Masteroppgaver 2019

NTNU
Norges teknisk-naturvitenskapelige universitet
Institutt for elkrafteknikk

Summary of Master's Theses 2019

Department of Electric Power Engineering


Foto: Kai T. Dragland/NTNU

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Summary of Master's Theses 2019

We are proud to present this pamphlet, which gives a summary of the 90 master's theses that were submitted to the Department of Electric Power Engineering in 2019. The Department's vision is to be "At the Center of the Digital, Green Shift," and our master's students make important contributions to this vision.

The master's thesis is independent, research-oriented work undertaken by the student under the guidance of academic staff as a finalization of a master's degree. The topic is most often chosen from a set composed by the Department's 5 research groups. The topics offered are closely related to the core research being conducted in the groups, often in cooperation with our industry partners and our neighbor institution SINTEF Energy Research. Thus, this folder also gives an impression of the general research activity at the Department. Our 5 research groups are:

- Power Electronic Systems and Components (PESC)
- Electricity Markets and Energy System Planning (EMESP)
- Electrical Machines and Electromagnetics (EME)
- High Voltage Technology (HVT)
- Power System Operation and Analysis (PSOA)

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

We are sure that the candidates that we educate from our department will continue to shape the future, especially within the fields of Electric Power Engineering and Energy, as they have done in the past.

We also take the opportunity to invite existing and new partners to contact us to discuss topics for future master's theses. Read more about our department here: https://www.ntnu.edu/iel.

NTNU, November 2019

Ole-Morten Midtgård (sign)
Head of Department

Aging of a high voltage insulation system exposed to AC sinusoidal and fast rise time repetitive pulses

Student: **Mads Alfer**
Supervisor: **Kaveh Niayesh, NTNU**
Co-supervisor: **Lars Lundgaard, SINTEF**

Collaboration with: **SINTEF Energy Research**

Problem description

The anticipated large-scale integration of renewable energy sources with variable power production calls for the use of switching power supplies and frequency converters with power electronics. The fast rise time repetitive pulses used operate at voltages with high switching rates and can create high peak voltages with large, dV/dt. Combination of these two factors will trigger partial discharges (PD) and accelerate the aging of the insulation systems. However, benefits from power electronics are the possibility of shaping the required voltages, enabling a wider range of energy sources such as renewable energy sources and getting more efficient use of equipment.

The task

The main objective of this master thesis is to compare the aging and breakdown behavior of a high voltage insulation system exposed to AC sinusoidal and fast rise time repetitive pulses. This will reaffirm which waveform has the most harmful impact on a high voltage insulation system. For this purpose, two test setups have been appropriately modified to register breakdown (as an indication for the degradation rate of the insulation system) of the insulation system. The breakdown is obtained with two tests consisting of increasing the voltage to breakdown and time to breakdown (Aging, at constant peak voltage). Impact of different parameters of the applied voltage (amplitude, frequencies/repetition rate) has been studied.

Conclusion

For fast rise time repetitive pulses, the positive unipolar pulse has been more harmful for the insulation than the negative pulse, which is justified by theory. Comparison between unipolar, bipolar and AC sinusoidal have been performed from ramped and aging test results. The breakdown values for bipolar are lower than AC sinusoidal and significantly lower than unipolar.

Testing shows clear evidence that the fast rise time repetitive bipolar pulses expose the insulation in a more harmful manner compared to the conventional AC sinusoidal on all voltage levels tested. Similar for both ramped and aging test, the increase of repetition rate cause breakdown either at a lower voltage or at a shorter time by puncture of the insulation, implying more severe deterioration on the insulation. The same effects are evident for time to breakdown, as the voltage level increases the deterioration is more severe.

Reducing Neighborhood Peak Load with a Peer-to-Peer Approach under Subscribed Capacity Tariffs

Student: **Ola Mathias Almenning**
Supervisor: **Hossein Farahmand**
Co-supervisor: **Sigurd Bjarghov**

Problem description

Peer-to-peer (P2P) energy trading markets have been proposed as a way of reducing power peaks in the grid and promote local energy consumption. P2P markets can benefit both end users and distribution system operators (DSO) by reducing costs via economic incentives and preventing expensive grid upgrades.

With this in mind, a model of a neighborhood capable of P2P energy trading has been created to investigate how end user flexibility and P2P trading is being utilized to dampen the strain on the power grid under different grid tariff structures.

Model/ measurements

The neighborhood model was created in Pyhton using the Pyomo software package. The neighborhood is fictional and was generated by gathering load data from 30 different households in Steinkjær, Norway and adding flexible appliances in the form of water heaters, electric vehicles and batteries as well as PV-production.

Four case studies were developed in order to see how the neighborhood would utilize the available flexibility and P2P energy trading opportunities when operating under different grid tariffs at different levels. The four case studies are summarized in Table 1 below.

Table 1 Summary of case studies

Case	Tariff level	Tariff	P2P
Case 1	Consumer	Energy	No
Case 2	Neighborhood	Energy	Yes
Case 3	Consumer	Subscription	No
Case 4	Neighborhood	Subscription	Yes

The two grid tariffs tested are the current energy based tariff and NVE's subscription based tariff. They were applied to two different levels; Neighborhood level and consumer level, this is visualized in Figure 1 below.

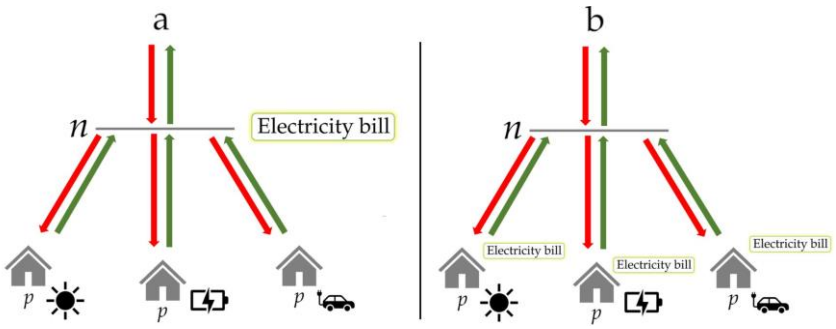


Figure 1: (a): Tariff applied on the neighborhood level, (b): Tariff applied on consumer level

When the tariff is applied at the neighborhood level, all of the consumers will be working towards minimizing a common electricity bill and P2P energy trading is enabled. For the consumer level, all consumers are working towards minimizing their own electricity bill and will not take into consideration the other consumers in the neighborhood.

Results

The main results from the simulations are shown in Figure 2 and Figure 3 below and is sorted from largest to smallest with respect to the energy based tariff and. Figure 2 displays the total neighborhood grid import during national scarcity hours when grid tariffs are applied to the neighborhood level showing how the subscription based tariffs outperforms the energy based tariff in terms of average import and peak power reduction. The peak power import is reduced by 7% when operating under the subscription based tariff.

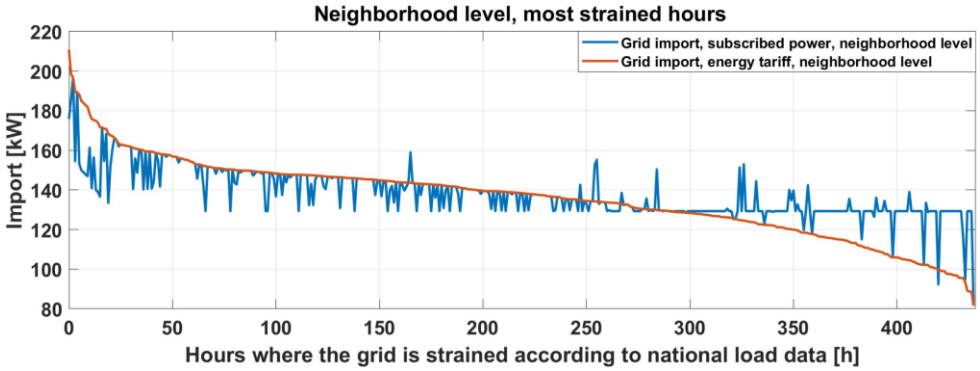


Figure 2 Total import for the neighborhood during scarcity hours with grid tariffs applied at neighborhood level

Figure 3 displays total neighborhood import when tariffs are applied at the consumer level. The subscription based tariff structure reduces the peak power import by 11% compared to the eneryg based structure, but the average import is increased.

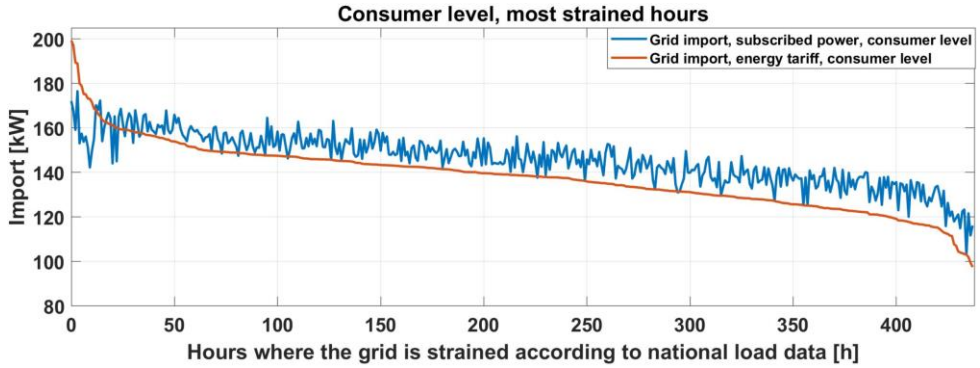


Figure 3 Total import for the neighborhood during scarcity hours with grid tariffs applied at consumer level

Conclusion

The main conclusion from the research done in this thesis is that a subscription based grid tariff applied to the neighborhood as a common node, enabling P2P, is most capable of reducing peak power import during scarcity hours by up to 7% while maintaining a lower and more stable grid impor

Impact of Combining a STATCOM and an Active Filter on the Modular Multilevel Converter Controller

Student: **Hanna Authen**
Supervisor: **Kjetil Uhlen**
Contact: **Jarle Eek**
Collaboration with: **Statnett**

Problem description

"Harmonic distortion is an increasing concern for secure and reliable operation of the power system due to implementation of more power electronics. Harmonic sources may interact with the grid dependent on the grid operating state. The STATCOM may have the ability to provide active filtering of harmonics compared to the traditional SVC. The STATCOMs may change the active filtering based on operational state of the grid to which its connects, which would be a benefit compared to the passive filtering where the filter resonance is fixed. The master's thesis should explore how this active filtering can be implemented and how it will influence the overall design and control of the STATCOM."

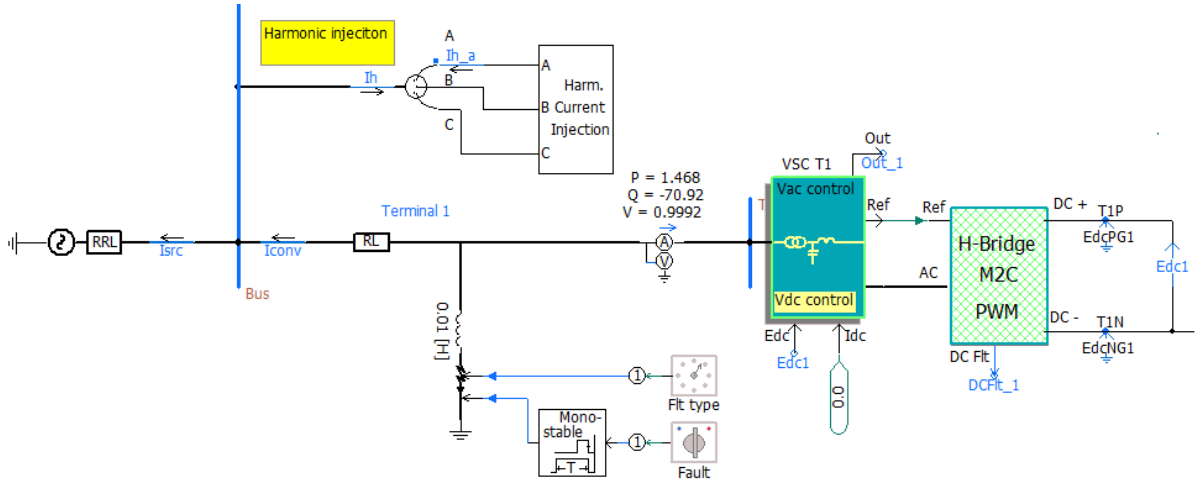
The task

The active filter components and configuration are similar to the STATCOM. These similarities suggest that a STATCOM also can perform active filtering. However, the STATCOM controller must be altered to enable this feature. A device like this is referred to as a developed STATCOM.

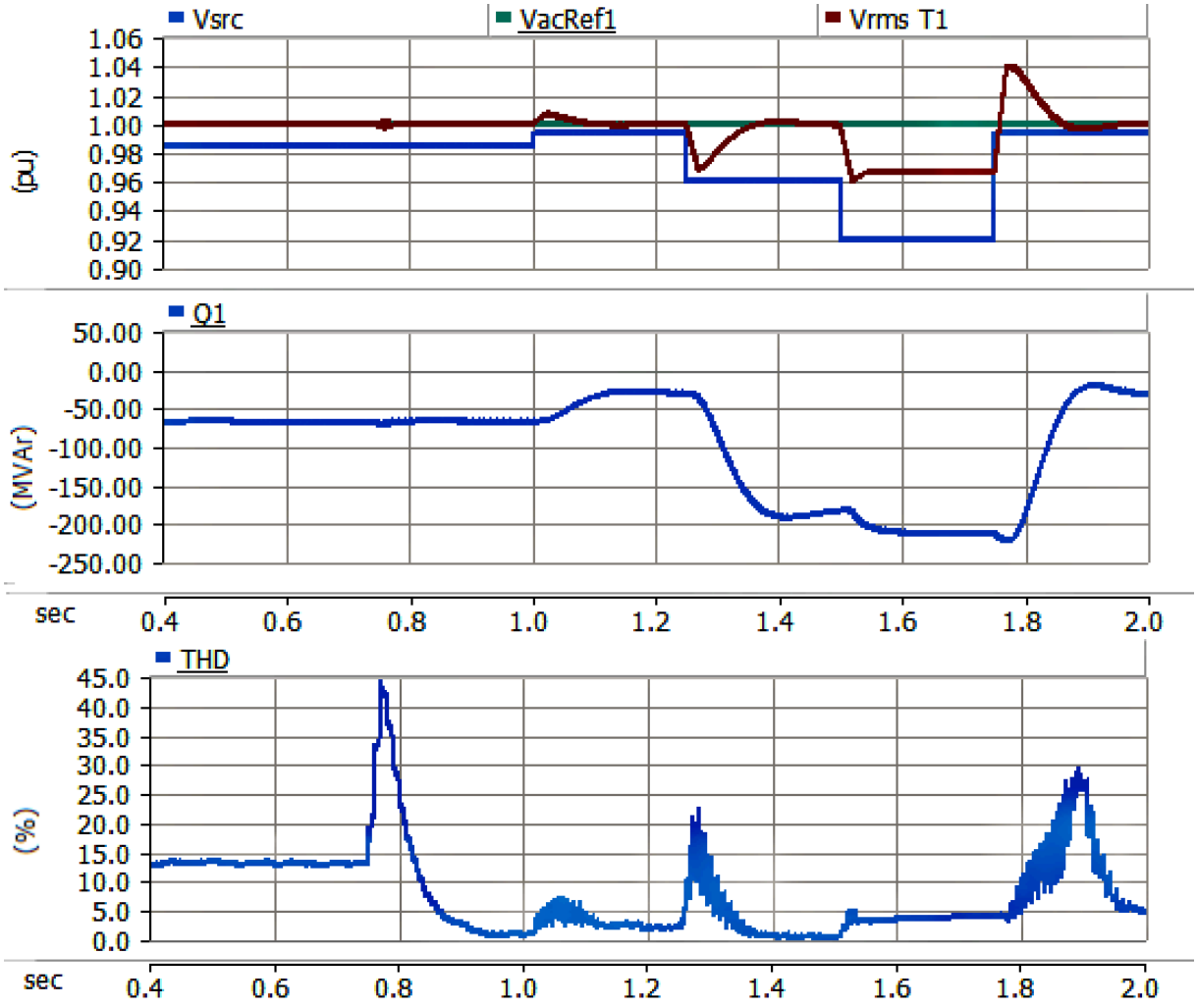
This thesis presents a STATCOM MMC controller that combines reactive and harmonic compensation. The proposed controller combines the traditional control methods of the STATCOM and the active filter. Moreover, the controller has been altered and adapted so that both features are optimized. The proposed controller is named a combined controller.

Model/ measurements

The combined controller is modeled in PSCAD. Simulations show promising results. The developed STATCOM is tested in both a simple and a more complex system. The results confirm that the developed STATCOM improves the voltage level while reducing the harmonic content. This is the case for all the simulated cases and different system configurations. This suggest that the controller is working.



Calculation



Conclusion

The combined controller does not impose large changes to the traditional STATCOM MMC controller. The main changes are located in the outer control loop. Dq frame theory is used to calculate the reference harmonic compensation current. Then the reactive and harmonic compensation currents are added and fed into an inner current control loop. The inner current control loop output is later feed into VSC. The reactive compensation current is calculated in the same way as for traditional STATCOMs. The voltage controllers, current controllers and VSC blocks are almost identical to the traditional STATCOM.

Simulations of the combined controller and developed STATCOM confirm that the controller operates in line with the presented objectives and the requirements of the traditional STATCOM. The voltage is improved and harmonic content reduced for all the simulated cases and system configurations. With minor alterations and adaptations, it is believed that the controller works for all other systems as well.

Investigation into the impact of thermal energy flexibility on cost optimal design and operation of Zero Emission Buildings

Student: **Marius Bagle**
Supervisor: **Karen Byskov Lindberg**

Abstract
Zero Emission Buildings (ZEBs) are energy efficient buildings that produce on-site renewable energy, in order to compensate for their consumption. The ZEB-concept is based on the 2010 report by EU's Energy Performance of Buildings Directive (EPBD), which suggests that all buildings constructed after 2020 should reach "near zero energy level". In previous research on energy systems in ZEBs, deterministic linear optimization techniques, in conjunction with a wide array of input data, such as load data, temperatures and technology prices has been used to determine the cost-optimal design of technology investments in low energy buildings. Usually, the heat demand of the buildings considered has been treated as an aggregated load.

