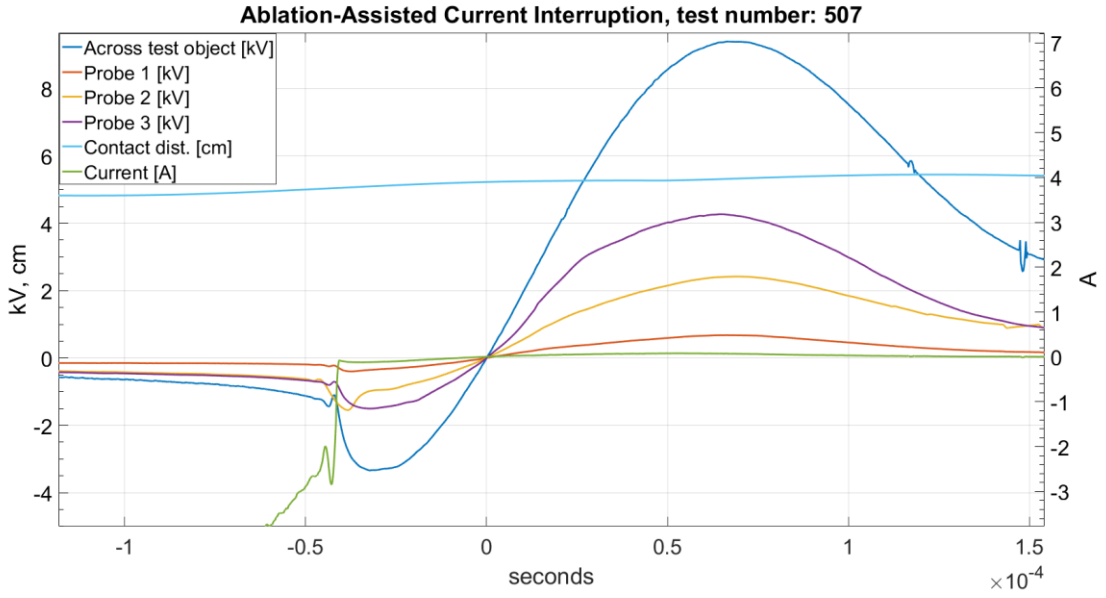
Student: **Torjus Ramm Settendal**
Supervisor: **Kaveh Niayesh**

Due to its excellent arc quenching capability, SF_6-gas is widely used for medium voltage switchgear. Because it is a highly potent greenhouse gas, it is expected to be many restrictions for the allowed use of this gas in near future. It is therefore important to conduct research on development of more environmental friendly switchgear. The challenge is to keep both the interruption capability and volume, of today's SF_6 insulated switchgear. One of the most promising solution to this challenge, is to use ablation material to improve the current interruption capability. Experimental work with an ablation-assisted circuit breaker, was the foundation for the work in this thesis.

The primary aim of this thesis was to evaluate the arc voltage distribution inside an ablation tube during ablation-assisted current interruption, using air as the insulation medium. This was performed by gathering the readouts from three high voltage resistive probes placed at different key locations in the plasma arc.

The first part of the thesis contained work performed to weed out any large sources of measurement error. From previous work, it was found that the experimental setup used in this work contained one or more of these sources. The second part of this work contained the experimental portion of this work. This part explained how the tests were conducted, and listed the results together with a discussion around their significance and wider implications. By applying the corrections suggested in this work, the probes gave valuable results for conductivity measurements in switching arcs. The results were considered valid for measurements from contact separation and until 100 µs after current interruption.

The results showed clearly that the field strength was significantly higher where the gas outlet was located, when the pressure inside the ablation tube was low. When acting as a "self-blast" switch, which increased the pressure, gave the system an increase in field strength. Additionally, there was also a change in the position of the field strength peaks. With an increase, in pressure, the field strength changed from being largest over the gas outlet to being largest over the first few millimeters of the arc.



Arc voltage distribution for one of the tests conducted in the thesis

Overoppheting av mellomspennings PEX-kabelskjøter

Termisk aldring karakterisert ved PD-målinger

Student: **Karoline Skjelsvik**
Faglærer: **Frank Mauseth**

Sammendrag

En betydelig andel av det norske mellomspennings kabeldistribusjonsnettet har passert den forventede levetiden på 30 år. Driftserfaringer viser at kabeltilbehør som f.eks. kabelskjøter har en kortere forventet levetid enn selve kabelen, og i den sammenheng har det blitt observert flere feil på varmekrympede kabelskjøter som ble installert på 1980-tallet. Årsaken til feilene som har oppstått er ofte overoppheting av skjøtehylsene på grunn av høy kontaktmotstand. På bakgrunn av dette har det i masterarbeidet blitt laget PEX-kabelskjøter med redusert ledertverrsnitt, med et ønske om å oppnå en redusert kontakt eller en økt kontaktmotstand mellom lederen og skjøtehylsen.

Det er et økende behov for tilstandskontroll av høyspenningskomponenter på grunn av det stadig økende elektrisitetsforbruket, og at det stilles strenge krav til stabil strømforsyning med hensyn til spenningsstabilitet og frekvenskvalitet. En av metodene for å undersøke tilstanden til isolasjonen i kabelskjøtene er ved hjelp av målinger av partielle utladninger (PD). Dette har derfor blitt gjort i dette masterarbeidet. I tillegg til å montere kabelskjøtene har det vært fokus på hvilken effekt forhøyet lokal temperatur vil ha på isolasjonssystemet ved måling av PD, og det har derfor blitt satt opp en laboratoriekrets for å kunne vurdere tilstanden til kabelskjøtene.