The main purpose of this thesis is further development of a Mixed Integer Linear Program (MILP), implemented in the open-source general purpose programming language Python, using the modelling extension library Pyomo. The starting point of the work was the two-stage stochastic model developed in a previous master thesis, transitioning back to a deterministic framework. At first, the separation of the heat demand into two separate loads is carried out, one for space heating and one for domestic hot water. Then, a model based on point-source technologies is synthesized. The first of two main objectives is to analyze and compare the operation and investment of the point-source model and the already existing waterborne model, both with and without the ZEB-constraint. The emission constraints are defined in such a way as to consider the emissions in the operational phase of the building, an ambition level known as "ZEB-O EQ". The input data used for the optimization is based on simulated load data of the heat and electricity demand. Data from 2012, considered to be an average climatic year, is used. Since the separation of the heat demand into two different loads causes a drastic increase in the number of variables, a simple reduction technique, selecting the week with the highest space heating load from each season, is used to construct a reduced scenario.

The second main objective of the thesis is to investigate the load flexibility of the ZEB, using the thermal mass of the building as a short-term thermal energy storage. A two-node model representing the thermal mass of the building is implemented, in both the point-source and the waterborne model. Then, the impact of adding this storage is analyzed and compared for the respective systems. Since there is some uncertainty associated with the parameters of the two-node model, a sensitivity analysis is performed, in order to determine both the suitability of the two-node representation in a MILP-framework, and also to find a range of values for the cost reduction that can be expected when using the building thermal mass as an energy storage.

The results show that the waterborne system is the cost-optimal choice for the energy system in a passive house, both with and without emission constraints. A significant part of its advantage lies in the greater efficiency of the waterborne heat pumps, in addition the flexibility inherent in the waterborne system, since the technologies can operate on both the SH- and DHW-load. Furthermore, the grid impact of the waterborne system is more

favorable, as the duration curve for total electricity import is significantly flatter than for the point-source system. When adding the building thermal mass as a storage technology, a reduction in peak load capacity can be seen for both systems, which suggests that the thermal mass can be used as a substitute for the peak load technologies, e.g. the electric boiler, in passive house energy systems.
Furthermore, significant decreases in the net present value of both the total system cost and operational cost can be seen. The most promising cases were found when both systems were forced to obey the ZEB-constraint with the thermal mass as a storage technology, showing reductions in operational costs of 8.60 % and 7.79 % (compared to no thermal mass/noBITES) for the point-source and waterborne systems, respectively. Additionally, a similar reduction in total electricity import was seen in these two cases, suggesting that the the on-site production from the photo-voltaic panels are used to pre-heat building for the evening, when spot prices generally are higher. The sensitivity analysis shows that the thermal mass representation used exhibits a relatively small sensitivity to its parameters. The values considered, which in the most extreme case varied by five orders of magnitude, yielded a range for the total cost reduction of between ca. 1300 euro and 2500 euro through the lifetime of the building.

Reliable Power Cable Screen Connections

Evaluation of test procedures for power cable screen connections

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Supervisor: **Frank Mauseth**
Contact: **Hans Lavoll Halvorson**
Collaboration with: **SINTEF Energy research AS**

Problem description

In recent years, several comprehensive and expensive faults have occurred in the Norwegian power grid due to local hotspots in power cables. The main reason for this is poor contact within the ground screen connections at joints and terminations. There is generally little experience exchange and there are no international nor Norwegian standards that require testing for such connections.

Based on this, REN AS initiated a project that deals with reliable ground screen connections in 2016. The project is in cooperation with SINTEF Energy Research, Norwegian utilities and cable manufacturers, and will run until the end of 2019. The intention of the project is to develop a better understanding of the fault mechanisms and further use this information to introduce a standardized test for screen connections.

The task

A laboratory setup was made to evaluate two test procedures that uses different load types and methodology for testing screen connections. Two identical test setups were made with 6 test objects that consisted of the common screen connection type “constant force springs”. The first test procedure was a heat cycle test which initiated cyclic strains in the test objects by continuously heating and cooling down the test objects. The second test procedure was a constant current test which had a simpler approach with constant loads throughout the entire test period.

Model/ measurements

An illustration of the laboratory setup for the first test procedure with corresponding test objects can be seen in Figure 1. An identical setup was made for the second test procedure.

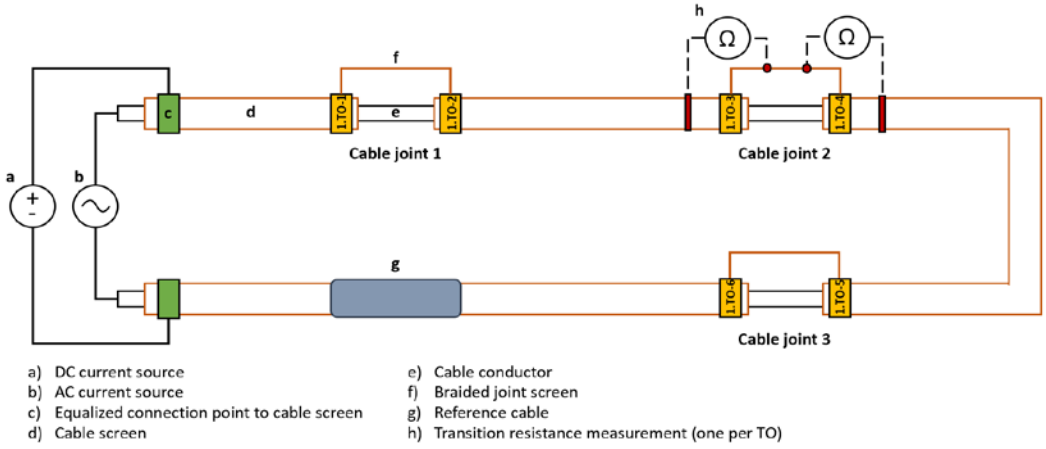


Figure 1. Illustration of laboratory setup 1 with corresponding test objects

The test object temperature and transition resistance were measured throughout both test procedures. After the test procedures were completed the test objects were dissected, and a

visual inspection was conducted to compare and evaluate the properties of the different screen connections.

Calculation

Results show that test objects from both test procedures experienced a significant increase in contact resistance with an average increase of 507 % for the heat cycle test and 190 % for the constant current test. Figure 2 compares the average test object resistances for the heat cycle test and the constant current test at stabilized test object temperatures of 85-90 °C.

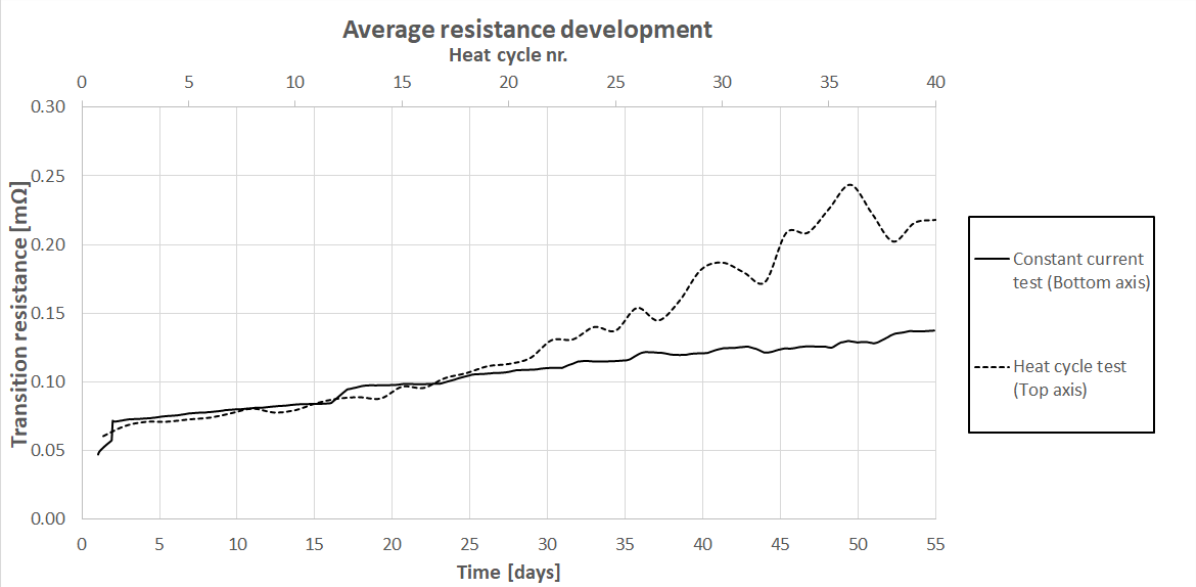


Figure 2. Average test object resistance development at 85-90 °C.

The heat cycles introduce cyclic relative movement inside of the screen connections which leads to a decrease of mechanical load and fretting corrosion between the electrodes. This effectively increases the contact resistance over time and gradually weakens the ampacity of the screen connections as more heat cycles are conducted.

The constant load currents generate high temperatures which gradually causes a loss of contact area at the electrode interface inside the test object. This loss is due to, among various other mechanisms, oxide formation or perhaps a loss of mechanical force throughout the test period.

Conclusion

The results show that the test objects from the heat cycle test gradually worsened and gained variating contact resistances compared to the test objects from the constant current test. Both test procedures experienced an increase in contact resistance, but the heat cycle test seemed to have had a bigger impact on the ampacity of the screen connections over time.

The experiments performed in this master thesis proved that both test procedures give a certain value for testing screen connections, but the results showed that the cyclic strains from the heat cycle test is a necessary factor to fully evaluate the properties of power cable screen connections.

EMD and Online EMD for Harmonic Detection in Power Systems

Student: **Martine Johanne Nordengen Baksvær**
Supervisor: **Olav Bjarte Fosso**
Co-supervisor: **Paula Bastos Garcia Rosa**

Problem description

In this thesis, power system harmonics and detection methods for power system harmonics have been investigated. Harmonics have been an issue in power systems for a very long time, but due to the increasing use of nonlinear loads, like power electronic converters, the harmonic pollution have increased. Electrical grids where new type of components interact are becoming prone to harmonic pollution as well. Harmonics can cause severe damage to components in the power system, like overheating of components or false tripping of circuit breakers, and thus, it should be reduced. A mathematical model that describes accurately the physical behaviour of harmonics can be a challenging task in a large scale system. Even if a detailed mathematical model is available, such model can be of high order and can result in a complex controller. As an alternative to high fidelity modelling, this thesis is based on data analysis and on-line identification techniques that can characterize the grid under operation.

Objectives

The aim of this work is to evaluate the decomposition provided by the empirical mode decomposition (EMD), and one of its extensions - the online EMD, for a real signal containing harmonics. The online EMD allows the analysis of data streams, which can be beneficial for real-time harmonic detection and control purposes. However, the decomposition of the online EMD has a time delay that should be estimated if the aim is to use the resultant signals for control purposes. Thus, this work also aims to investigate the time delay of the online EMD decomposition of a signal containing harmonics.

Analysis and results

In this thesis, EMD has been applied to a current measurement using both a Python code and MATLAB code, which revealed differences in the decomposition. The Python code was able to identify all the frequency components of the current measurement, while the results obtained with MATLAB suffered from mode mixing. A duplication of the current measurement was made in order to make it suitable for the online EMD. This duplication was analyzed using the standard EMD, both in Python and MATLAB, and online EMD. When the measurement was duplicated, mode mixing became an issue for both codes. In order to investigate why mode mixing occurred, a synthetic signal mimicking the current measurement was constructed and analyzed with the online EMD. It was found that if the amplitudes of the harmonic components were doubled, the mode mixing disappeared. This decomposition is illustrated in Figure 1. For real-time applications, it is important to know the time delay of the online EMD decomposition. Thus, the time delay for the synthetic signal without mode mixing is examined, and the calculated time delays can be seen in Table 1.

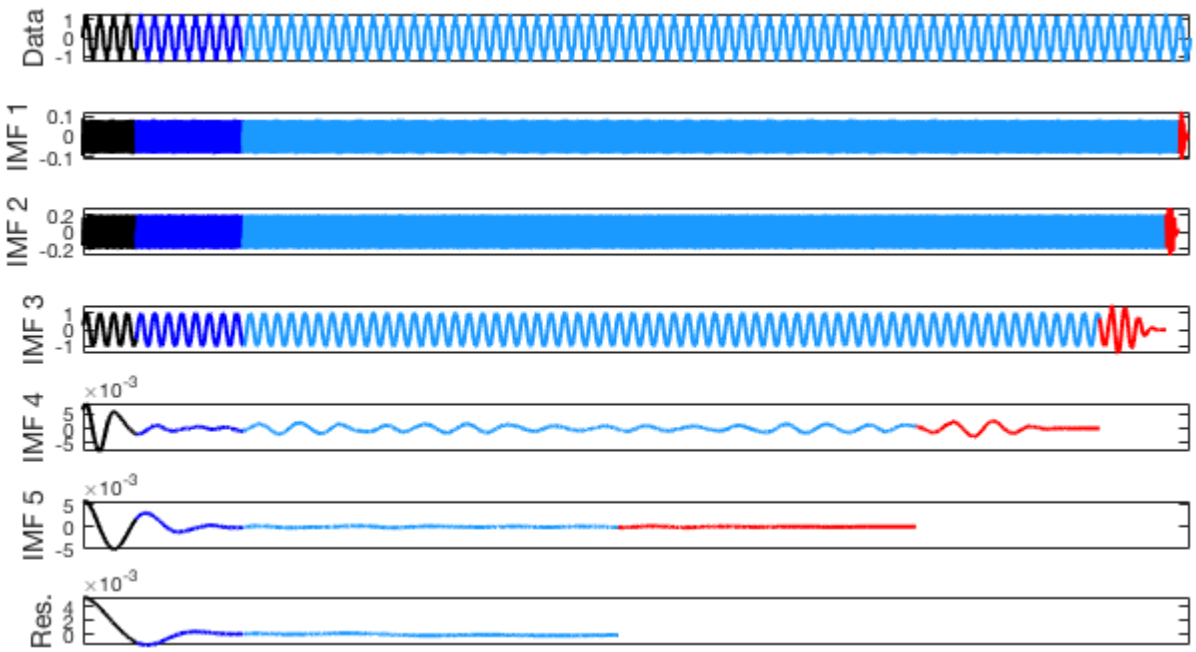


Figure 1: Decomposition using online EMD of the synthetic signal sin(2π60t) + 0.2sin(2π300t) + 0.08sin(2π740t). The first plot shows the signal, which is 1.35 seconds long, and the frequency components of the signal are represented by IMF 1, IMF 2 and IMF 3.

Table 1: Time delay in seconds for each of the IMFs of the decomposition illustrated in Figure 1.

Component	Time delay (s)
IMF 1	0.0112
IMF 2	0.0267
IMF 3	0.0961
IMF 4	0.2906
IMF 5	0.6971

Conclusion

- Online EMD, compared to the standard EMD, is a method that enables analysis of data streams, which is beneficial for control purposes in for example active power filters.
- When the amplitudes of the current harmonics in the current measurements are doubled, mode mixing does not occur.
- The standard EMD and the online EMD codes in MATLAB used in this thesis are more prone to mode mixing than the standard EMD code in Python for this specific current measurement.
- Even though the method is called online EMD, the method imposes a time delay to each of the IMFs, which makes the method not completely online.

SiC-based power electronics for subsea remote operated vehicles in the petroleum industry

Student: **Ask Storjord Baraa**
Supervisor: **Tore M. Undeland, Subhadra Tiwari and Pål Keim Olsen**
Contact: **Svein J. Vareberg**
Collaboration with: **IKM Technology**

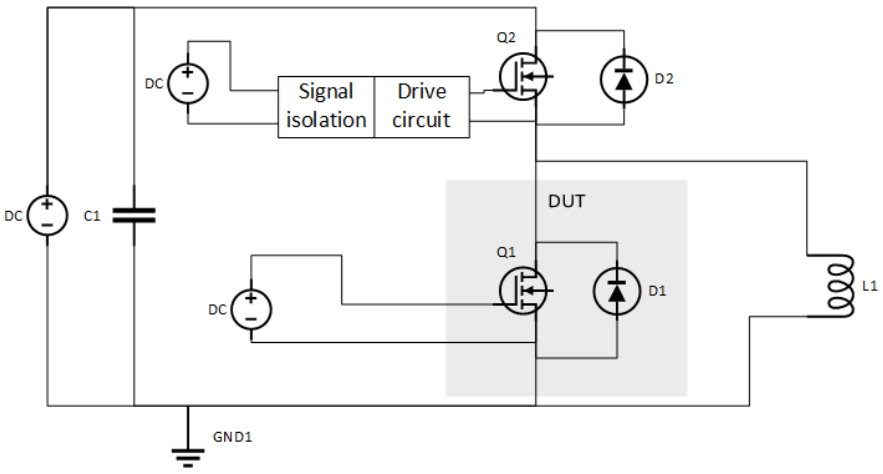
Problem description

Remotely operated vehicles (ROV) are an essential part of subsea operations, preforming tasks including installation, inspection, diver observation, valve operation, system cutting and more. As the offshore petroleum industry move towards more subsea production, the demand for reliable, efficient and versatile ROVs will likely increase. The introduction of other offshore and subsea industries such as offshore power transmission cables, offshore wind farms and subsea mining, will likely also broaden the scope of ROV operations.
Recent development in wide bandgap semiconductor power devices made from silicon carbide (SiC), enables more compact and more efficient power conversion topologies to be developed. Wide bandgap materials can endure higher blocking voltage, compared to silicon (Si). As a result of this, fast switched components can be made with SiC instead of Si and can replace high voltage silicon components that switch slower. High voltage Si-IGBTs can be replaced with SiC-MOSFETs and high voltage p-n diode can be replaced with Schottky barrier diodes. A new power system topology for the ROV was suggested prior to this thesis. The new topology includes DC power transmission, and fast switched power electronics for DC-DC conversion.

The main objective of this master thesis to compare the characteristics of relevant semiconductor devices from silicon (Si) and silicon carbide (SiC). The primary emphasis has been on comparing Si power diodes and SiC Schottky diodes for diode rectifiers.

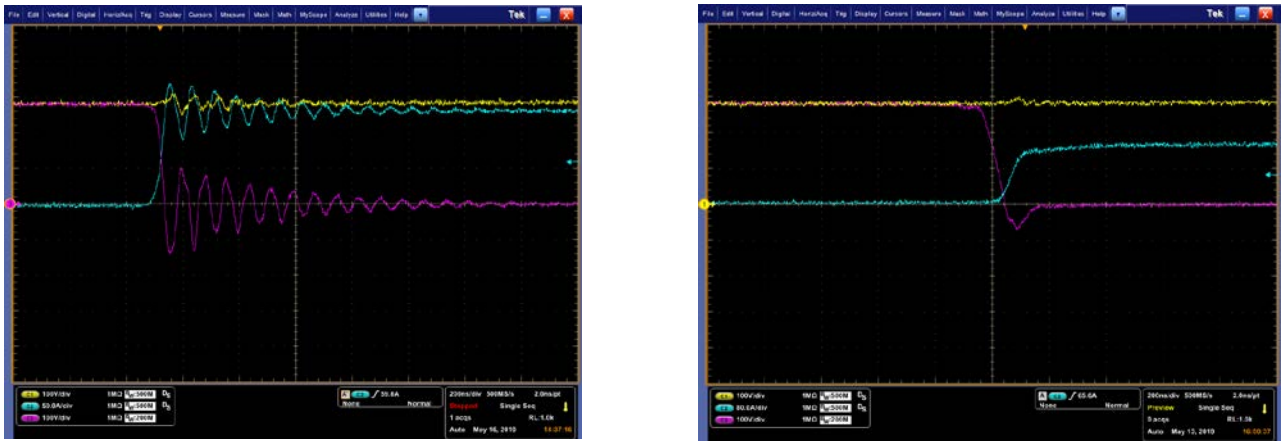
Model/ measurements

An experimental setup was constructed to test the switching characteristics of different diodes. A double pulse setup was chosen, as shown in figure (right). This setup was chosen due to it requiring relatively few components to preform the experiment. The setup allows for variation of the voltage and current experienced by the diode (DUT). The test was preformed on a Si-IGBT half-bridge module and on a SiC-MOSFET half-bridge module with and without a RC-snubber at the DC-link. The Si-IGBT module use Si p-n diodes, while the SiC-MOSFET module use SiC Schottky Barrier diodes. Both modules consist of three half bridge topologies in parallel. The bottom transistor is connected to a negative DC voltage to avoid unintentional turn-on.



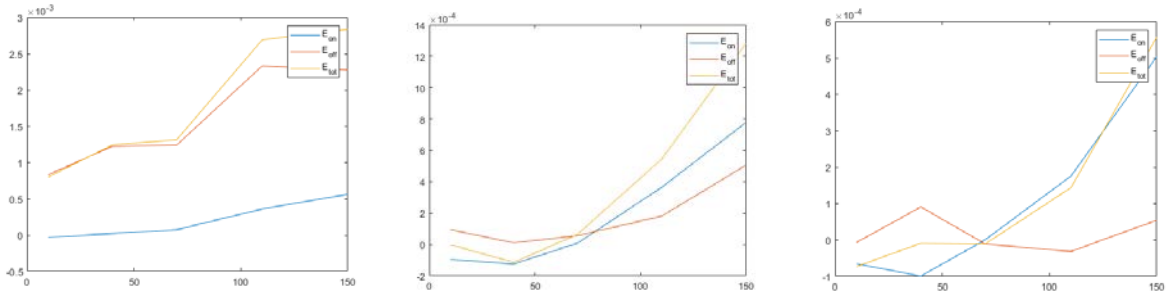
Conclusion

The SiC Schottky barrier diodes had improved switching characteristics over the Si p-n diode, regarding switching speed and losses. However, the SiC Schottky barrier diode suffers from having significant voltage and current overshoots and damped oscillations after swithing. This can be mitigated be designing a protective RC-snubber connected either directly to the diode or to the DC-link input. However, the snubber tested in this experiment had been previously made to dampen oscillation of the MOSFET and increased the switching losses and increased oscillations. The losses were still lower than that of the Si p-n diode. The SiC Schottky diodes can therefore be chosen for diode rectifiers to lower losses. However, when using SiC Shottky diodes overshoots and oscillations need to be examined and potentially mitigated, to prevent it from causing harm to the diodes or affecting other parts of the power system.



(a) (b)

Turn-on characteristics at 300 V, 150 A, for Sic Schottky diode (a) and Si p-n diode.



(a) (b) (c)

Switching losses in watt for Si p-n diode (a), SiC Schottky diode with (b) and without (c) snubbers.

Combining analytical power system reliability assessment methods with Monte Carlo simulation

Student: **Trygve Vesseltun Berg**
Supervisor: **Gerd Hovin Kjølle**
Contact: **Iver Bakken Sperstad**
Collaboration with: **SINTEF Energy Research**

Problem description

The electricity demand in the world is increasing, and power systems are getting more and more complex, due to the inclusion of more renewable energy sources, new network components, changes in consumer patterns, etc. It has been experienced from other fields of study, such as gas supply, water supply and nuclear power, that for increasingly complex systems, a probabilistic approach, as opposed to a deterministic approach, is required for assessing the reliability of the system. Reliability evaluations can be utilized as aid for decision making regarding planning, or to some extent operation, of power systems.

The probabilistic reliability approach can broadly be divided into two types of reliability assessment methods, analytical reliability analysis methods, and Monte Carlo simulation. These types of methods have been studied for nearly half a century, and the advantages and disadvantages related to each method are well documented. An idea arises, which is to combine both types of methods, into a hybrid reliability analysis method, to enhance the advantages and minimize the disadvantages of both methods.

The task

A thorough literature study is done in the field of power system reliability analysis methods. The advantages and disadvantages of each method is explored and evaluated for the basis of combining different methods into a hybrid version. Two possible hybrid methods are proposed. Both methods are then implemented and tested on two test systems for reliability, RBTS and The Four-Area Network.

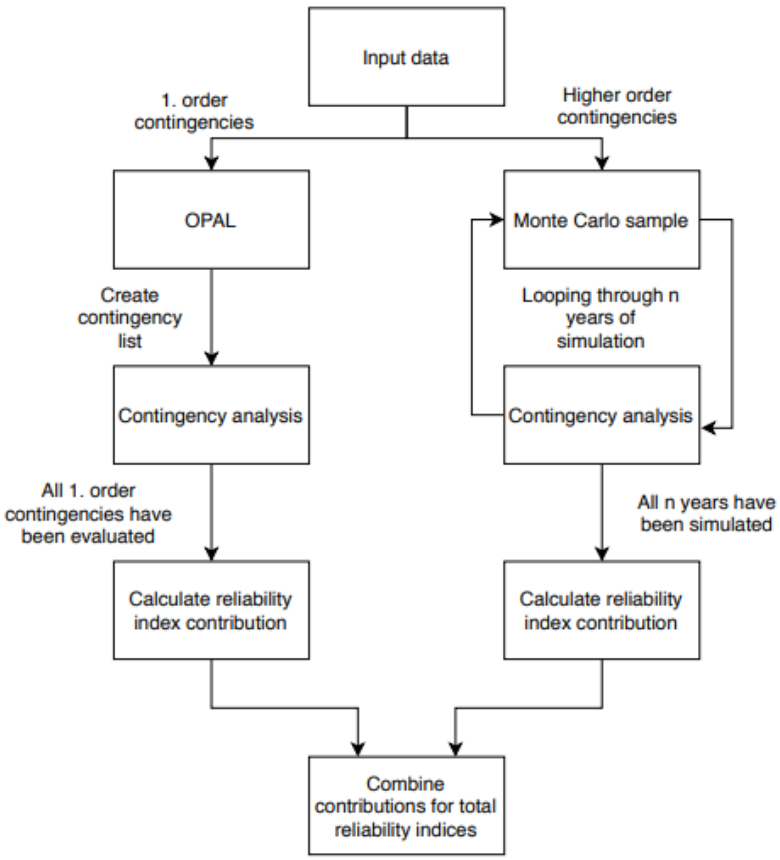
Implementation

The two proposed hybrid reliability analysis methods are: 1) Combining the contingency enumeration analytical reliability analysis OPAL methodology with a state sampling Monte Carlo simulation, 2) Combining the contingency enumeration analytical reliability analysis OPAL methodology with a pseudo-sequential Monte Carlo simulation. The methods are implemented in MATLAB. A general hybrid reliability analysis method flowchart is depicted in the figure on the next page, where the contingencies are outages of lines, or other components, that can possibly lead to loss of load (interrupted power).

Testing

The proposed hybrid methods are tested on the RBTS and The Four-Area Test Network. The methods are compared against a benchmark test, which is done by utilizing the OPAL method alone. The reliability indices; frequency, duration and severity (lost power, and energy not supplied) of interruptions on the test networks are calculated for both the load points in the system, and the system as a whole. The reliability indices are used to quantify the reliability of the systems. The results show that the hybrid methods are working, and that the calculated reliability indices lie within reasonable values of the benchmark test. The computed system

index for the expected energy not supplied, for both hybrid variants, differs at a maximum of 2.8% from the calculated index of the benchmark test.



Conclusion

Two proposed hybrid reliability assessment methods have successfully been implemented and tested on two reliability test systems, RBTS and The Four-Area Test Network. Their computed reliability indices are comparable to that of the analytical reliability analysis method OPAL, which is used as a benchmark. The hybrid methods do however come at an increased computational cost. Further optimization and testing of the hybrid methods are needed in order to establish if they are in any way more useful than the OPAL method or the Monte Carlo simulation methods individually.

Impact of Location of Frequency Reserves

Student: **Bjelland, Sunniva**
Supervisor: **Uhlen, Kjetil**

Problem description

The share of variable renewable production and HVDC interconnectors in the power system is increasing. This causes challenges in system operation thought large and frequent power fluctuations, reduced inertia and limited balancing reserves available from hydro generators. Active power regulation of synchronous generators operating in the system has traditionally been sufficient for maintaining the power balance. Reserve provision from other resources such as HVDC connectors, demand response and wind power plants are becoming increasingly important for the power balance. These resources may also providereserves whichare activatedfasterthan thetraditional reserves. The power output from these reserves are controlled based on local frequencies, which may vary significantly during disturbances. Location of the reserves will therefore impact performance of the reserves and system stability.

The goal of this thesis is to get further insight into how location of frequency reserves impacts system stability and frequency response. To assess the impact of location of frequency reserves, an aggregated model of the Nordic synchronous named Nordic 44, was simulated in PSS\E, and the response of frequency reserves were resembled through the use of a battery model. A 1200 MW fault was simulated through the outage of a generator, and all reserves were located at one location. Different fault locations and reserve locations were compared, and the results showed that fault location had a significant impact on the importance of location. For a fault in electrically remote locations, large initial power swings caused the initial power output from the reserves to increase when the reserves were placed close to the fault. At other locations, the initial impact of location were less significant. For all fault locations, the initial power output from the reserves were largest when reserves were placed close to the fault. The location did however have little impact on the frequency nadir. A benefit related to location of reserves was increased damping of low frequency oscillations when reserves were located at certain locations.

Comparison between Si MOSFETs and GaN HEMTs with special emphasis on low load problems occuring in the LLC resonant converter

Student: Lyder Rumohr Blingsmo
Supervisor: **Roy Nilsen**
Contact: **Tore Undeland, Ole Christian Spro**
Collaboration with: **Eltek AS**

Rectifiers for supplying data center with power from the grid are subject to many requirements, one of which is very high efficiency. One of the most common converter architectures consists of a PFC rectifier stage, used for achieving sinusoidal mains current, followed by a DC-link and a LLC resonant converter for the DC-DC conversion. This topology is already quite efficient. However, one possible solution to increasing the efficiency further is lowering the on-state resistance of the transistors used. Regular silicon(Si) metal-oxide-semiconductor field-effect transistors(MOSFET) however are quickly approaching their theoretical limit in terms of tradeoff between die size and on-state resistance. To reduce on-state resistance further, the die size must then be increased. An increased die size comes with the disadvantage of large terminal capacitances, which can lead to problems.

One of the main enabling technologies for increased efficiency is therefore gallium nitride(GaN) high electron mobility transistors(HEMT). This is because they have smaller terminal capacitances for the same on-state resistance, owing to superior material properties. It is expected that replacing the Si MOSFETs in the LLC converter with GaN HEMTs could improve efficiency, while also avoiding the some of the problems that could occur with excessively large output capacitances. Especially low load regulation problems is considered in this regard.

In this report, only the LLC converter will be considered. The PFC converter will not be discussed. More specifically the LLC topology with a half-bridge structure at the input will be considered. On the secondary side a full-bridge diode-rectifier is used. Design methods, transfer functions, zero-voltage switching, operation modes and low load problems are discussed. Other broad topics such as control is only briefly mentioned. Si MOSFETs and GaN HEMTs are the only transistor types considered.

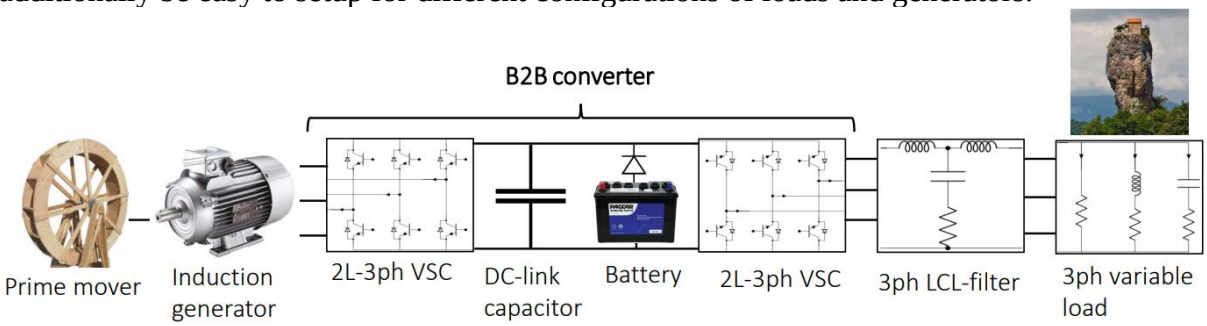
This report starts with a literature study on GaN devices, more specifically GaN HEMT. In the second part the LLC series resonant topology is discussed. Possible implementation of new GaN-switches in the LLC converter is researched. A direct comparison between GaN HEMTs and silicon MOSFETS is done. Special emphasis is put on considerations that are important to soft-switching topologies such as the LLC converter. Simulations in LTSPICE are done to validate some of the discussed concepts, especially the derived transfer function from the fundamental harmonic approximation(FHA), which shows good results. Lab measurements are also done, and it is seen that the GaN HEMT can improve upon the low load problems occurring in the LLC converter when using Si MOSFETs. The results show that this is achieved with the same degree of efficiency, and using GaN HEMTs the efficiency might even be increased.

B2B Converter-Based Voltage Control for Isolated Induction Generator supplying Local Variable Loads

Student: **Sondre Drevdal Borge**
Supervisor: **Trond Toftevaag**

Problem description

The modern world has grown a custom of utilizing electric power to operate a vast range of technologies and utilities. Though todays grids are generally stable and interconnected, an isolated power system could be useful for certain applications. The objective of this thesis is to study the use of a filtered back-to-back system topology to control an isolated power system composed of an induction generator (short-circuit rotor, 3-10kW) and local variable AC-loads. Emphasis is placed upon designing a system that can operate the generator within rated conditions, whilst ensuring a stable and high-quality load voltage. The system should additionally be easy to setup for different configurations of loads and generators.



Approach

The task is approached by building a complete model of the system in MATLAB-Simulink, evaluated by corresponding simulation-tests. Following this is a lab-setup of the proposed system with corresponding experiments, and a controller-implementation test on the Arduino Uno electronics board.

Theory and system design

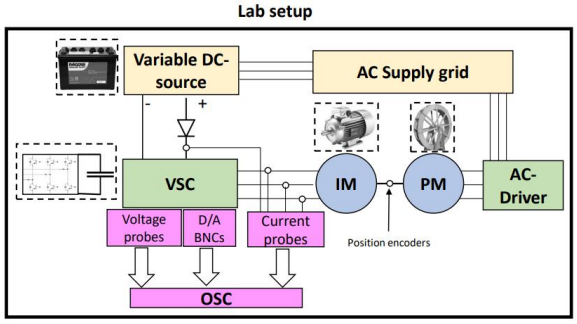
An extensive literature study is conducted to gain insight/models for the different aspects of the system. This includes the different components, such as the induction machine, LCL-filter, 2L-3ph VSC, variable AC-loads and rotational system with prime-mover. The control-theory covers methods such as V/f (scalar control), FOC (Field oriented control) and DTC (Direct torque control). The signal generation includes methods such as S-PWM, SV-PWM and hysteresis-based switching.

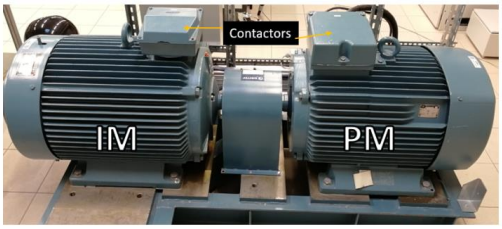
The outcome of the research is used as a basis to design two generator control-systems with the purpose of maintain the DC-link voltage of the converter. They are based on the principles of V/f and FOC, requiring measurements of mechanical speed and stator-currents. One voltage controller is also designed for the loads, with inputs of load-voltage measurements. Some new contributions are the design of a custom increase/decrease flux-controller in the FOC control-system and an RMS/DC-voltage approach to predict the output RMS-voltage of the converter. A step-by-step procedure to dimension the components of the system and tune the controller-parameters is also made and used to create four different test-configurations based on machines in the range of 4-16kW. The load-grid is defined as 230V (rms) 50Hz. Several simulation-tests are performed to evaluate the performance, investigating aspects such as the influence of the battery-voltage, the magnetisation and DC-link voltage build-up, operation during load-changes and different speeds.

Simulation-study results

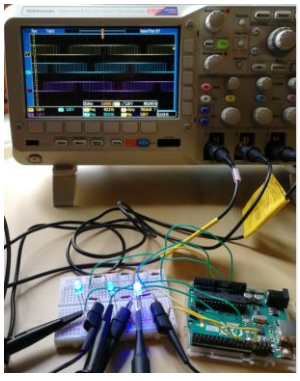
From analysis of the simulation-tests, the dimensioning and tuning from the proposed design-procedure seems to overall function well. The load-voltage is well maintained, keeping the magnitude within +- 2% RMS and THD <3%. High levels of lagging reactive loads negatively affects the LCL-filter performance, and an increase of reference DC-link voltage is suggested for better margins. The FOC-method is the best performing control-system, handling all test-cases whilst hardly exceeding the rated levels of currents and showing low DC-link voltage overshoots (<3%). It does however exhibit a high torque-ripple, it utilizes a high switching-frequency (50kHz) and its flux-controller results in high currents during light/no-loaded conditions. The V/f-method shows a more oscillating response, with overshoots of current up to 160% and overshoots of DC-link voltage up to 14%. A redesign of the tuning/structure is suggested to improve the performance. In comparison to the FOC-method, it does however display lower torque-ripples and it operates at a lower switching-frequency (10kHz). In terms of the battery, the amount of work delivered is generally low compared to the machine-ratings. Lower speeds and higher battery-voltages gives higher peaks of battery current.