Kabelskjøtene som ble laget i denne masteroppgaven ble utsatt for en akselerert aldringsprosess, der én kabelskjøt ble temperatursyklet, mens to andre kabelskjøter ble påtrykket en konstant temperatur på 150 °C. Én temperatursykel tilsvarer en runde med oppvarming til 150 °C ved lederen, og deretter nedkjøling til romtemperatur (~ 20 °C).

Resultatene viser at effekten av å utsette det ene testobjektet for en temperatursykling i 528 timer viser ingen tydelige tegn til aldring av testobjektet. Det konkluderes med at forholdet mellom temperatur og tidsperioden forsøkene ble gjennomført på ikke var tilstrekkelig for å kunne detektere PD, som følge av aldring.

Den ene kabelskjøten som ble påtrykt en konstant temperatur var utsatt for fuktige omgivelser, mens den andre var i tørre omgivelser. Etter bare to uker i aldringsprosessen, kunne det registreres PD-aktivitet på den fuktige kabelskjøten. Da hadde kabelskjøten gått fra å være PD-fri opp til 40 kV, til å ha en tennspenning på 8 kV. Gjennom aldringsprosessen har det sannsynligvis trengt vann inn i skjøten. Det kan derfor være av interesse å fortsette å gjøre målinger på denne kabelskjøten for å se om tennspenningen vil øke igjen når fuktigheten trenges ut av kabelen.

Kabelskjøten som ble påtrykt en konstant temperatur i tørre omgivelser registrerte ingen PD under noen av målingene de første ukene i aldringsprosessen. Etter hvert oppstod det derimot et termisk gjennomslag, og disseksjon av kabelskjøten måtte til. Disseksjonen viste at det hadde oppstått et termisk gjennomslag langs den feltstyrende slangen i skjøten.

Ombygging av 230 V IT-installasjoner til 230/400 V TN-installasjoner

Student: **Eirik Kvinge Skogseth**

Veileder: **Eilif Hugo Hansen**

Sammendrag:

På grunn av forventede endringer i bruksmønster og behov er det fra norske myndigheters side et ønske om å tilpasse seg den europeiske modellen for utforming av lavspenningsnett. I Norge i dag er størstedelen av lavspenningsnettet bygget opp som IT-nett og det er ønsket en overgang til TN-systemet. Som del av nasjonal overgang til TN-systemet er det interessant å se på hvordan eksisterende installasjoner bygget opp med IT-systemet kan la seg bygge om til TN-systemet.

Denne oppgaven har sett på hvordan eksisterende installasjoner i eneboliger, flermannsboliger og næringsbygg kan bygges om fra IT-system til TN-system. Da forskrifter for utforming av elektriske installasjoner ikke har hatt tilbakevirkende kraft, har det blitt lagt spesiell fokus på eldre installasjoner. Det har vist seg at eldre IT-installasjoner avviker mest fra dagens standard for utforming av TN-installasjoner. Hovedfokus i oppgaven har vært hvorvidt eksisterende installasjonsmateriell i IT-installasjoner fortsatt kan brukes etter en ombygging, hvilket som ikke kan brukes og hvilke ekstra tiltak som må utføres.

I vurderingen av hvilket installasjonsmateriell som kan brukes og ikke kan brukes, har det vært diskutert hvorvidt utstyret opprettholder beskyttelse mot elektrisk sjokk og brann, og hvorvidt gjeldende utstyr følger siste versjon av forskrift og norm. Hva man legger i begrepet elsikkerhet og myndigheters tilhørende ansvar i å kontrollere har vist seg å være viktig. En presisering av elsikkerhetsbegrepet vil i enkelte tilfeller avgjøre hvilke installasjonsmateriell og metoder som fortsatt kan brukes etter en ombygging. I oppgaven er det vurdert hvilke tiltak som går på tradisjonell elsikkerhet og hvilke som blir en kostnad og funksjonsvurdering.

Ved bruk av eksempler har det blitt vist hvilke tiltak som må gjennomføres ved ombygging av IT-installasjoner etter nevnte vurderingskriterier. Med enkelte dispensasjoner fra å følge NEK400 vil en ombygging av de installasjoner som fraviker mest fra NEK400 2014 kunne ombygges med enkle metoder. Blant annet vil tillatelse til å fortsatt bruke ikke-ledende omgivelser gi en mindre kompleks og kostbar ombyggingsprosess. Generelt kan det sies at mye installasjonsmateriell fortsatt kan brukes og mange tiltak er enkle og kan utføres i sikringsskapet. Omfanget av en ombygging vil variere for hver installasjon avhengig av når installasjonen først ble installert og eventuelt modifisert. De samme anleggsdelene må kontrolleres ved hver ombygging, men behovet for tiltak varierer avhengig av hva som er installert. Dette henger sammen med at en moderne IT-installasjon bruker mye av det samme installasjonsmateriellet som en moderne TN-installasjon. Det er liten variasjon i nødvendige tiltak mellom de ulike typer installasjoner.

Assessing the economic benefits and power grid impacts of the power link island project

Student: **Erik Solli**
Supervisor: **Magnus Korpås**

Problem description

This master's thesis assesses one of the hottest offshore projects nowadays, namely the power link island project. It is intended for the North Sea Region and includes the construction of an artificial island in the Dogger Bank area with associated transmission lines connecting all participating countries. Three different case studies were developed during this research with the aim of finding the economic viability of the power link island project, what impact this project may have on the future power situation in Europe, and possible ways to make it even more attractive for future investors.

The task

The three case studies differ in focus area. The first case study includes three different degrees of offshore power grid development. In the second case study, three predetermined percentages of the onshore renewable energy production are moved from onshore to offshore nodes in the power system. The last case study includes three different placements of additional offshore wind power.

Model/ measurements

The transmission expansion model PowerGIM was used for simulations in this thesis, and it includes six countries, all bordering the North Sea. These countries are Great Britain, Belgium, the Netherlands, Germany, Denmark and Norway. The original representation of the North Sea grid in PowerGIM is shown in Figure 1. The investment model is given the opportunity to invest in the power link island node and corresponding transmission lines during simulations. The input data in the investment model is divided into four different .csv files named «nodes», «branches», «generators» and «consumers». The data sets used in the investment model are based on future visions for the European power system collected from TYNDP 2016 published by ENTSO-E. All case studies include two sets of simulations, one for the least optimistic vision, and one for the most optimistic vision.

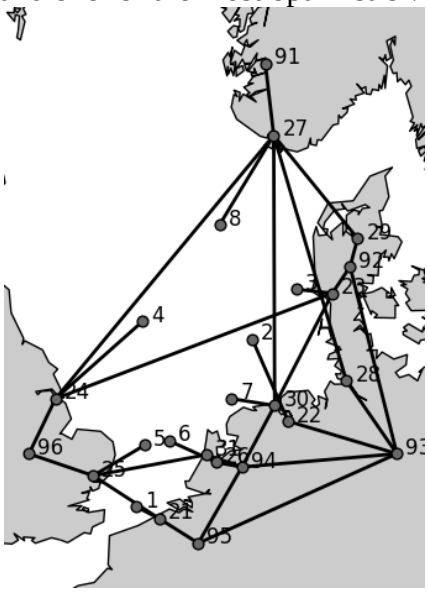


Figure 1: The original power grid representation in PowerGIM

Calculation
The results analysed in this thesis includes project costs, distribution of transmission investments between participating countries, branch capacity expansions done in association with the power link island, average area prices for each participating country and transmission line utilization of power lines connected to the power link island.

Conclusion
It was an economic advantage to invest in the power link island in all simulated scenarios which allowed the power link island to be built, independent of futuristic vision. When examining different degree of power grid development, the power link island was even more profitable for futuristic scenarios with higher penetration of renewable energy. Moving predetermined percentages of the onshore renewable generation to offshore nodes had a positive effect on the total costs of the project up to a certain percentage.

Combining the best scenarios from the two first case studies gave 12.56% and 15.85% reductions in project total costs for vision 1 and vision 4 respectively. Installing new offshore wind capacity in association with the power link island gave a reduction in total costs, compared to distributing the same capacity between offshore nodes of each area.

An uneven distribution of transmission investment costs, different impacts on area prices in participating countries and the amount of capacity upgrades needed demands a strong cooperation between all participant countries regarding maritime spatial planning as well as a development of new incentive schemes.

Electrical Treeing in Insulation Materials for High Voltage AC Subsea Connectors under High Hydrostatic Pressures

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Collaboration with: **SINTEF Energy Research**

Problem description

To enable the next generation subsea boosting and processing facilities, high power electrical connectors are strongly needed and considered one of the most critical components of the system.
Electrical tree growth is a precursor to electrical breakdown in high voltage insulation materials. Therefore, the study of the tree growth dependency with hydrostatic pressure is needed to understand the behaviour of the insulation material used in subsea connectors.

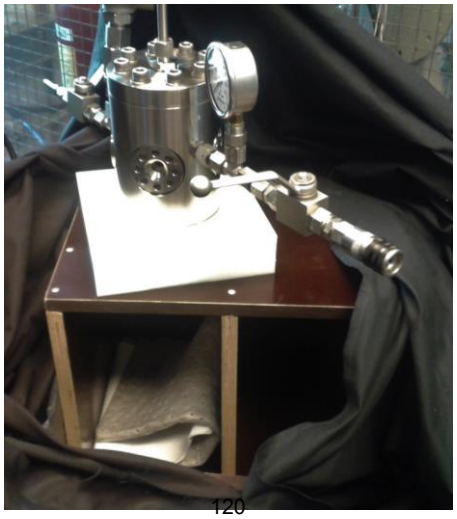
Silicone rubber (SiR) is used as an insulation material for these applications thanks to its higher viscosity characteristic in comparison with other solid insulation materials used in subsea cables. This property is the main factor that allows the water to be swiped off the connector when a receptacle is mated into the plug of a subsea connector. In addition, the silicone rubber must provide similar electric field control as other insulation materials used in cable terminations and connectors.

The task

The characteristics of partial discharges generated during the electrical tree growth and the light emission from the partial discharge pulses, have been studied under different pressure conditions.