Experimental results





The lab-experiment is conducted on a 55kW induction machine connected to a 60kVA 2L-3ph VSC and another speed-controlled machine. The built-in control system of the lab-VSC is used as provided. A DC-source in series with a diode is connected to the DC-link. Experiments are performed for various conditions of initial DC-link voltage and speeds. The results verify that a low-voltage source is sufficient in order to magnetize the IM and build up voltage. It managed to successfully magnetize and build up voltage to a 400V reference with initial voltages as low as 10V at rated speed (1000 rpm). Lower speeds did however require a higher initial voltage, up to 40V. No clear pattern is seen in terms of DC-source peak-current, but it seems to generally be low, suggesting that a battery could be a viable DC-source.



A simplified version of the proposed V/f-control system is implemented on the Arduino Uno using MATLAB-Simulink. By comparing the measured output signals to what is theoretically expected, the performance is best for references signals with frequencies below 100Hz. Though the code could be optimized, the Arduino Uno is probably best suited for simple applications that does not need precision down in the milli-seconds range.

Conclusion

The proposed B2B-topology seems to be a suitable candidate for an isolated power system, where a low-voltage source can be used to initiate the magnetisation of the generator. The proposed design-procedure demonstrates promising results with the generator being operated reasonably and load-voltages supplied within +- 2% RMS and THD <3%.

Impact of Fast Charging Stations on the Reliability of Electricity Supply in Distribution Networks

Student: **Marte Røine Brurås**
Supervisor: **Gerd Kjølle**

Abstract

By 2050, Norway has an ambition of becoming a low-carbon country with a zero-emission transport sector. This leads to a massive increase in electrified transport and the following need for charging. Thus, fast charging stations with significantly high power demands are currently being installed across Norway.

This master thesis investigates the impact a fast charging station will have on the reliability of electricity supply in a power system. Reliability analyzes by the simulation tool named the FASaD prototype is conducted for an existing distribution grid operated by Skagerak Nett. A fast charging station with a power demand of 10 MW is included in the simulations. Different locations for the fast charging station near the main road in Sande municipality are explored, in order to find an optimal location that minimizes the impact on the reliability of supply. Further, a reliability analysis of the 'worst-case' scenario is performed. June 29 is chosen to be the 'worst-case' scenario, as it is assumed that the maximum power demand for the fast charging station will occur on this day.

The results of the reliability analyzes show that the location for the fast charging station, relative to the transformer and the reserve connections, will have an impact on the reliability of supply. It is found that the most optimal location in the examined grid is a substation located some distance downstream from the transformer and very close to a reserve connection. From the simulations, it is found that the different locations lead to changes in the switching sequences during a fault, which impacts the reliability of supply. All the examined alternative locations gave a massive increase in reliability indices. The increase was 176% for the annual interrupted power, while it was found a 236% - 258% increase in the annual cost of energy not supplied (CENS) and a 206% - 237% increase in the annual energy not supplied (ENS) for the different scenarios.

From analyzes of the 'worst-case' scenario, it was found that the variation in fault frequency during a day had minimal impact on the reliability of supply. Further, it was found that total ENS and interrupted power for the investigated grid depended strongly on the load profile of the fast charging station. From hourly simulations using the FASaD prototype, minimal variation in the CENS during a day was found.

Investigation of a 200kW SiC-based IBC for high-speed hydrogen ferries

Student: **Håkon Magne Bye**
Supervisor: **Prof. Dimosthenis Peftitsis**
Contact: **Fredrik Aarskog**
Collaboration with: **IFE**

Problem description

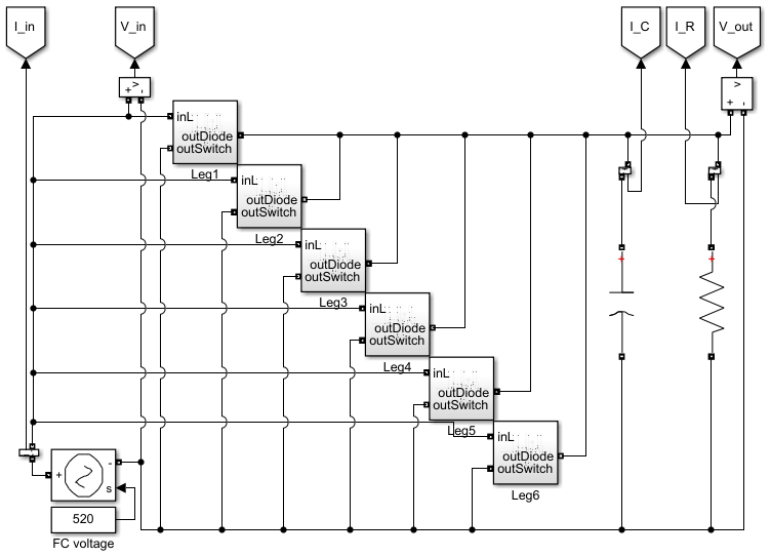
Hydrogen powered ferries are not a topic that is yet thoroughly investigated. It is difficult, and many uncertainties exist. It is, however, the only solution that per now is considered viable for electrification of lightweight applications with high power-capacity. Especially the electrical system in a hydrogen ferry needs to be addressed for weight minimization. This is due to mainly two reasons. Firstly, the voltage-variable behavior of a fuel cell and its inability to flow reversible power results in need of additional converters compared to battery alternatives. Secondly, fuel cells sensibility to current ripple requires sophisticated converter technologies to achieve an adequate fuel cell converter weight. It is this fuel cell converter that will be investigated in this thesis, mainly in terms of weight but also in terms of efficiency and volume.

The task

The objectives of this thesis are a continuation of the specialization project written in fall 2018. During the specialization project, it was found that the IBC topology was the most suitable topology and that three-phase bridge topologies were the most suitable if galvanic isolation was a requirement. Hence, the following objectives were set for the master thesis:

- Conclude on a converter topology by determining whether galvanic isolation typically is a requirement or advantageous.
- Electrical dimensioning of the power electronic converter.
- Optimization study of the converter in terms of efficiency, volume, and weight.
- Modelling and simulation of the complete system in Simulink under various load profiles.

Model/ measurements



The following Simulink model was used to determine static load operations. All legs contain one inductor, one switch and, one diode so that one leg alone correspond to a boost converter. This is the basic principle behind the IBC. The PWM signal to the gates is then phase-shifted in a manner that leads to current and voltage ripple cancellation for the total fuel cell current. A more complex model is used for dynamic analysis. Mainly the total FC current ripple and the output voltage ripple was measurements of high significance for this thesis.

Calculation

For 6 200kW IBC converters supplying a 1.2MW ferry demand the following entities were found.

- Total weight of 319.2kg
- Total volume of 180liter
- Maximum 2.56% current ripple during 8% power operation

Conclusion

Either using SiC in a standard boost topology or substituting SiC with the investigated Si components would lead to a weight of almost 3 tons. Hence, both IBC structure and high-frequency components utilization are considered necessary for a satisfactory weight of the converter under the ripple requirements assumed in this thesis. The semiconductors were found to dominate the losses while the inductors were found to dominate the weight and volume. An operation scheme called “part-load” operation could be implemented quite easily and would reduce in increased overall efficiency and reduced ripples.

A DC-Grid Proposal for Deep Sea Mining focusing on Power Quality Aspects

Student: **Diogo dos Santos Silva**
Supervisor: **Elisabetta Tedeschi**

Problem description
The Deep Sea Mining technology, which consists of a process to retrieve minerals such as silver, manganese, cobalt, and zinc, from the seafloor, has become more attractive over the years, due to the recent advance in several technologies, especially in the offshore drilling business. In order to retrieve the minerals from the seafloor the mining tools, equipment based on world-class Remote Operated Vehicles (ROVs), will require power in a range of a few megawatts continuously during operation. Therefore, such vehicles must be connected to a reliable and efficient power system, bringing power from offshore to the subsea environment.

The task
This thesis focuses on proposing a DC-grid to power the Deep Sea Mining tools enabling a reliable and efficient operation from the Deep Sea Mining Support Vessel. The thesis proposes a subsea DC-grid with a subsea DC-hub providing power to the subsea consumers. The thesis evaluates the DC harmonics of the grid, which is one of the critical power quality issues in similar systems. The harmonics are a particular concern when the power system is connected to a weak source, as diesel generators installed in the vessels, for instance.

Model/ measurements
The system modeled the four main blocks of the power system: the top side AC system, the 2-level Voltage Source Converter, and its controls, the power umbilical, the subsea DC-DC buck converter, and its controls and the load. The topside Voltage Source Converter is responsible for control the power delivered to the subsea grid while the subsea DC-DC converter is responsible for keeping the DC-link voltage to the loads stable during operation.

Calculation
The converters are controlled using Pulse Width Modulation technique. The system is tested against load disturbances, and the harmonic content is assessed for different loading conditions. A simple soft-start for the converters is designed avoiding undesired trip due to inrush currents during the charging of the capacitors. And the DC-harmonics are evaluated for different scenarios considering a stiff and weak topside grid.

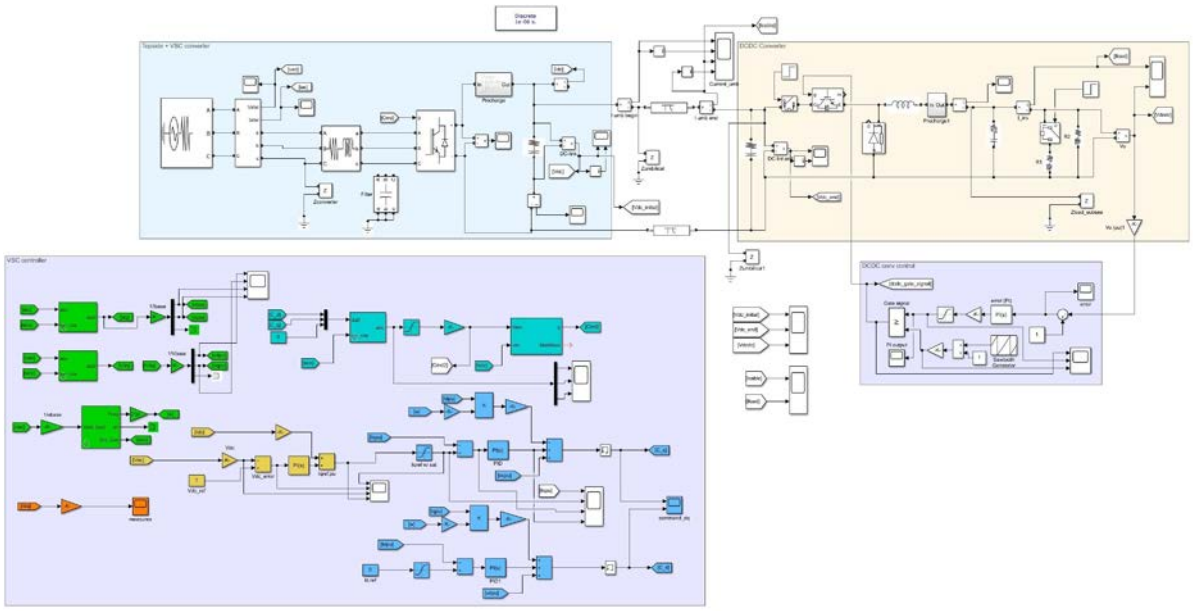


Figure 1: DC grid for Deep Sea Mining (Simulink/Matlab model)

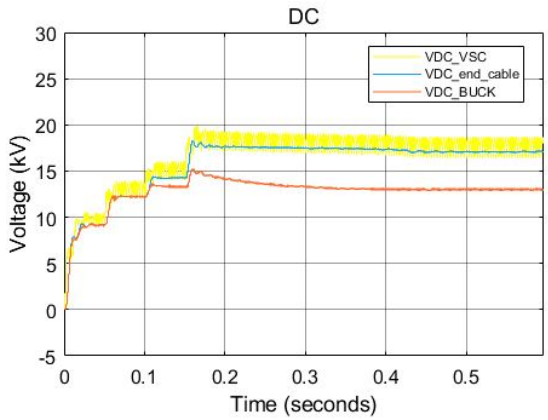


Figure 2: System voltage with the soft-start enabled

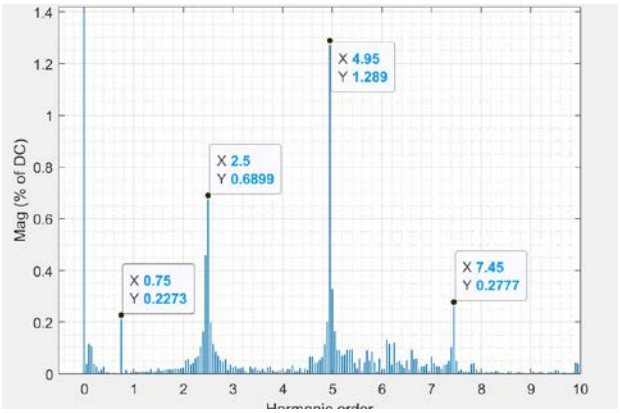


Figure 3: DC harmonics in the voltage of the subsea DC-link without filtering

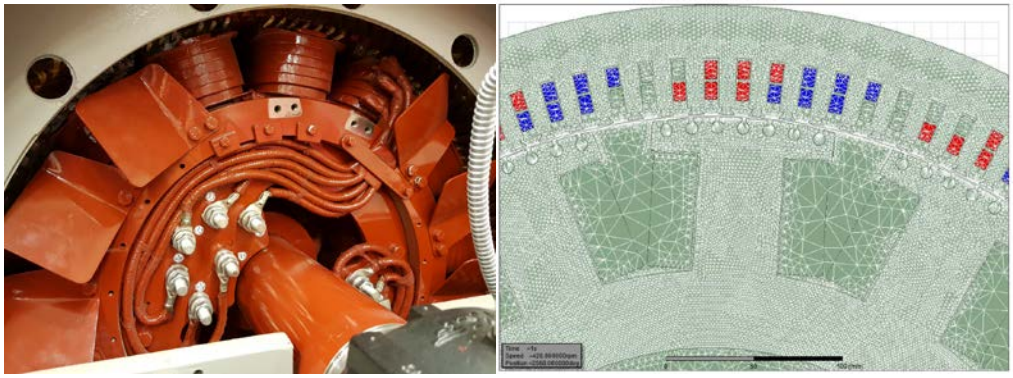
Conclusion

The main results are acknowledging how the AC harmonic mitigation affects the DC harmonics. The passive LC filters have a marginal DC harmonic reduction while the Voltage Source Converter line reactors can improve the power quality substantially reducing considerably the high-frequency harmonics generated by the switching of the IGBT converters. The voltage and current ripples are reduced by reducing the DC harmonics, which is a benefit to the life span of the capacitors in the DC-links.

Deteksjon av rotorfeil under drift i vannkraftgeneratorer

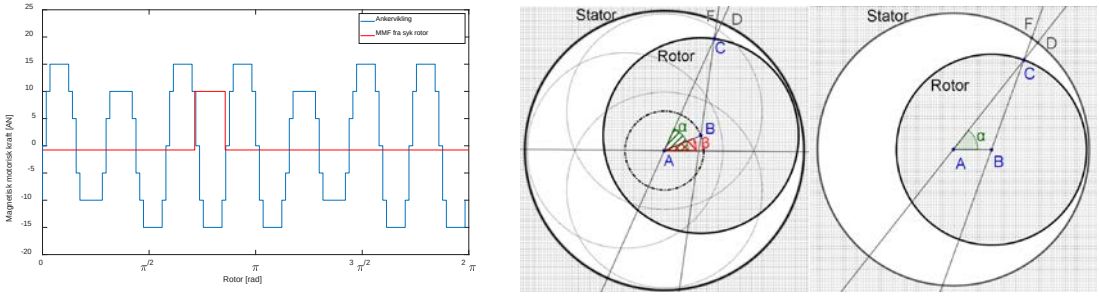
Student: **Johan Henrik Holm Ebbing**
Faglærer: **Arne Nysveen**
Veileder: **Arne Nysveen**

Sammendrag:
Denne masteroppgaven har undersøkt hvordan rotorfeil kan oppdages i vannkraftgeneratorer ved å måle klemmespenning og ankerstrøm. Det ble gjennomført forsøk på en 100 kVA laboratoriegenerator med 14 poler der vindinger i feltviklingen kunne kortsluttes. Resultatene fra laboratorieforsøkene ble sammenlignet med resultater fra en numerisk modell laget i ANSYS Maxwell, der både kortslutning mellom vindinger i feltviklingen og eksentrisitet ble simulert.



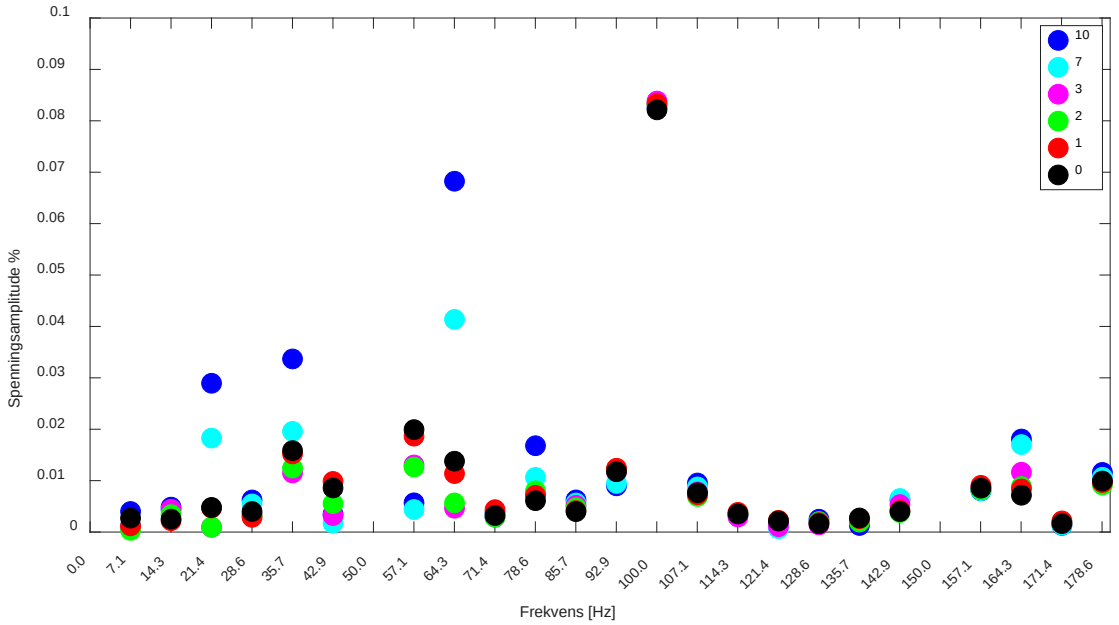
Figur 1: Venstre: Laboratoriegeneratoren. Høyre: Numerisk modell av laboratoriegeneratoren.