Model/ measurements

SiR samples, with a needle to plate electrode configuration, have been put into a pressure vessel to grow the electrical tree in the material under high hydrostatic pressure conditions. The electrical tree growth has been divided in three stages (initiation, intermediate and final or prebreakdown stage) and tests have been performed at 1bar, 20bar and 60bar. A digital NIKON camera and a CCD camera have been used, both attached to a long-distance microscope, to observe in real time the tree growth and light emission (respectively).

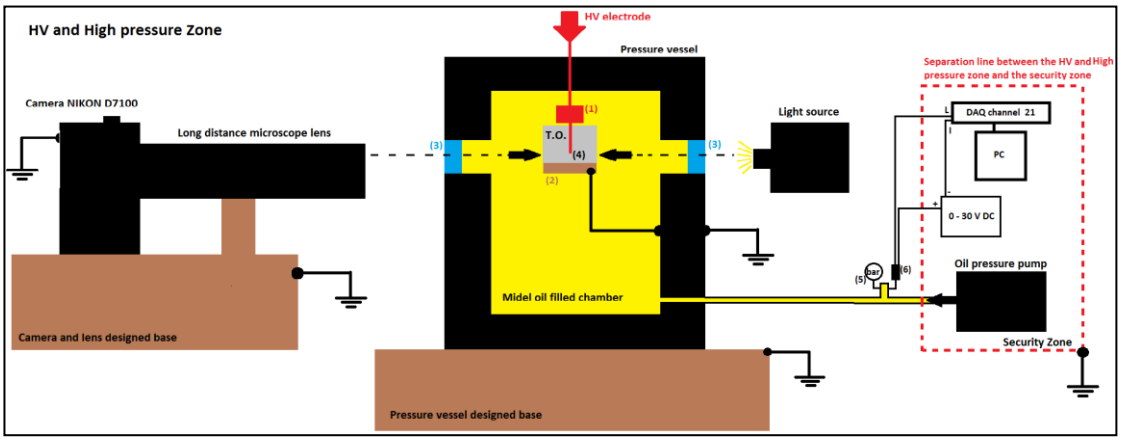


Pressure vessel used in the thesis. Up to 100bar can be applied.

Monitoring system for PD and control system for the CCD camera (left). CCD camera and pressure vessel covered to create darkness conditions (right).

Calculation

Electrical tree growth observability, electrical tree light emission observability and pulse sequence analysis (PSA) for partial discharges (PD's) in combination with two developed MATLAB codes, have been the calculation or analysis methods used.



Scheme for the electrical tree growth observability.

Conclusion

Pictures showed a higher growing speed for the electric tree as voltage and pressure were increased. The length of electrical trees pre-grown at lower pressures collapsed faster as the pressure increased, than those pre-grown at higher pressures under the same pressure increasing conditions. Pulse Sequence Analysis performed to the partial discharges measured, confirmed the partial discharge inception and extinction voltage increase with pressure and showed a polarity dependency to space charge generation in addition to other patterns regarding the charge magnitude and phase of occurrence characteristics. Difficulties on detecting the light emission from the electric tree, have affected negatively the results from the light emission measurements. Pressure vessel internal reflections have suggested changes to be done in next studies. Finally, partial discharge patterns from the electrical tree growth process have been identified to be characteristics from void faults in the dielectric with a spherical void shape.

Norwegian Energy Scenarios

Student: **Audun Tysnes**
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Contact: **Stefan Jaehnert**
Collaboration with: **Sintef Energy Research**

The penetration of renewable energy sources is increasing in the European power system. Their interaction with the power market is fundamentally different from that of traditional thermal power production. This thesis aims to highlight the consequences this development has for the Nordic power system. The consequences studied are mainly related to power flows, power prices and storage handling.
To fulfil the research objective, a new EMPS[1] dataset has been created. The dataset uses the overall data and consistency from ENTSO-E TYNDP Vision 4 2016, but applies a different areal resolution than that of TYNDP Visions. The dataset uses the same areas as used in the current power trade of Nord Pool Spot, for Norway, Denmark, Sweden and Finland. This way, the dataset can better answer questions regarding consequences for the Nordic power system.
Two datasets have been simulated with the EMPS model[1]. One using data from Vision 4 2016, V4-16, and one where the installed capacity of solar and wind power has been doubled, DoubleRES.
The share of production from RES is 39 % in V4-16, a number which increases to 69 % in DoubleRES. The consequence of this increase includes a 49 % reduction in total net load, while the peak net load is reduced with 3 %. Where net load is defined as demand minus production solar, wind and run-of-the-river hydro power. An estimate for an upper limit for feasible battery storage capacity has been found to be 0.5 GWh/TWh/year. This would reduce the peak net load with 20 % in V4-16 and 30 % in DoubleRES.
Norway has an average power deficit of 22 TWh in V4-16, hence the Nordic average prices are no longer among the lowest in Europe.
The storage from summer to winter is on average reduced by 11 TWh in the Nordic areas from V4-16 to DoubleRES. A result of the increased use of Nordic reservoirs for year to year storage. Mostly to withstand year to year variations of neighbouring areas. This leads to larger seasonal average power price difference in the Nordics in DoubleRES than V4-16, increasing the economic benefit of reservoirs and storage units.
The Nordic areas have been found to push low summer prices to its neighbouring areas, driven by the risk of spillage and coherent low water values. The Nordic areas does however absorb daily price differences from its neighbours. So much so that the lowest average price of the day is at noon, and the highest average price of the day is in the evening, even in the Nordics.

Hywind Powering Utsira

A reliability study of offshore wind connected to multiple oil and gas platforms

Student: **Idun Deildokk Vetvik**
Supervisor: **Kjetil Uhlen**

Summary

Today four oil and gas platforms are being commissioned at the Utsira High area on the Norwegian Continental Shelf. One of the platforms is already powered from shore by a 120MW/+-80 kV high voltage direct current (HVDC) cable. The other platforms are equipped with gas turbines in order to generate their required electric power before a second HVDC-cable rated at 200 MW is connected. Following this, all the platforms will be powered from shore and linked together in a radial grid [1]. The gas turbines will work as backup generators. Connecting floating wind turbines to the platforms could be a way of decreasing emissions from the gas turbines, and/or decreasing the power imported from shore, while at the same time improve the reliability of the system.

The aim of this master thesis is to investigate the possible benefits of including an additional connection between the platforms at the Utsira Hight area and connecting a floating wind farm. Wind speed fluctuations and unpredictable power production may affect the reliability and operation of power systems. The impact of integrating offshore wind to the power system at Utsira High needs to be carefully investigated. Different ways of incorporating wind power in reliability evaluations will be investigated and compared. The study consists of a generation adequacy analysis and a composite generation and transmission reliability analysis.

In this thesis, two different connecting schemes and two different generation options have been studied, creating four different cases for the composite generation and transmission reliability study.
Base Case: Radial grid, no connected wind power
Case 1: Radial grid, 60 MW connected wind power
Case 2: Ring grid, no connected wind power
Case 3: Ring grid, 60 MW connected wind power

All the different cases are assumed to have both HVDC connections to shore connected and to have the gas turbines installed. In addition, several analyses have been made on variations of these cases. Among these variations were varying reliability parameters and different load values.

For the generation adequacy analysis, only the generation system is studied, and the transmission system is neglected. The simplified system models in the generation system adequacy consist of the installed generating units (three gas turbine generators and two HVDC-connections to shore) and the total system load. Hence the different composite cases, the Base Case, Case 1, 2, and 3 are not studied in the generation adequacy analysis. In this thesis, the generation system adequacy is studied with and without 60 MW wind power, with different system load values, different reliability parameters for the wind turbines, and different methodologies to model the wind farm.

For the generation reliability analysis, a tool was developed in MatLab to analytically calculate the reliability indices for different input. Wind was modelled using different methodologies, incorporating technical unavailability (forced outage rate) of each wind turbine as well as unavailability due to the wind speed. Varying reliability parameters were used and compared to see the impact of the technical availability of wind turbines. For the composite generation and transmission system reliability analysis, Matlab and Microsoft Excel was used to build a mathematical model of the system and calculate the reliability indices using an analytical method.

By performing several reliability analyses and considering the actual production from the generating units and the different power demands, the amount of energy that is not served has been calculated for the different cases and for the generation systems.

Based on the analyses performed on the different cases in the composite analysis, it is fair to conclude that adding wind power has a larger impact on the reliability compared to the impact from creating a ring grid. The results yielded by the analyses show that Case 3 is the best option among the four when focusing on improved reliability. The improvement from adding both wind power and the extra cable proved to be less than the combined improvement of adding the cable and the wind farm individually, and was almost equal to the improvement from wind alone, hence Case 1 would be a preferable solution. From the generation system analysis, it is clear that the choice of wind model methodology has a larger impact on the reliability compared to the forced outage rate of the wind turbines.

Integrating Battery into MMC Submodule using Passive Filter and Control Technique

Student: **Sigurd Byrkjedal Wersland**
Supervisors: **Lars Norum**
Anirudh Budnar Acharya

Summary
The growing need and importance of Battery Energy Storage Systems (BESS) in grid support applications as well as in the transportation sector, has brought attention to the adaption of the Modular Multilevel Converter (MMC) to be used in BESS. The MMC is already known for its high efficiency, high voltage capability and good harmonic performance, but the modular arrangement of the converter also allows the battery to be implemented in a distributed manner. Known as a split-battery topology or split-storage. Connecting individual battery units directly into the submodules of the MMC. Opening the possibility of high AC-side voltage without a transformer even with low battery voltage.

However, the current flowing through the submodules inherently consists of oscillating components on top of the DC-component. This thesis show that these are at fundamental and 2nd harmonic frequencies with amplitude of two and one times the DC-component respectively. It is assumed that this is unacceptable due its negative impact on battery performance and lifetime. In most literature, this is solved by interfacing the batteries with the submodules using a DC-DC converter. But this thesis explores the possibility of mitigating these components using a control technique and an interface consisting of a filter based on passive components.

More elaborate, the proposed technique is two-legged. **1.** Injecting a circulating current that cancels the 2nd harmonic power fluctuation in the arms and hence submodules. **2.** Employing a resonant filter to mitigate fundamental component together with a lowpass filter.
The performance and feasibility of this technique is analyzed theoretically and through simulations. Resonant branch of the filter is analyzed in simple lab experiment. And results indicate that the proposed solution works and could be attractive, especially in applications where high reliability is of concern.