Det ble også utviklet analytiske modeller som beskrev vindingskortslutning i feltviklingen, statiske eksentrisitet, dynamiske eksentrisitet og vindingskortslutning i ankerviklingen. De analytiske modellene ga en god indikasjon på hvilke frekvenser som kunne forventes i spenningsspekteret til en bestemt generatortopologi.



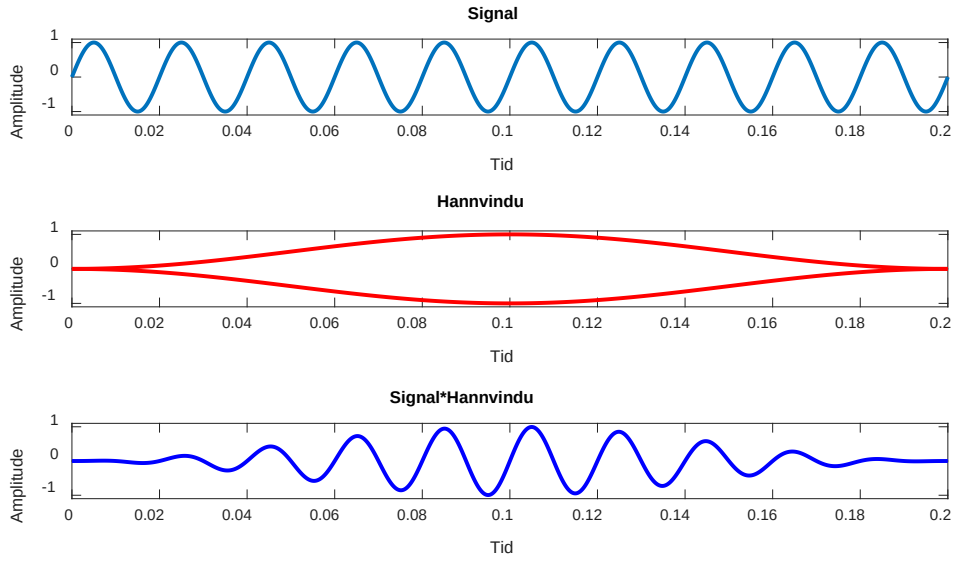
Figur 2: Analytiske modeller av kortslutning i feltviklingen, dynamisk eksentrisitet og statisk eksentrisitet

Resultatene fra de to modellene stemte til dels overens med resultatene fra den fysiske laboratoriegeneratoren. I visse henseender kan modellene brukes for å predikere frekvensspekteret en rotorfeil vil gi i ankerstrøm og klemmespenning, men det viste seg å være vanskelig å bedømme feilgraden med sikkerhet. Lave feilgrader var vanskelig å detektere. Store feilgrader av kortslutning i feltviklingen kan trolig oppdages ved å sammenligne resultatene med en numerisk eller analytisk modell. Oppdagelse av mer moderate feilgrader fordrer historiske data å sammenligne med. Eksentrisitetsfeil ble ikke eksplisitt testet på laboratoriegeneratoren, men målingene antydet at det både kunne være statiske og dynamisk eksentrisitet i laboratoriegeneratoren. Den statiske eksentrisiteten så ut til å forandre seg med varigheten av hvert enkelt forsøk, trolig på grunn av termisk ekspansjon.



Figur 3: DFT av spenningen til laboratoriemaskinen med varierende grad av kortslutning i feltviklingen

Det ble brukt to forskjellige oscilloskop. De tolket signalene noe forskjellig. Dette gjorde det vanskelig å sammenligne resultatene på tvers av oscilloskopene. Prøvene fra begge oscilloskopene viste de samme trendene. Frekvensspekteret til strøm og spenning ble analysert ved å bruke diskret Fouriertransformasjon (DFT/FFT). Signalet ble behandlet og manipulert på flere forskjellige måter for å undersøke hvilken effekt dette hadde på analysen. Fokuset lå på frekvensområdet null til 200 Hz, men forsøkene utelukker ikke at høyere frekvenskomponenter kan egne seg for deteksjon av rotorfeil.



Figur 4: Øverst: signal. Midten: vindusfunksjon (Hann). Nederst: signal behandlet med vindusfunksjon.

Det ble også tatt strøm- og spenningsprøver fra to vannkraftgeneratorer på 2.1 MW og 2.9 MW. Disse var, i motsetning til laboratoriegeneratoren, koblet til et stivt nett. Dette hadde innvirkning på resultatene. Instrumenteringen fungerte problemfritt. Det var enkelt å koble seg til eksisterende 110 V/5 A kontrollanlegg.

Tilstandsvurdering for optimal fornyelse av distribusjonsnett

Student: **Malin Eidem**
Veileder: **Eivind Solvang**
Utføres i samarbeid med: **SINTEF Energi**

Denne oppgaven er skrevet i samarbeid med SINTEF Energi og forskningsprosjektet REPLAN. Formålet med prosjektet REPLAN er å utvikle metoder, modeller og verktøy for teknisk-økonomisk analyse av framtidig fornyelsesbehov i kraftnett, fortrinnsvis 11-22 kV distribusjonsnett.

Metodikken i REPLAN baserer seg på å utføre fornyelsesbefaring for å tilstandsvurdere anlegg. Det aggregeres en tilstandskarakter (TK) for de aktuelle komponentene der tilstandskarakterene er knyttet til utskiftningtidspunkt. Sammen med forhåndsdefinerte fornyelsesalternativer og kostnadsmodeller legger dette grunnlaget for utførelse av teknisk-økonomisk analyse for å finne optimalt tidspunkt for reinvestering.

Det er kartlagt hvordan luftlinjer og nettstasjoner er bygd opp med hensyn til anlegg, anleggsdeler og komponenter. For luftlinjer inkluderte dette komponentene stolpe, bardun, travers, fundament, isolator, oppheng, line og gjennomgående jord. For nettstasjoner var fokus på anleggsdelene bygg, høyspenningsanlegg, lavspenningsanlegg og transformator med tilhørende komponenter som for eksempel brytere og ventilasjon. Det er gjort rede for tilhørende skadetyper, tilstandskontrollmetoder samt kriterier for karaktersetting.

Deltakelse på fornyelsesbefaring hos Istad Nett danner grunnlaget for beskrivelser av praktisk utførelse knyttet til luftlinjer og nettstasjoner. Basert på erfaringer fra gjennomføringen og utkast utarbeidet av Istad Nett ble det for nettstasjoner utviklet et forslag til skjema for registrering av tilstandskarakterer med tilhørende veileder.

Videre har fokus vært å identifisere utfordringer og begrensninger knyttet til implementering av metodikken for nettstasjoner. Noen elementer som er trukket frem i rapporten inkluderer økt kompleksitet med tanke på oppbygningen av nettstasjoner og varianter knyttet til komponentene og anleggsdelene. I tillegg er det behov for mer avanserte tilstandskontrollmetoder, og videre utvikling av kriterier for karaktersetting med tanke på inkludering av sikkerhetshensyn. Den økte kompleksiteten har ført til at det ble behov for å justere elementer av metodikken i REPLAN ved opprettelse av fornyelsesalternativer og kostnadsmodeller for nettstasjoner.

Det er gjennomført case for luftlinjer og nettstasjoner der det benyttes data innhentet ved fornyelsesbefaring. For luftlinjer benyttes det et Excel-verktøy for å finne det mest lønnsomme fornyelsesalternativet. Casen for nettstasjoner er et eksempel som illustrerer metodikken for deler av en nettstasjon. Arbeidet har ført til bedre beslutningsgrunnlag for fornyelse av luftlinjer og nettstasjoner. Likevel er det knyttet større usikkerheter til nettstasjoner, så videre arbeid vil være nyttig for utarbeidelse av et fullstendig verktøy tilpasset den økte kompleksiteten.

Dynamic Simulation of Power Systems Based on a Second Order Predictor-Corrector Scheme

Student: **Håkon Eidsvik**
Supervisor: **Olav Bjarte Fosso**

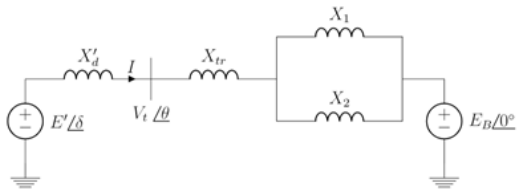
Problem description

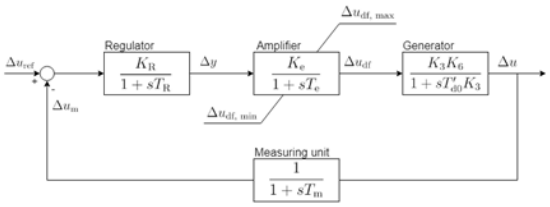
Penetration of RES and power electronic grid interfaces is increasing. This makes dynamic simulation of large power systems challenging, as required details and time-steps of components differ. The method implemented in this thesis controls the accuracy and utilizes variable time-steps to simulate an arbitrarily large system with arbitrarily rapid dynamics for an arbitrary amount of time. A discrete event will cause discontinuities in the tracking of first and second order derivatives, posing a challenge to the algorithm.

The task

Implement and gain experience with the usage of Gear's method in the Python programming language. Implement a strategy for constraining the step length adaptation during simulation to minimize the number of step length adjustments and improving run-time. Subject the model systems to disturbances and implement a strategy for re-initialization of the state variables and their derivatives following a disturbance.

Model/ measurements

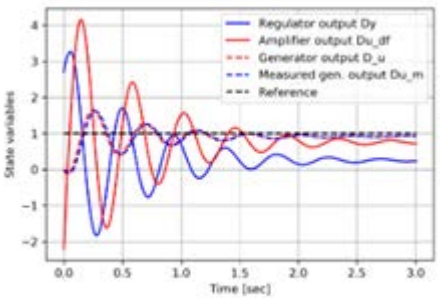




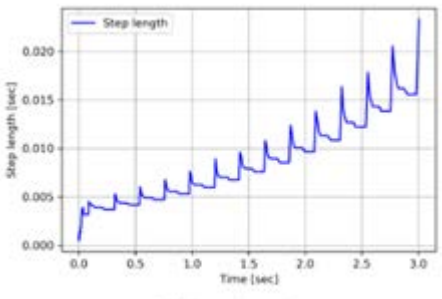
The two systems above were simulated using Gear's method. The left hand system was subjected to a short circuit of transmission line 2 (X2) and the right hand system was subjected to a saturation of the amplifier output. The step length throughout the simulation period was then calculated and plotted.

Calculation

The following figures are from simulation of the block diagram above. Without step length adjustment strategy implemented:

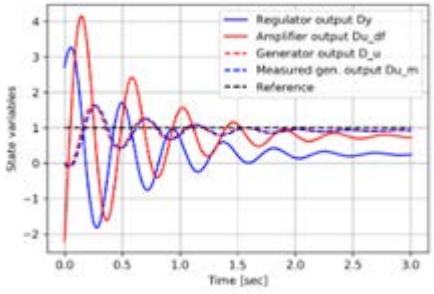


(a) Tracking of y

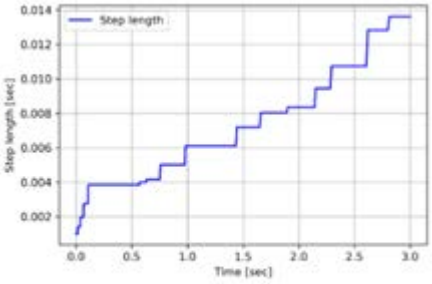


(b) Step length

With step length adjustment strategy implemented:



(a) Tracking of y



(b) Step length

The strategy developed reduces the number of step length adjustments by more than five times, and is thus proven to be very effective in that regard.

Conclusion

The step length adaptation strategy is very effective and should be used whenever possible. The strategies for re-initialization displayed a 5% increase in performance for the short circuit case, but yielded identical results for the saturation case. This will be subject to further work in a master's thesis next year.

A 1 kW PFC converter with GaN-transistors and planar magnetics

Student: **Ådne Finnes Engetrøen**
Supervisor: **Roy Nilsen**
Co-supervisors: **Tore M. Undeland & Ole Christian Spro**
Collaboration with: **Eltek, Drammen**

Problem description

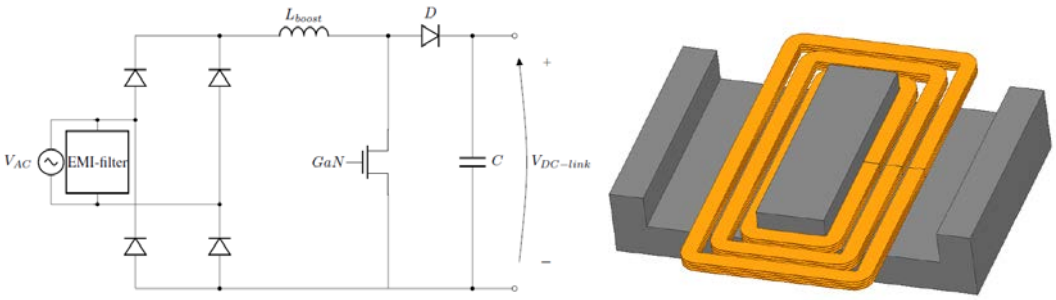
In nonlinear loads, for example in switch mode power supplies (SMPS), the current drawn from the grid is distorted. This results in a poor power factor and a high total harmonic distortion (THD). A power factor correction (PFC) stage is commonly used to mitigate the negative effects of high THD on the grid. The PFC stage often comprises, in addition to switching devices, a magnetic element to store energy. With the advent of wide bandgap devices, the performance of the switching device is greatly improved. A reduction in conduction and switching losses is possible. Moreover, new topologies can be realized utilizing the capabilities of these new devices.

The task

This thesis examines the possibility to utilize GaN-HEMTs and a planar (PCB) inductor in the boost stage of a classic PFC boost converter. An expected increase in switching frequency while still maintaining lower or equal losses in a PFC converter lowers the inductance demand.

Model/ measurements

To examine GaN benefits over the more common semiconductor material silicon, LTSpice was used. For simulations regarding the planar inductor, FEM-simulations in Ansys Maxwell 3D was used.

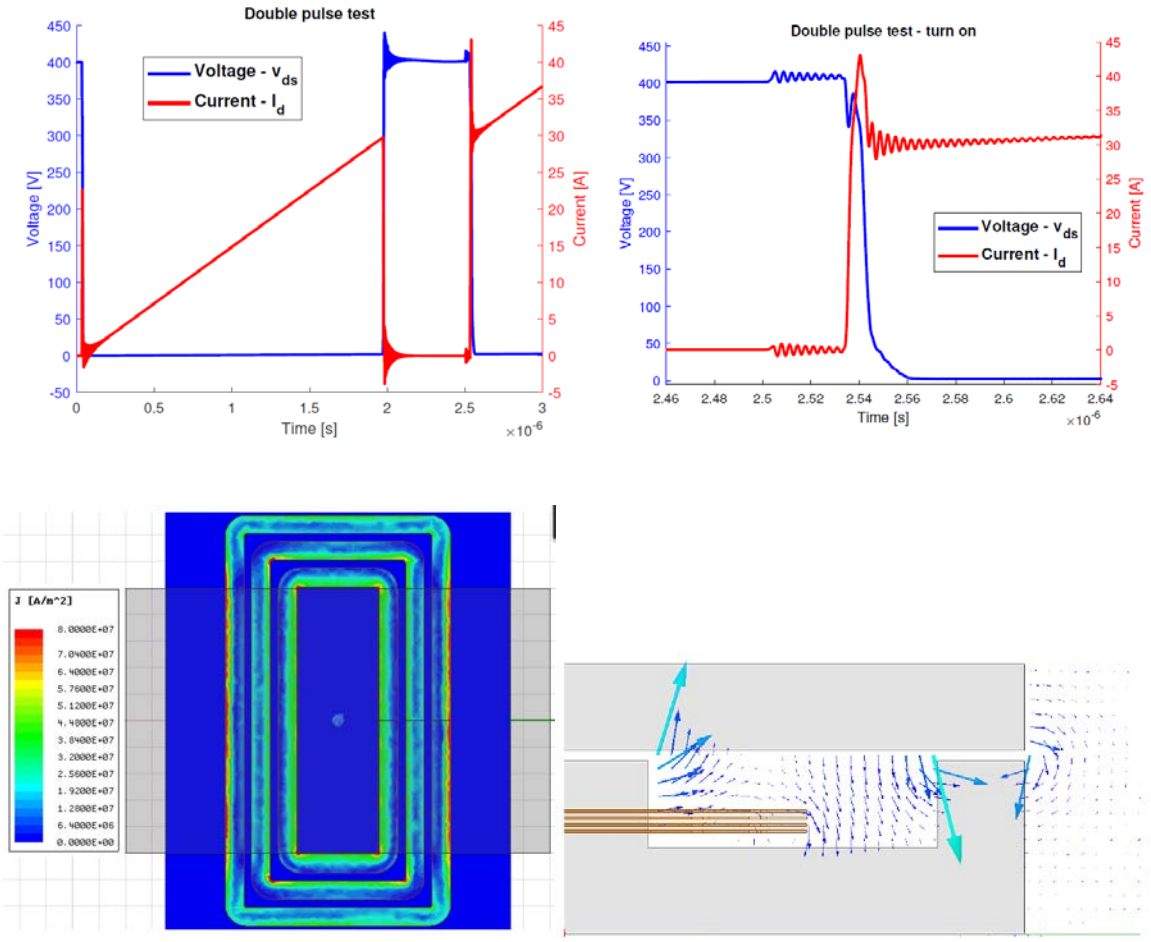


Figur 1: A PFC boost converter circuit & a planar inductor

Calculation

A double pulse test was performed for different transistors (mainly MOSFETs and GaN-HEMTs) to determine switching losses during turn on and during turn off. Parasitic elements were also included. A double pulse test for a GaN-HEMT with a rated 30A continuous drain

current is shown below. By integrating the power curve (drain-current multiplied with drain-source voltage), switching losses were obtained.