A Study of Deep Sea Mining Electrical Power System Topologies

Student: **Fredrik Sigmund Qvigstad Williksen**
Supervisor: **Elisabetta Tedeschi**
Co-Supervisor: **Razieh Fard**

Summary:

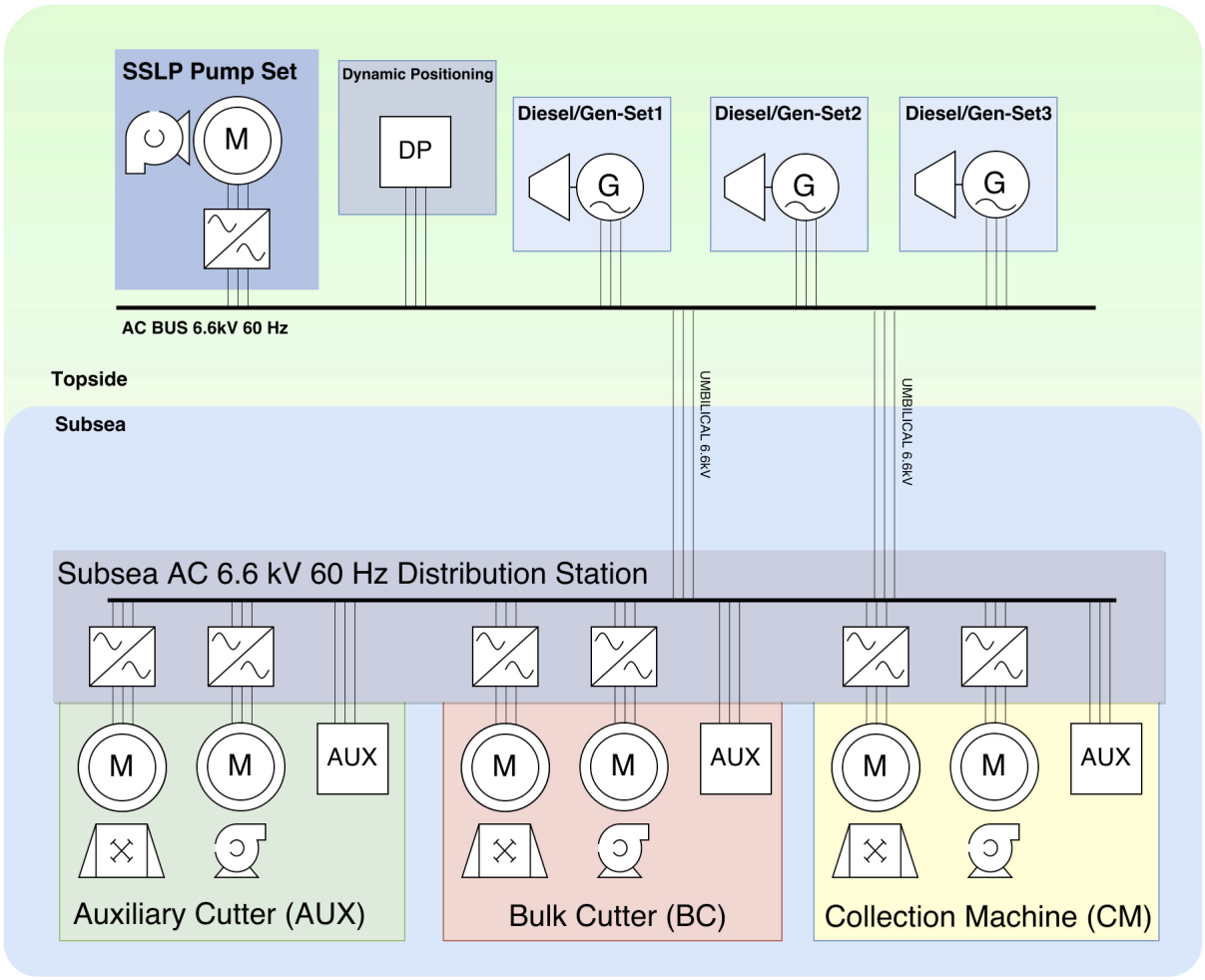
Deep sea mining (DSM) is an emerging technology. The ever-increasing world-wide need for minerals in growing markets and industries of developing countries has made DSM financially reasonable. As there are few known system concepts for DSM it is important to investigate the different possibilities of system design and operation of the future DSM production systems. This thesis has, by investigating R&D and system concepts that are under development, presented different solutions for the electrical distribution system of a DSM production system capable of operating in the Norwegian Sea.

In this thesis is it assumed that the DSM production system will consist of three subsea mining machines (referred to as seafloor production tools (SPTs)) designed to excavate, process and collect ore at the seafloor. The electrical power system is estimated to operate at depths up to 3,500 m, where the production system will mine seafloor massive sulfide deposits formed through hydrothermal activity. A positive displacement pump, powered by pressurized seawater from the topside installation, is used for all the proposed system topologies.

Firstly, simplified models where made in order to investigate three different system topologies of powering the SPTs. In the first model the different components of the SPTs where to be powered individually, thus reducing the number of subsea components by placing the frequency converter of the components at the TS. The simulation proved that powering the SPT components individually would result in excessive power losses, thus ruling out this system topology. In addition the machines of the SPTs perform better when the converters are installed on board the SPTs. Two other system topologies where proposed. The first is powering each of the three SPTs individually from the topside installation. The second is having a combined power distribution to a subsea distribution station which distributes the power to the SPTs. Both these system topologies where deemed suitable for powering a DSM system. Therefore, four simulation models where made in order to investigate the possibilities of power distribution to a DSM production system. The simulation software PowerFactory is used. Two models utilizes AC distribution to the subsea components of the production system, and the two other models use DC distribution. The AC models have a distribution voltage of 6.6 kV operating at 60 Hz and the DC models operate at ±3 kV. The voltage levels are chosen in order to obtain a realistic comparison between the two.

The simulations performed in this thesis proves that the distribution losses will be lower when powering the subsea mining machines through a subsea distribution station compared to the individual power distribution. In addition will the losses be even lower if DC distribution is utilized. By reducing the power losses the production system will be less expensive to operate due to lower fuel consumption. Harmonic content will also be an issue for the proposed AC system topologies, and measures should be done in order to reduce the influence of such power quality pollution.

Although the combined distribution to a subsea station will have the lowest power loss, this system will have a large investment cost as the number of subsea components are increased. Advanced analysis will therefor be necessary to evaluate which system topology should be used for powering a DSM power system. However, due to the large power requirement of possible DSM in the Norwegian Sea, a com- bined distribution to a subsea distribution station will most likely be recommended for DSM operations in the Norwegian Sea.


SSLP Pump Set
M
Dynamic Positioning
DP
Diesel/Gen-Set1
G
Diesel/Gen-Set2
G
Diesel/Gen-Set3
G
AC BUS 6.6kV 60 Hz
Topside
Subsea
UMBILICAL 6.6kV
UMBILICAL 6.6kV
Subsea AC 6.6 kV 60 Hz Distribution Station
M
M
AUX
M
M
AUX
M
M
AUX
Auxiliary Cutter (AUX)
Bulk Cutter (BC)
Collection Machine (CM)

Composite Distribution System Reliability Evaluation

- Including Effect of Interaction Between Distribution Substation and Primary Distribution System

Student: **Zaw Win Htun**
Supervisor: **Vijay Vadlamudi**

Summary

A electric power system is generally composed of generation system, transmission system and distribution system. The reliability evaluation of the power system has become important and many researches have done in the power system reliability study area in order to improve the performance of the power system and economic reasons. As substation is one of the most important infrastructure in electric power system and has the great impact on the distribution system reliability, reliability evaluation of the substation and its impact on the distribution system reliability can be a great interest for this thesis.

This thesis uses minimal cut set method and fault tree analysis method to investigate the substation reliability and composite distribution system reliability. Minimal cut set method has been widely used in the reliability evaluation of substation, switching station and distribution system due to its benefits to list all possible causes of system failure depending on the failure mode of each component in the system. Fault tree analysis is also utilized extensively to conduct the reliability evaluation of the power system. It is especially utilized in reliability evaluation related to the protection systems.

This thesis work examines the reliability of five substation configurations by using the minimal cut set methods. The alternative approach for substation reliability evaluation has also been investigated by fault tree analysis. Many of the research papers and thesis works have done in this field by using commercial software such as NETPLAN, PSS/E, SUBREL, RISKSPECTRUM and so on which are expensive to buy as individual student and relatively few studies have done detailed calculations of the reliability indices of the substation and distribution system. Therefore, the detailed calculations of the evaluation of substation reliability and the effect of interaction between the distribution substation and primary distribution system are conducted based on one of the existing research paper to prove the correct approach for the analysis and to improve the better understanding of the methods without using any commercial software. Fault tree analysis is also investigated to use as an alternative approach to evaluate the reliability of distribution substation and composite distribution system.

Network Fault Forecast from Automatic Power Quality Analysis

Student: **Shishay Lemlem Wineh**
Supervisor: **Kjell Sand**

Summary

The network faults (unplanned power interruptions) are being main concerns of several network operators and customers as they cause economical loss, fires and life damages. Thus, the primary aim of this thesis is to investigate a potential use of power quality measurements to forecast some of network faults (power interruptions). Moreover, its secondary purpose is to propose an automatic algorithm that forecasts some of the power interruptions or faults by monitoring and analysing the power quality measurements. So that the network operator would be able to take counteractions to avoid some of the network faults (power interruptions) before they occur.

The cycle-by-cycle RMS voltage trends of 300 power interruptions occurred in 41 distribution and transmission operators in Norway have been investigated. The measurements are registered in SINTEF Energy AS and Statnett databases using Elspec's investigator (power quality analysers). In addition, the fault statistics reports from the distribution and transmission network operators in which the faults occurred have been analysed to verify the connection between the network faults (power interruptions) and their preceding pre-fault events by identifying their source locations, nature and causes.

Consequently, the results showed that 25 percent of the power interruptions whose fault statistics were analysed could have potentially been predicted before they occurred using their preceding pre-fault events as fault indicator signals (warnings) by monitoring and analysing the power quality measurements. The network faults that could have been forecasted were caused by tree falling on overhead lines, clashes of overhead line conductors and defected underground cables. Therefore, the findings of this study discovered a promising potential use of power quality measurements to forecast some of the network faults (power interruptions). In addition, based on the findings, an automatic algorithm that makes network fault predictions by analysing the power quality (RMS voltage) measurements automatically is proposed.