The current density distribution and the flux density distribution is shown in the figure above. With FEM-simulations, a planar inductor was optimized with a given design criteria.

Conclusion

GaN-HEMTs show almost 15 times lower switching losses than silicon. This makes higher switching frequencies possible with the same or lower total losses. Higher switching frequencies lowers the inductance demand in a PFC boost converter, thus making new inductor topologies possible. A planar inductor is low profile, has economical assembly, excellent repeatability and it also shows superior thermal characteristics over the more common toroidal inductor. By distributing air gaps in a planar inductor, a significant reduction in total (inductance specific) losses can be obtained. Additional design rules are: keep the PCB far from the air gaps, keep a low side margin from the centre leg to the first turn and keep low copper space between turns. The PCB copper width is determined by the current magnitude.

Modeling of Multiterminal HVDC grids with Renewable Energy and Storage Integration by Open Source tools

Student: **Joachim Espvik**
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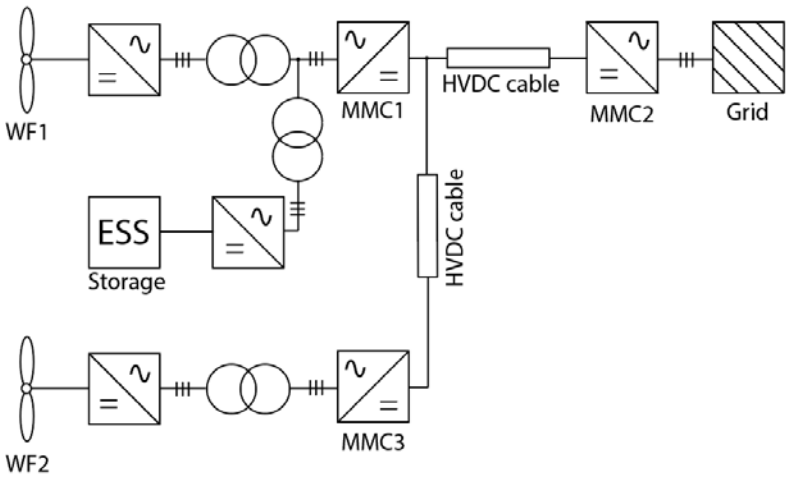
Co-Supervisor: **Santiago Sanchez**
Contact: **santiago.sanchez@sintef.no**
Collaboration with: **DNV GL**

Summary
The world is in urgent need of low emission renewable energy production to meet the limits set for temperature increase in the Paris Climate Change agreement. Offshore wind power is one of the most promising technologies to reduce greenhouse gas emissions and meet this target to secure a safe future for generations to come. When the amount of offshore wind power installed increases, it is useful to connect offshore wind farms in a grid to increase the flexibility and reliability of the system to ensure the security of supply to shore.

At long distances of large-scale electrical power transmission by sub-sea cables, high-voltage direct current (HVDC) is often preferred over high-voltage alternating current (HVAC). In future and present offshore HVDC grids for large scale wind power integration, the modular-multilevel converter (MMC) is a key component to convert between AC and DC power, providing fast control and the possibility to change the paths of the power flows in the HVDC grid. Additionally, energy storage systems can be integrated in HVDC grids to deliver power and absorb power from offshore wind farms to complement the varying power production due to the intermittency of the wind.

HVDC grids are expected to develop into large and complex systems, and therefore it is useful to study the interactions between the various components such as wind farms, energy storage systems and the HVDC grid including converters and cables. To perform such studies, simulation tools using models that emulate the physical components can be used to gain knowledge on the operation of the system. One emerging modeling tool is the open-source software OpenModelica, which is based on the Modelica modeling language. In this Thesis, OpenModelica was used to model a multi-terminal HVDC system with offshore wind and energy storage integration, as shown in the figure.



Three-terminal HVDC grid with offshore wind and energy storage integration.

Before building the final simulation system, some aspects of OpenModelica were studied closer. The first aspect was a preliminary assessment of the performance of the software with the accuracy of results and speed of simulations as criteria and Simulink as a benchmark. The results showed that OpenModelica could reproduce the fast dynamics in the current waveforms on the AC-side of a 10kHz 2L-VSC switching model that was implemented in both OpenModelica and Simulink. Additionally, the speeds of simulations in OpenModelica were similar to the speed of Simulink for most of the solvers in OpenModelica. The second aspect was on how OpenModelica could be used with one of Opal-RTs real-time simulators, facilitating future hardware-in-the-loop simulations of HVDC systems modeled in OpenModelica. No such guides were found in the literature, and the built-in guide in Opal-RT's software was lacking details. Therefore, a guide on how to build and prepare models for Opal-RTs real-time simulator, ePHASORSIM, was included in the Thesis. The guide included models of a resistor, a voltage source converter (VSC) and a point-to-point MMC based HVDC model. OpenModelica models were successfully tested with the real-time simulator in the National Smart Grid Laboratory.

Next, the three-terminal MMC based HVDC system was modeled with two wind farms where one of the wind farms was complemented by an energy storage system. Three simulation cases were studied. The first case, Test case 1, showed that the three terminal HVDC system had a stable step response to changes in power references in both directions. Test case 2 focused on the dimensioning of the energy storage system using real wind speed data. A configuration where the power from the wind farm was filtered, and the difference in power was delivered and absorbed by the energy storage system, was used. Test case 3 combined the wind farm models and the energy storage configuration at one of the wind farms to study the difference in responses of the HVDC system to events at the two wind farms.

The simulation results of Test case 3 showed that having a fast and somewhat well dimensioned energy storage at the same MMC converter station as one of the wind farms improved the responses and operation of the HVDC system. It was observed that during large drops in wind speed, the DC-voltages and the internal energies of the converters had transients of lower magnitude than the case without an energy storage system connected. At sudden losses of wind farms, the response of the internal energies of the converters also had improved responses with transients of lower magnitude.

Overall, the experience of using the OpenModelica tool for this Thesis was positive, and the software is recommended for similar studies in the future.

Functional Testing of Protective Relays in Digital Substations

Student: **Kristian Soleng Evjen**
Supervisor: **Hans Kristian Høidalen**
Contact: **hans.hoidalen@ntnu.no**
Collaboration with: **Statnett**

Problem description

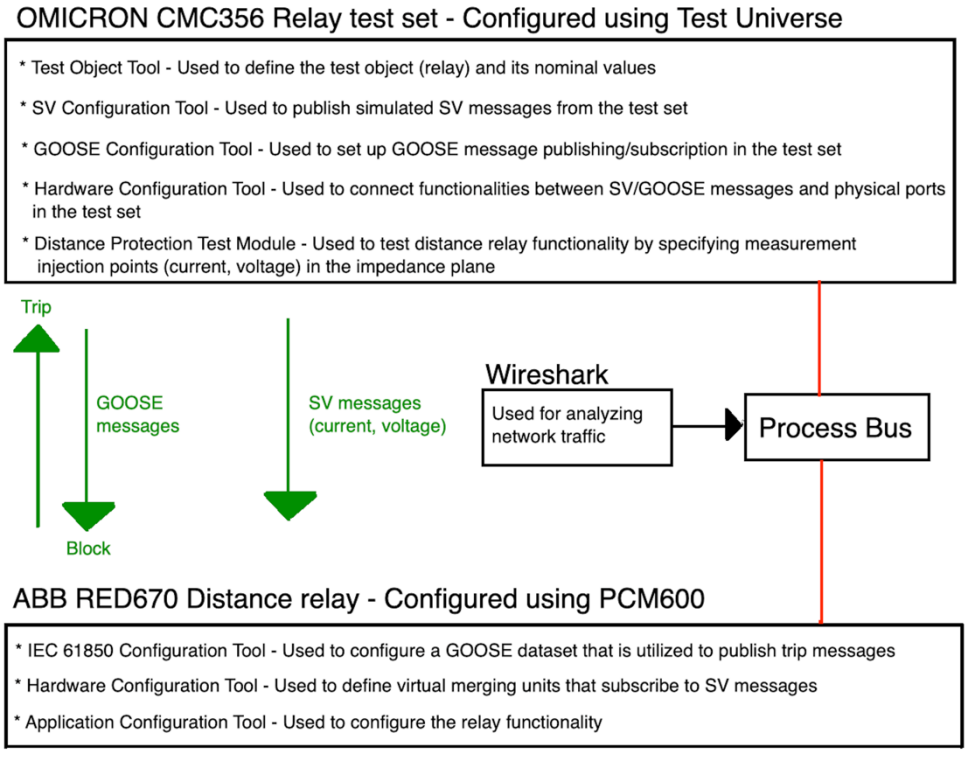
Digital substations introduce fundamental changes to substation communication, and protective relay testing procedures have to be changed accordingly. The purpose of this master thesis is to analyse how testing of protective relay functionality can be performed in IEC 61850 digital substations, and how this differs from testing conventional substations. A laboratory setup that can be used to perform relay functionality testing in a digital substation environment is to be established. This is the first master thesis to cover digital substation testing using the NTNU relay laboratory and works as a first step into this topic. Hence, an essential part of the thesis is to provide description and documentation of the utilized laboratory equipment, setup, and configuration. The established laboratory setup should then be utilized for performing basic functionality testing of an isolated relay to see how this may be performed in a digital substation environment. IEC 61850 testing tools are needed to perform isolated relay testing in a full digital substation, and these should be covered both in theory and in practice using the laboratory setup.

The task

Establish a digital substation environment in the NTNU relay laboratory, and use this to perform a series of laboratory experiments that illustrates key principles of relay functionality testing.

Model

A principle illustration of the established laboratory setup is given below.



The laboratory setup consists of an ABB distance relay and an OMICRON test set, communicating over an Ethernet switch that is used as digital substation process bus. Measurements from ITs are simulated from the test set as SV messages, while control blocking messages are sent as GOOSE messages. The relay is able to respond with corresponding GOOSE trip messages. Wireshark is a network analysis tool that is connected to the Ethernet switch to analyse the GOOSE and SV traffic.

After establishing the laboratory setup, as set of experiments are performed. First, the communication is tested to verify that all GOOSE and SV messages are correctly published, received, and interpreted by both the relay and the test set. The second part of the test procedures verifies fundamental protective relay requirements like stability at load situations, stability at external faults, and correct handling of internal faults. The last part of the experiments study IEC 61850 testing tools defined for digital substations in practice, with GOOSE and SV test messages and IED test modes as the most important tools.

Conclusion

The laboratory setup was successfully established. The first two parts of the laboratory experiments worked as expected, verifying correct digital communication and relay operation. However, it was shown that the utilized relay did not fully support IED test mode as described in the IEC 61850 standard. Problems related to different interpretations of the IEC 61850 standard is not unknown within the industry, but is likely to be solved as the technology matures.

Voltage Control for Distribution Systems using Chance Constrained Linear AC OPF

Student: **Martin Hergot Festøy**

Supervisor: **Hossein Farahmand, Jamshid Aghaei**

Problem description

Currently, distribution networks are experiencing a significant share of photovoltaic (PV) integration. The PV systems can provide reactive power control as vital means to provide voltage support. However, widespread use of local reactive power control by PV systems can interfere with existing voltage regulation schemes by the distribution system operators. To enable a higher penetration of renewables in the distribution system, it is therefore necessary to address this challenge.

At the same time the generation from PV is at all times subject to the irradiation, and this can be hard to forecast precisely. Thus a model that deals with generation from PV should also consider the uncertainty involved when simulating the system. PV generation is also purely limited to the time of day the sun shines. To better utilize and further enable high PV penetration distribution grids, some form of energy storage is highly desirable.

The task

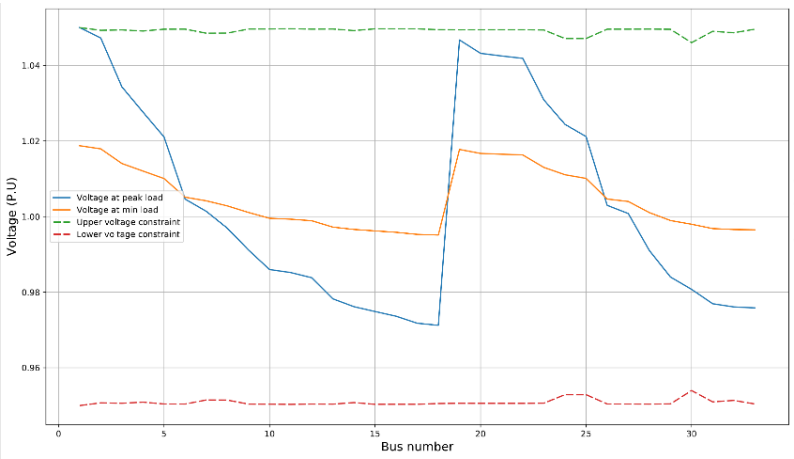
In this thesis, a coordinated operation of distributed voltage controllers/reactive power compensators is modeled that reveals an appropriate operation that brings the performance of the tap-changer and distributed generation sources together.

The suggested method takes into account the impact of the forecast error of power demand and PV generation, and adopt the chance constrained framework to consider uncertainty without requiring the historical data of the system.

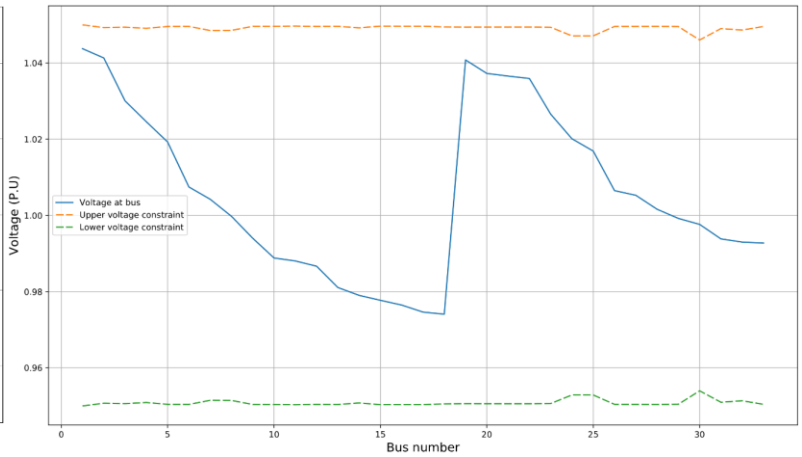
For testing the method, a linearized optimization problem is implemented on the standard IEEE 33-bus network. After the initial simulation, basic sensitivity analysis is performed on the system, with specific focus on how changes to the system impacts the voltage profile and chance constraints.

Results

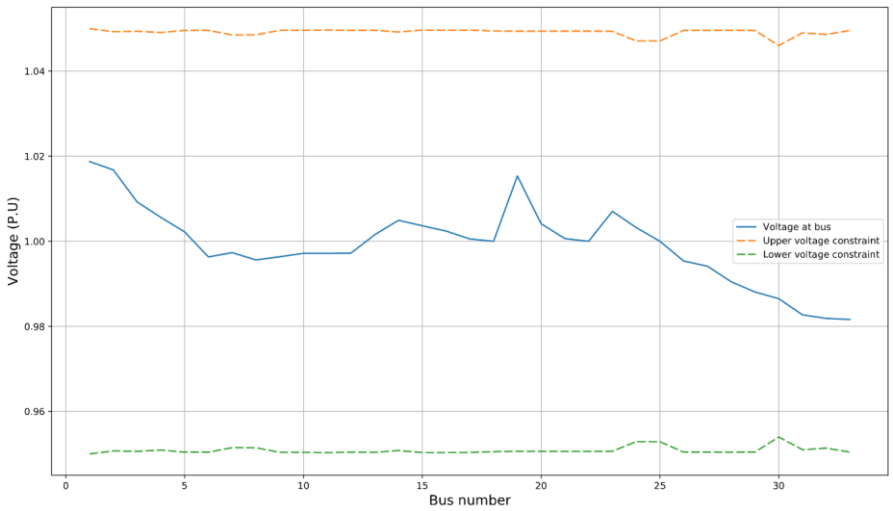
The following three figures show the voltage profile of the system for three different simulation scenarios: a normal distribution system, 1 MW PV installed at bus 30, and a decentralized system with 1 MW PV at buses 14, 21, 24 and 30. Additionally, the chance constrained boundaries for the voltage at peak load is plotted in each figure.



Normal distribution system



1 MW PV at bus 30



Decentralized PV at buses 14, 21, 24 and 30

Conclusion

The results reveal that there is a significant improvement in voltage profile if the tap changer is utilized together with distributed voltage regulators like PV and storage. Installation of distributed PV at one of the buses in the IEEE 33-bus test system, improved the voltage with on average of 0.0044 P.U for every bus at every time increment, while also reducing the deviation of the voltage peaks. Introducing a distributed PV + storage system drastically reduced the voltage peaks, and improved the average voltage with 0.012 P.U over all buses and time increments. Overall, the result of this analysis is that the voltage at the buses is significantly more affected by the placement of the voltage regulators rather than the size of the regulators.

Changing the value of the forecast error resulted in more narrow voltage constraints, and the base case PV-system failed to solve within a 90 % certainty when the forecast error became 0.252. Increasing the scale of the distributed regulators was shown to improve this tolerance, and increasing the size of the inverter by 50 % increased this tolerance to 0.757. Thus, the price of increased capacity can be viewed as the price of certainty.

On-line Voltage Estimation during Sensorless Control of an Induction Machine Drive

Student: **Viljar Fjellanger**
Supervisor: **Roy Nilsen**

Problem description

One of the main challenges during sensorless control of an induction machine is *drifting* of stator flux estimation. Drifting is a consequence of inaccurate measurements or errors in parameters estimation and can lead to vibrations in the machine and unstable control. Stator voltage is one of the input parameters necessary to achieve sensorless control. Stator voltage can me measured directly on the inverter output. High rise-time and high voltage potential makes measuring equipment expensive. It is possible to estimate stator voltage by using the knowledge of IGBTs on-time and measurement of DC-link voltage. However, blanking time and switching characteristics of the invert, introduces time delays between IGBTs control signal and the actual voltage pulse on the inverter's midpoints. This time delay must be compensated for if one wishes to get accurate voltage estimates.

The task

This thesis focuses on modelling and control of an induction machine drive. It also focuses on implementation of an on-line voltage estimation technique for a two-level three-phase inverter. The voltage estimator uses both the CPU and the FPGA on the control board. The CPU is programmed in C++ using Xilinx SDK and the FPGA is programmed by construction an IP-core design in Xilinx Vivado. New IP-core are generated using *Xilinx System Generator DSP* for MATLAB Simulink. IP-core development using Xilinx System Generator DSP at the department of Electrical Power Engineering has previously only been done to a small extent. This thesis present and explain the tool in detail with the intention of being an example for future development.

Model

The logics used to introduce the correct time delay from IGBTs control signal to voltage pulse signal is presents in the figure below. A rising and falling edge detector together with a current direction detector decides how the time delay effect the IGBT signal. Positive current gives a reduction of the signal and negative current gives an extension of the signal. The voltage pulse signal is used to drive a counter and the contend value is used to calculate output voltage

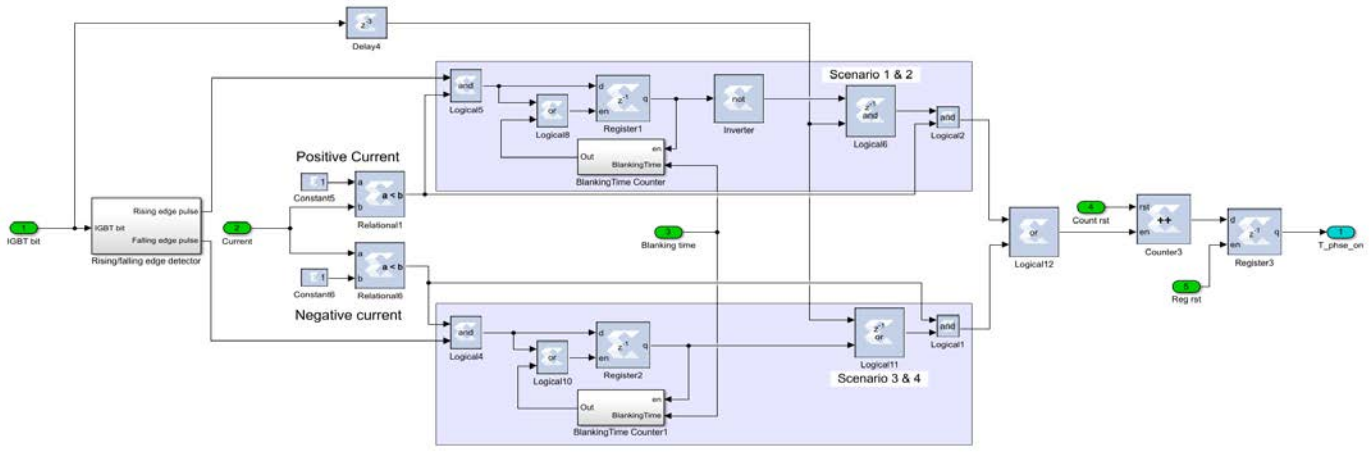


Figure 1: Logical circuit for the IP-core

Phase voltage calculation are done using the equation below. Figure 1 gives an estimate of the on-time of one of the phases. The other two phases are found using an identical logical circuit. The counter value will increase with one for each clock cycle of the FPGA as long as the voltage pulse signal is high. The counters are reset every time the CPU gets an interrupt. T_{samp} is found by counting the total amount of clock cycles between to interrupts.

$$U_{as}^{*} = \frac{1}{3} \cdot U_{dc} \cdot \left(\frac{2T_a^{*} - T_b^{*} - T_c^{*}}{2T_{samp}} \right)$$

Results

Figure 2 and Figure 3 shows the test results of the voltage estimator during open loop V/f-control, without and with blanking time, respectively. The red signal shows the reference voltage, calculated by the modulator and the green signal shows the estimated output voltage. When the system is not subjected to a blanking time, the results show that the voltage estimator indicate an output voltage identical to input voltage. When blanking time is introduced, it is seen that the voltage estimator is able to estimate a discontinuous output voltage, in accordance with what is expected from the theoretical study.

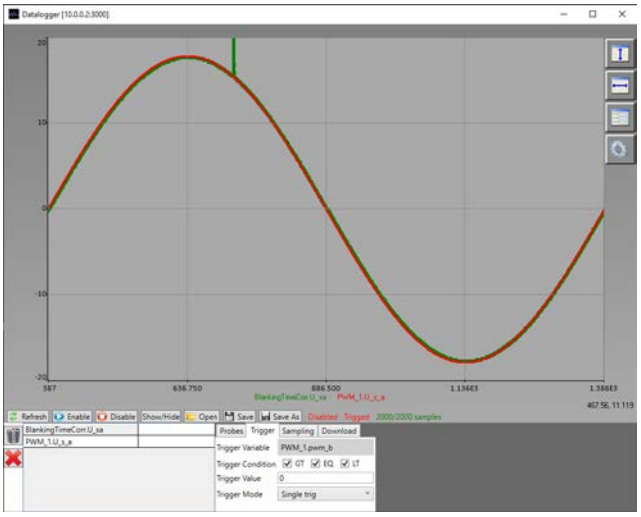


Figure 2: Without blanking time

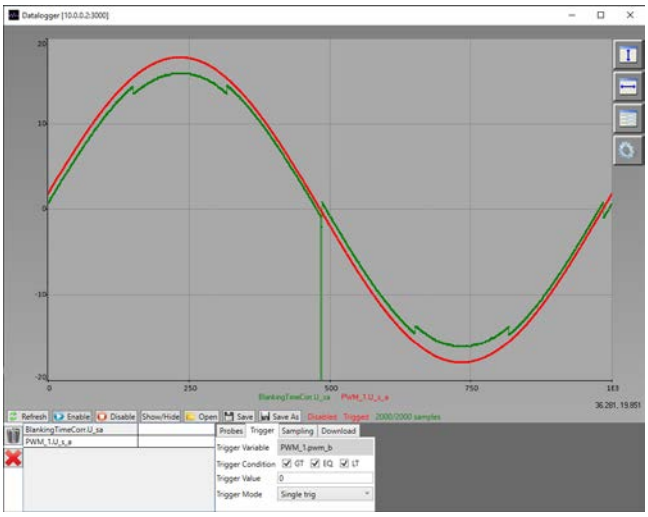


Figure 3: With blanking time

Conclusion

The tests were conducted on the control board with no inverter connected. It is expected that test results of voltage estimation when connected to a physical drive, would show a lower accuracy than presented in this thesis and tuning of the estimator might be needed. However, given the test results it can be concluded that the voltage estimator was able to estimate correct output voltage given the correct input parameters.

The IP-core was designed and tested using Xilinx System Generator tool in MATLAB Simulink. This tool has proven to be an effective way of programming complex FPGA programs without knowledge in VHDL programming. The tool has the potential to enable electric power engineers the ability to participate in designing, building and testing advanced FPGA designs, something that previously has required specialist programming knowledge.

Voltage-dependency of loads an its role in voltage control strategies

Student: **Aurora Fosli Flataker**
Supervisor: **Kjell Sand**

Problem description

- Provided that all customers receive a voltage of satisfactory quality – is it possible to control the voltage in a strategic way to for instance reduce network losses, peak demand or energy consumed by connected loads? I.e. implement a *voltage control strategy*. The concept is illustrated in figure 1.
- The response of a network to a voltage control strategy is determined by the voltage-dependency of the loads connected to the system as well as the voltage-dependency of the network losses. Since all networks have different characteristics and because the connected loads are not the same in all networks, the voltage-dependency can vary between networks. Therefore, to be able to estimate how a voltage control strategy will impact the power system in question, knowledge about the voltage-dependency of loads and network components is necessary. → Need of load models capturing the voltage-dependency of the real loads

- The large diversity of individual appliances in addition to the stochasticity in the utilization of the loads makes load modelling a challenging task. One approach is to use a bottom-up method where knowledge of individual loads' behaviour forms the basis for finding the load behaviour of the aggregate load.

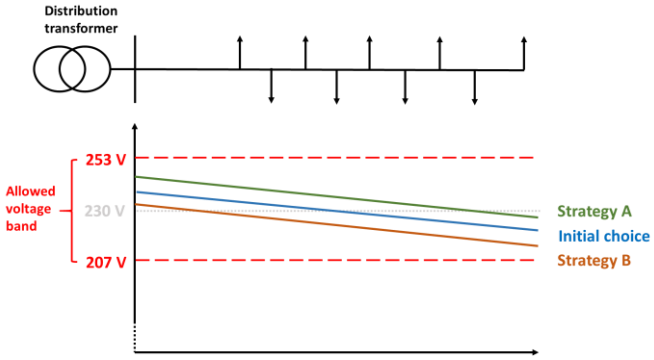


Figure 1: Radial feeder assuming no distributed generation and thus a voltage drop towards the end of the feeder. Nominal voltage is 230V. VQ-requirements for supply voltage variations are shown as dotted red lines. The blue curve shows the voltage along the line for a given load situation. The green and orange lines show potential strategies the DSO could choose from. For both strategies, all connected customers receive a voltage quality in compliance with VQ standards.

The task

The thesis consists of three parts, each covering different aspects of voltage-dependency and voltage control strategies:

Part I – Voltage control and voltage control strategies.

- Gives an overview of voltage control technologies in distribution networks and voltage control strategies implemented in by DSOs worldwide.

Part II - Voltage-dependency of individual loads and network losses.

- Contains information about load modelling, with emphasis on two widely used load models, namely the ZIP- and exponential load models.
- Laboratory experiments are performed to investigate the load behaviour and voltage dependency of five household appliances: induction cooktop, resistance heater, heat pump, washing machine and tumble dryer.
- The obtained measurement results are used to fit the load-to-voltage behaviour of the loads into the ZIP- and exponential load models by least squares minimization.

Part III- Aggregated loads and -load modelling.

- Focuses on component-based load modelling and addresses how the knowledge of individual loads obtained in Part II can be used for load model aggregation. Special emphasis is on modelling of thermostatically controlled loads. For such loads, it is not enough to examine the loads' instantaneous response to voltage change. By the fact that the applied voltage influences the duty-cycle of the load, one need to take into account how the voltage scheme influences the aggregate effect of the change in the duty-cycles of the appliances.

Model/ measurements

The lab tests and data analysis contain two basic steps:

1. Apply different voltages to the device under test (DUT) and measure active and reactive power (voltage- and current measurements)
2. Estimate the load model coefficients for the DUT based on the measurement data by utilisation of curve fitting techniques

Some of the tested devices have changing electrical characteristics throughout the cycle. They also offer several settings for the user to choose from (e.g. washing at 40°C or 60°C). For these devices two types of tests are performed:

1. Tests of different settings to capture the diversity in load behaviour depending on the user-defined setting. For these tests, nominal voltage (230V) is applied.
2. Tests of the same setting when different voltages are applied to capture the voltage dependency of the load.

Calculation

The table below summarize the results from the laboratory tests by simplifying the obtained load model parameters to categorize each appliance as either constant impedance, constant current or constant impedance. E.g. the curve fitting induction cooktop at 300W was Zp=0.74, Ip=0.44, Pp= - 0.18, but is in the table simplified as a constant impedance load (Zp=1, Ip=0, Pp=0).

	Constant impedance	**Constant current**	**Constant power**
Induction cooktop	Max Power, 300W and 800W-settings		1600W-setting
Resistance heater	Full-power and half-power settings		
Heat pump			All tested settings
Washing machine	Heating-stage of cycle	Rinse	Washing and spin
Tumble dryer		Whole cycle	

Conclusion

As a conclusion it can be stated that since load characteristics are different in different networks and at different times a day/year, there is no one-size-fits-all for voltage control strategies. Additionally, since one may have different goals with implementation of a VC strategy, the desired strategy can vary between grid operators or even grid areas/feeders for the same grid operator. In all cases it is obvious that the behaviour of the loads connected to the network plays a significant role in determining the outcome of a strategy. Knowledge about the load composition in the network and the loads' dependency of voltage is therefore a crucial part of assessing different voltage control strategies. The results from the laboratory tests performed in this thesis contributes to enhanced knowledge about load behaviour and can be used in further work for VC strategy assessment as well as in other applications were load models and knowledge about load behaviour is needed.

Streamer Propagation along Dielectric Surfaces

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

Problem description

A dielectric breakdown occurs when the insulating gas becomes conductive due to the ionization of the gas. While being obviously undesirable, dielectric breakdown is a geometry sensitive and complicated process to predict. Finding the withstand voltage for a component ultimately has to be done experimentally. It is therefore important to understand where and how breakdown will occur by improving simulation techniques and general knowledge in the field of research. Traditionally, the gas sulfur hexafluoride (SF_6) has been widely used in industry as both an interrupter and an insulator. SF_6 is a much better insulator than air and other gases that could potentially be used. However, SF_6 is also a highly potent greenhouse gas with a global warming potential 23 900 times worse than CO_2 on a 100-year horizon. This motivates industry and research efforts towards finding both gases to replace SF_6 and to improve on the design of high voltage gear. This thesis will aim at contributing to the latter one.

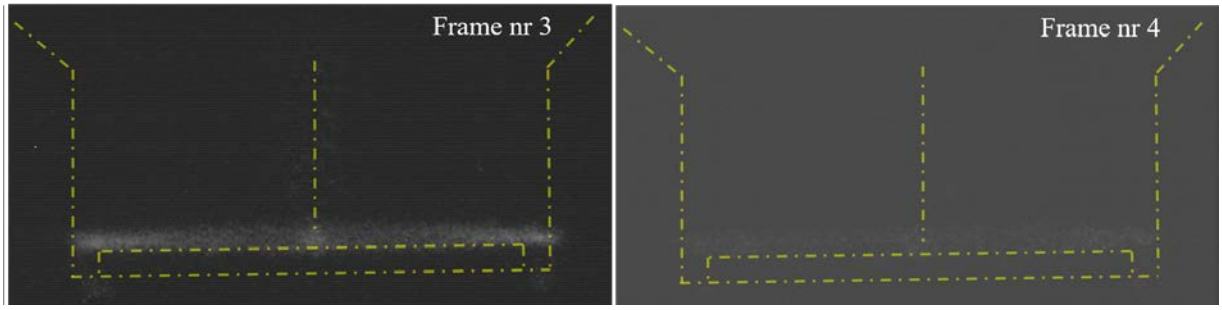
Objective

Because of the use of spacers and barriers in gas insulated switchgear, it is of research interest to know the dynamics of a potential discharge moving along a dielectric surface. Streamers are a type of partial discharge characterized by being a conducting ionized channel with a head of space charge creating electron avalanches to sustain the further propagation of the streamer. They can move over distances on the scale of millimeters to centimeters and can be an intermediate stage of a discharge leading to full breakdown. It is therefore interesting to study streamers from a withstand voltage perspective in industry. The effects deciding the propagation of the streamer are effects that take place on the milli- or micrometer scale.

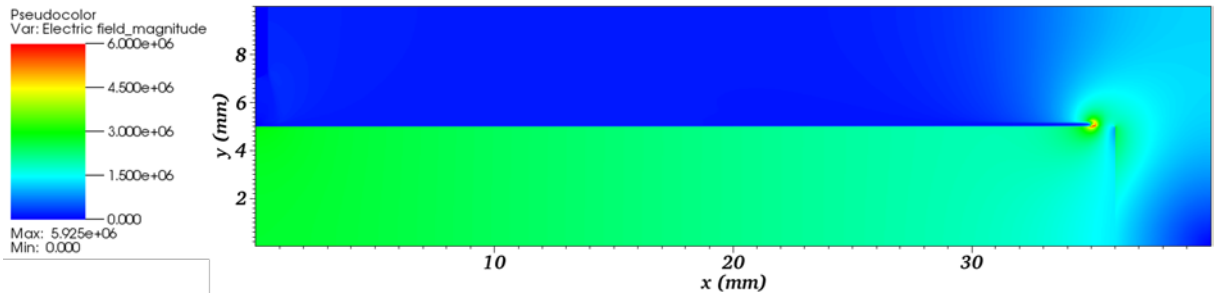
This master thesis aims at two main objectives. Firstly, the experimental results should increase the understanding of the nature of streamer propagation over dielectric surfaces. This includes obtaining results the streamer propagation range, the speed and the surface charging of the dielectric surface. Secondly, the results from the experiments will be compared to the results from the simulation software developed by SINTEF Energy Research in Trondheim, Norway. The simulation results are also expected to provide excellent insight into the experimental results. This way, the simulations will strengthen the experimental results and serve as a unique and powerful tool to analyze the streamer propagation along the surface.

Method

The main experimental focus was to apply a 35 kV and a 14 kV lightning impulse and record the time wise propagation of the streamer with the high speed camera. The following pictures shows the streamer propagation captured by the high-speed camera with an exposure time of 10 ns for the 35 kV streamer.



The simulations were used to show the dynamics of the same streamer propagation. The following figure shows the E-field when the same streamer as the latter figure shows propagates along the plane in the same geometry.



Conclusion

Through experimental work and 2D dynamic simulations, it has been shown how streamers propagate over a dielectric plane. The experimental setup is designed to reassemble the 2D model in the simulations and the experimental and simulation results show good coherence. The simulations show how the streamer propagates around 100 um above the dielectric plane.

Power Systems for Deep Sea Mining Applications, With Focus on Stability

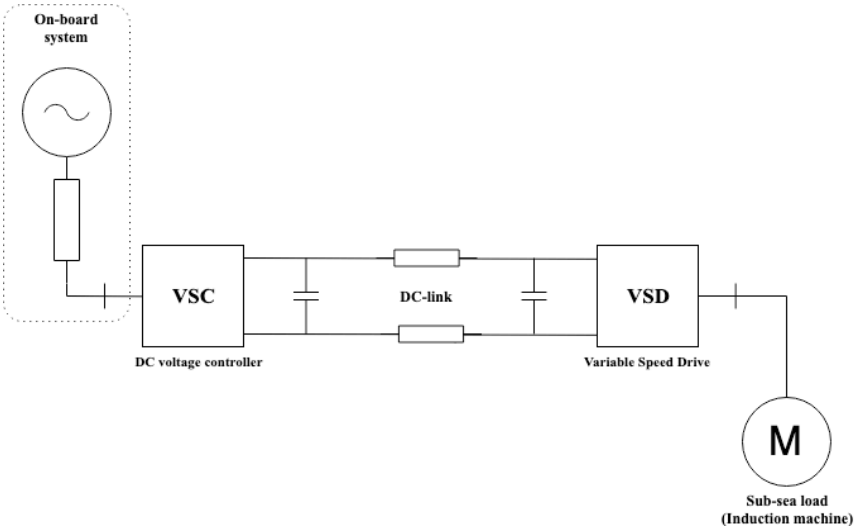
Student: **Jostein Gjevre**
Supervisor: **Elisabetta Tedeschi**

Problem description

Due to the ever-increasing demand for minerals and the depletion of terrestrial mines, the eyes of the mining industry has begun to look towards the great depths of the ocean. The deep sea is expected to hide sites with massive deposits rich in rare minerals such as gold, silver, copper and cobalt. Along Mohn's ridge between Svalbard and Jan Mayen, numerous seafloor massive sulphur (SMS) deposits, related to active and extinct hydrothermal vents, have been discovered. Among the discovered sites is Loki's Castle, at a depth of 2400 meters, recognized as one of the most promising locations for the extraction of minerals. At this point, there are few production systems developed for deep-sea mining (DSM) applications. Hence, it is of great interest for the development of future systems to identify operational and design related issues for this kind of systems.