In conclusion, the findings of this study may be used as initiative for future works and studies on power quality and network faults since the previous studies on network fault predictions are very limited. Besides, this study can also contribute considerably to the development of an automatic fault prediction algorithm as it proposes a possible way of predicting some faults.

Key Words: Failure causes of power system components, classification of network faults, power quality measurements, predictable power interruptions, network fault prediction, pre-fault events, and network fault prediction algorithm.

Power Electronics in Low-Voltage DC Circuit Breakers

Student: **Oda Elise Øverdal**
Supervisor: **Dimosthenis Peftitsis**

Summary

Low-voltage direct current (LVDC) microgrid has recently been recognized as a feasible solution for next generation electrical power distribution network, due to the added benefits that it offers an increasing amount of facilities. However, LVDC microgrids suffers from crucial concerns, which needs to be properly addressed before being conceived as a commercially and economically available solution. LVDC protection technology lack experience, standards and guidelines, resulting in typical expensive and overdimensioned electrical components comprising LVDC systems. It is necessary to develop an economical DC protection solution, which is capable of conducting with low losses and rapid short-circuit currents interruption, without being destroyed in the process.

This thesis presents a promising solid-state circuit breaker (CB) circuit design, comprising commercially unavailable reverse blocking integrated gate commutated thyristors (RB-IGCTs) from ABB. Replacing the RB-IGCT devices in the original CB design with insulated gate bipolar transistors (IGBTs) or asymmetric integrated gate commutated thyristors (A-IGCTs), will be evaluated. Based on proper parameterization, two CB configurations are presented, comprising either 12 parallel connected 3.3 kV rated IGBTs from Infineon, or 8 parallel connected 4.5 kV rated A-IGCTs from ABB. These configurations are compared against each other, using simulation models assembled in Matlab® Simulink. The higher voltage ratings of the A-IGCT allowed the CB to utilize larger metal oxide varistors (MOVs), which caused the energy dissipation period to reduce with approximately 1 ms. The A-IGCT based CB is indicated to be more expensive, due the CB configuration being 60 % heavier than that of the IGBT based CB. On the other hand, the A-IGCT based CB is able of conduct nominal current with 23 % of the losses to that of the IGBT based CB. Since excessive conduction losses are one of the major disadvantages of solid-state CB, the 4.5 kV A-IGCT is concluded to be the most promising semiconductor device for the CB design.

The preferred CB was later utilized to protect three simplified isolated LVDC systems against short-circuit faults, executed in Simulink. Its breaking performance indicated that the A-IGCT based CB might be overdimensioned for the considered LVDC system, but is however conceived as a feasible solution. The promising CB configuration comprising 4.5 kV rated A-IGCTs was able of interrupting faults of 17 kA within approximately 2 ms of fault injection.

Analysis of a Photovoltaic Power Plant at Evenstad

Student: **Therese Bjørånesset Åsheim**
Supervisor: **Lars Norum**
Erik Stensrud Marstein
Collaboration with: **IFE**

The aim of this master's thesis is to investigate the performance and operation of an existing grid connected PV power plant located at Evenstad in Norway. The PV system has a power rating of 70 kWp and has been operating since November 2013. Measurements of meteorological data and performance data are available for all years of operation. The assessment carried out on this PV plant may be of great significance to the PV industry in Norway. A goal for this thesis is to gain knowledge about performance and operation of PV systems in Norway, which may be of use in the development of the PV industry in Norway.

The first part of this thesis gives an introduction to the theory behind solar energy. This includes the explanation of the solar resource and the PV system with it's main components. This is knowledge necessary to understand the content of this thesis. The demands and requirements for grid connected power plants are also presented. To carry out the evaluation of performance and operation of the PV system at Evenstad, a model of the real system is established in the simulation software PVsyst. The next part of the thesis gives an introduction to this simulation software. The simulation model with the implemented settings and parameters is presented, and the reasons why selecting them are justified. Real meteorological data measured on-site is used in simulations to achieve correct comparisons of simulated production and measured production. Variations of the simulation model were used to obtain different studies.

The results of the thesis are divided into four main parts: A discrepancy analysis of the simulation model, simulations and study of one inverter, daily simulations and at last monthly simulations. In the discrepancy analysis the effect of the implemented parameters are analysed, and the results reveal which parameters are important to implement in the model for the system at Evenstad, in order to achieve accurate results compared to real measurements. Correct settings for the module and horizon line in the model proves to give the most impact on the results of the simulations. It is concluded that the relevance of the different parameters varies according to the system analysed. The study of a single inverter in the system provide an overview of the operation and design of the system. Factors like power ratio and power limit for the inverter are proven to be important to implement correctly in the model according to the actual operation of the inverters, to obtain accurate results. Study of the operation of the system implies that the system was installed with too many modules in order to meet the customers demand. Simulations of daily and monthly time frame show that the model give quite accurate results when comparing simulated production to real production. When performing this comparison for the month of May 2017, the difference becomes as low as 0.3 %. This indicates that the system is performing exactly as anticipated, and that so far there is negligible degradation of the system performance.