The task

This thesis has through studies of existing concepts and research on the field of deep sea mining, developed a model for the electrical power system of a DSM production system. The model is developed with the intention of investigating the power system stability issues related to such an isolated system with converter-fed loads. A production system developed by the company Nautilus Minerals has formed the base of the study. Based on the literature research a DC distributed system with a centralized submersed power hub is proposed. The system is designed for a depth of 3500 meters, with the intention of operating in sites located in waters within Norwegian jurisdiction. A time-domain model and a linearized model for small signal analysis have been developed in the MATLAB/SIMULINK environment. The developed model configuration is essentially a point-to-point DC-link supplying a variable speed drive connected to a large induction machine. The two models are used for systematic analyses of relevant test cases, with the intention of investigating the impact of the converter controllers and to reveal the stability limits of the system under different operating conditions.



Conclusion

The results have shown that the strength of the power system of the supply vessel is critical for the stability limits of the system. When the on-board system has a short circuit ratio of 2, the power transfer capability has been identified to deteriorate to an extent where the system is incapable of satisfying the power requirement of the sub-sea system. Low-frequency oscillations have been detected related to the instability events, indicating a system that is easily excited even at nominal conditions.

On-line Magnetic Flux Monitoring and Incipient Fault Detection in Hydropower Generators

Student: **Ingrid Linnea Groth**
Supervisor: **Arne Nysveen**

Problem description

In the Norwegian power system, almost 100% of the annual production of electric power is supplied by hydropower generators. On-line condition monitoring of electrical machines can provide valuable real-time assessment the machine's operating conditions and help detect gradually aggravating faults at an incipient stage before it forces an unplanned shut-down or causes irreversible and costly damage to the machine. Monitoring appointed parameters while the machine is in operation can help determine whether any corrective measures are required for further safe operation and potentially contribute to an improved and more cost-effective preventative maintenance strategy. The concept of on-line magnetic flux monitoring was introduced by GE for cylindrical-rotor synchronous generators already in the 1970's. Monitoring the air gap magnetic field or leakage field components of electrical machines has gained traction during the recent years, especially in large industrial induction motors. The amount of research that regards implementation in hydropower generators has however been limited, possibly due to the complexity of the magnetic field caused by the high number of pole pairs and saliency of the poles.

The task

This master's thesis has investigated how incipient electrical and mechanical faults in salient-pole synchronous hydropower generators can be detected by monitoring and analyzing the air gap magnetic field of the machine. The faults investigated during this thesis has been inter-turn short circuits in the field winding, broken damper bars, static eccentricity and dynamic eccentricity.

Model/measurements

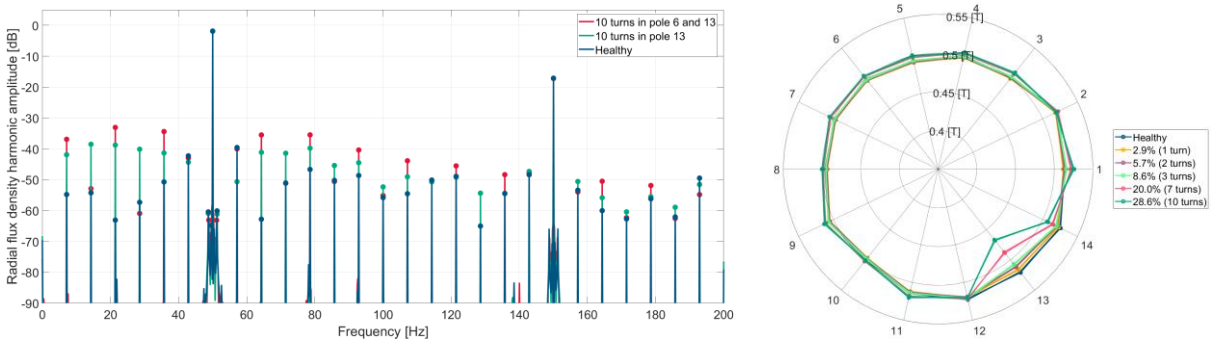
The analysis was approached through 2D finite element analysis performed on two modelled salient-pole synchronous generators. Experimental tests were performed on a 100 kVA laboratory generator and a 2.1 MVA hydropower generator in operation. Hall-effect sensors were mounted on the surface of a stator tooth, giving an output voltage proportional to the measured radial flux density. The measurement results were analyzed by the fast Fourier transform and by investigating the distribution of the flux density between the poles.

Laboratory test setup with a 90 kW induction motor as prime mover, gear box and the 14-pole, 100 kVA laboratory generator. The salient-pole synchronous laboratory generator has been designed to resemble a scaled-down version of a typical hydropower generator in the Norwegian power system. Intentional faults such as inter-turn short circuits in the field winding can be applied to the laboratory generator. The image to the right shows a Hall-effect sensor mounted on a stator tooth in the air gap of a 2.1 MVA hydropower generator.

Calculation

Since a fault will distort the inherent magnetic symmetry of the machine, the simulation results indicated that specific fault-related harmonic components appear in the frequency spectrum of the measured radial flux density, even for low-severity faults.

The measurement results of the 100 kVA laboratory generator indicated that a broken damper bar or fractured end ring can not be detected in hydropower generators at steady and synchronous operation by monitoring the air gap flux density. The implemented measurement setup could however successfully detect the inherent static and dynamic eccentricity of the laboratory generator. The severity of both types of eccentricity was estimated to about 3-5%. The measurements possibly also showed signs of low-mode dynamic stator bore deformation. Based on the tests performed with short-circuited turns in the field winding, it was estimated that fault severities down to about 15% of the total number of turns in a pole can be directly and reliably detected in hydropower generators.



The figures show the frequency spectrum of the measured radial flux density and the average flux density of each pole of the 100 kVA laboratory generator at full-load operation. The left figure shows a comparison of the harmonic content at healthy conditions, with an applied short circuit in the field winding in one pole and in two poles on opposing sides of the rotor. The right figure shows how the short-circuited turns in pole 13 reduces the magnetomotive force and measured flux density of the faulty pole.

Conclusion

Based on the results from the experimental tests, it was concluded that it can be challenging to differentiate the impact from a low-severity incipient fault from the normal inherent electromagnetic, structural and mechanical imperfections of the generator. The main conclusion of the thesis is that a great deal of information regarding the operational state of hydropower generators can be extracted by analyzing the air gap magnetic field. By implementing four evenly distributed sensors in the air gap, it is expected that short-circuited turns in the field winding, static and dynamic eccentricity can be detected and monitored.

Transmission investments under uncertainty

Assessment of how different European energy scenarios
for 2030 influence the North Sea Offshore Grid

Student: **Mina Mathilde Grøterud**
Supervisor: **Hossein Farahmand**
Co-supervisor: **Simon Risanger**

The North Sea Offshore Grid is considered being an important project towards more renewable power production and increased electricity market integration. The North Sea region has a significant potential for offshore wind production due to its favorable wind conditions. The wind power can be included in a way that ensures the security of supply by increasing the cross-border capacity between the North Sea bordering countries.

The main contribution of this thesis is the investigation of how investments in the North Sea Offshore Grid are affected by uncertainty. A stochastic two-stage model, formulated as a mixed integer linear program, is derived from the deterministic version of the transmission expansion model, PowerGIM. The model focuses on the expansion of three interconnectors; Great Britain to Norway, Germany to Norway, and Denmark to Great Britain. The model accounts for uncertainty, in terms of installed generation capacity, demand, and fuel and CO_2 prices, in the operation of the system in the year 2030. Two case studies are performed, and in total, seven scenarios for the year 2030 are applied. The input data and four scenarios in the first case study are collected from the Ten-Year Network Development Plan (TYNDP) from 2016 published by ENTSO-E, while the TYNDP 2018 is utilized in the three scenarios in the second case study.

The case studies demonstrate that more installed capacity from renewable energy sources (RES) and higher marginal costs of the generators result in a higher optimal capacity of the interconnectors in the model. Among other things, this occurs because the need for flexibility increases and interconnectors can contribute with that flexibility by transferring excess power produced by RES, from power surplus areas to power deficit areas. The two case studies have almost the same optimal capacity investment of the interconnectors. However, in the second case study, the model finds it optimal to invest 1000 MW less in the interconnector between Great Britain and Denmark due to the amount of installed solar capacity. Furthermore, the power generated from renewable energy sources in the system increases by 2% with optimal interconnector expansion. Consequently, the average area prices decrease.

A deterministic model is used, in addition to the stochastic model, to quantify metrics concerning the Expected Value of Perfect Information (EVPI) and the Value of the Stochastic Solution (VSS). With the given data and assumptions, it is shown that a system planner is willing to pay a maximum between 0.17% to 0.22 % of the stochastic cost for perfect information about the future generation capacity, demand, and prices. The expected cost saving for a system planner by use of a stochastic program is 5.06% or 3.2 % of the stochastic cost, depending on the case, in comparison with a deterministic approach that copes with uncertainty.

Modelling of An Offshore Wind Farm for Multi-Frequency Stability Analysis

Student: **Susanne Othilie Gulbrandsen**
Supervisor: **Elisabetta Tedeschi**
Co-supervisors: **Fernando P. Marafão, UNESP**
Łukasz Kocewiak, Ørsted
Collaboration with: **São Paulo State University (UNESP), Campus of Sorocaba**

Problem description

The increasing complexity of the electrical infrastructure over the last years has turned out to introduce new challenges related to multi-frequency stability in terms of interactions and resonances between physical components in the grid and the converter control. CIGRE's working group C4.49 *Multi-frequency stability of converter-based modern power systems* is established to describe the phenomenon and explain available *methods* for analyses, in addition to provide a common understanding on modelling, analysis, evaluation, and mitigation methods. The scope of this master thesis has been to make a contribution to C4.49 related to the modelling.

The task

In this master thesis, two functional simulation models which resemble the benchmark systems suggested by C4.49 have been developed in Matlab/Simulink. The benchmark systems represent power electronic dominated grids where both power generators and loads are interfaced by power electronic converters. The system design suggested by C4.49 is not limited to a certain type of power source. However, it has been chosen for this thesis to treat the generating units in the benchmark systems as wind turbines. The first system consists solely of a single generating unit, while the second system is built up of two converter configurations connected to the grid. The two converter configurations in the second system are in this thesis representing a cluster of 58 wind turbines. To make the model as realistic as possible, parameter data from the Hornsea Project ONE wind power plant has been used. The design of the converters' control system is derived from a methodology-based approach and has been explained thoroughly.

Model

An illustration of the system with two converters representing 58 wind turbines in total, is presented in the figure below. The control system has been designed in the *dq* reference frame with input measurement taken from the medium voltage side of the LV/MV-transformer. The tuning of the control parameters is derived from a methodology-based approach.

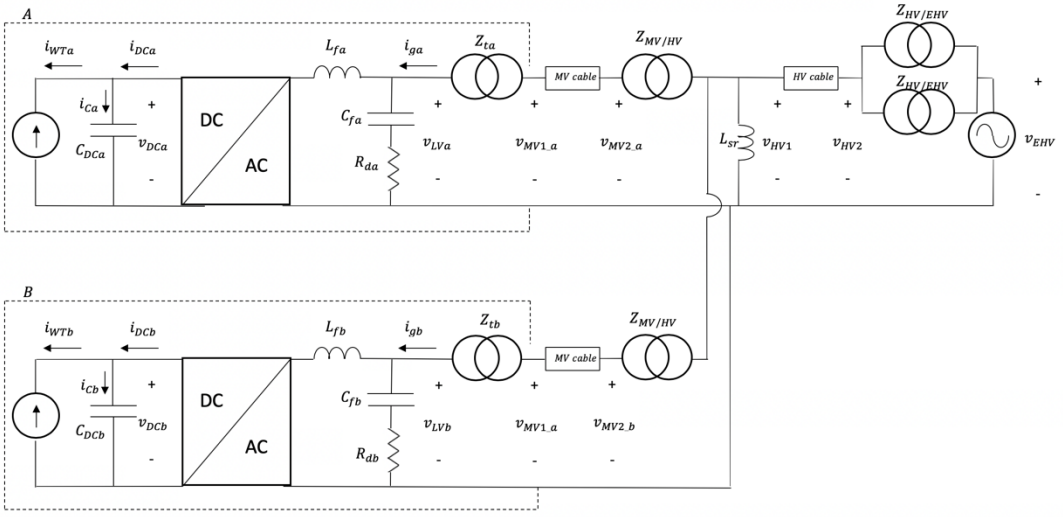


Figure 1 Illustration of the second system built in Matlab/Simulink

Figure 2 shows what the second benchmark system in Figure 1 is representing in reality.

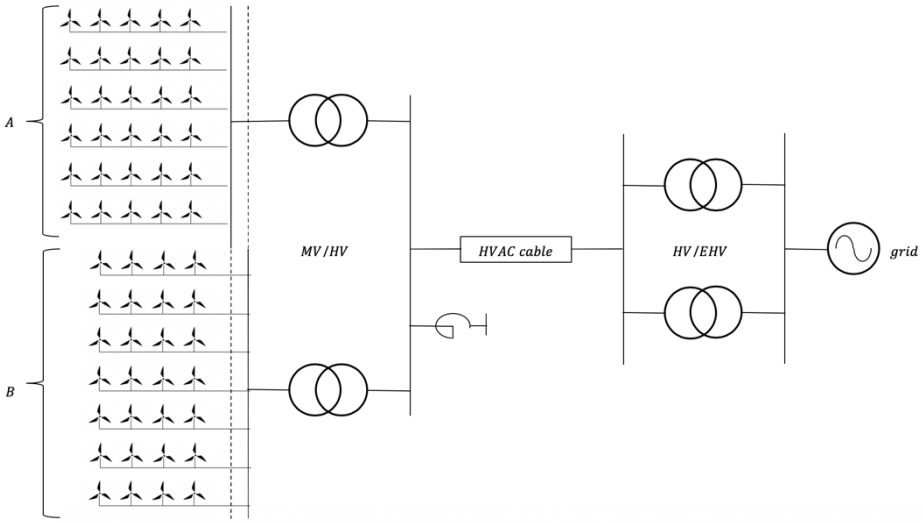


Figure 2 Illustration of what Fig. 1 is representing in reality

Conclusion

The modelling process revealed a challenge with the up-scaled representation of a single wind turbine with the chosen control strategy. The trouble, which introduced a tremendous amount of harmonic distortion to the system, is believed to originate from an increased difference in the energy storage capability of the filter inductors and filter capacitor. The problem was solved by adjusting the voltage level on the DC side of the converter. Investigation indicated that the reason for the successful adjustment of the DC voltage was a sufficient regulation of an uncontrolled power flow between the two converter sides due to the large filter capacitance. Seen from the grid, the representation of the filter impedance is adequate. However, the problem is not expected to be present in real-life applications as the wind farm in reality consists of many separate units with a much lower ratio between the inductance and capacitance. The finding is considered as a weakness with the model which is worth being highlighted and discussed.

A frequency sweep of the converter model under different operating condition showed a significant and hardly predictable variation in the impedance magnitude for frequencies below 200 Hz. In this region, the impedance was susceptible to all the various operating conditions applied.

Analysis of Conducted Disturbances from LED-Technologies

Student: **Christoffer Rojh Gundersen**

Supervisors: **Kjell Sand & Eilif Hugo Hansen**

Co-supervisor: **Henrik Kirkeby**

Collaboration with: **PQA AS**

Problem Description:

LEDs are luminaries which are expected to phase out the use of incandescent lightning, and they are in many ways regarded as superior to other lightning appliances because of its sparse energy-consumption. LEDs are however non-linear loads and the current they draw may be very distorted. In large Installations of lightning, these distorted currents may potentially cause unwanted problems with regard to power quality and electromagnetic compatibility. Traditionally only lower order frequency disturbances up to 2000 Hz has been in focus. Recent observations and research have however shifted the focus to higher order frequency components, especially the range 2-150 kHz. The special case about this frequency range is that it is more or less unregulated and it exist no clear limits for how large disturbances existing in the supply can be, and how much noise electrical appliances are allowed to generate. Several observations for this frequency range indicates that the framework below 2 kHz cannot simply be extended for higher frequency ranges.

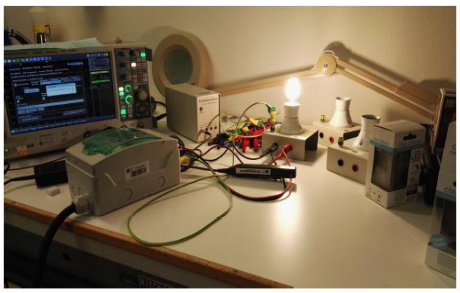
The Task:

This thesis further explores the differences between conducting analysis of low- and high-frequency disturbances from LED-Technologies, with respect to:

- Limitations in equipment
- Analyzing methods
- Measurement environment

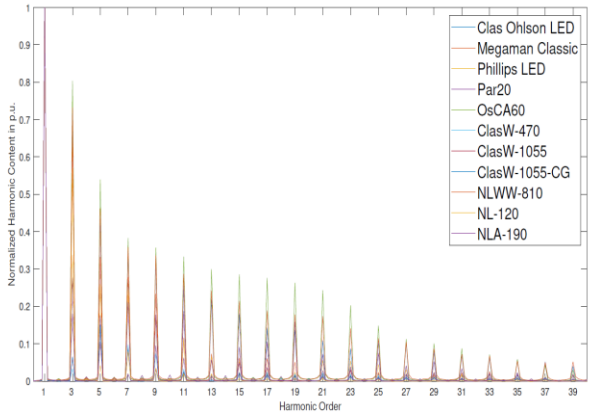
Model/Measurements:

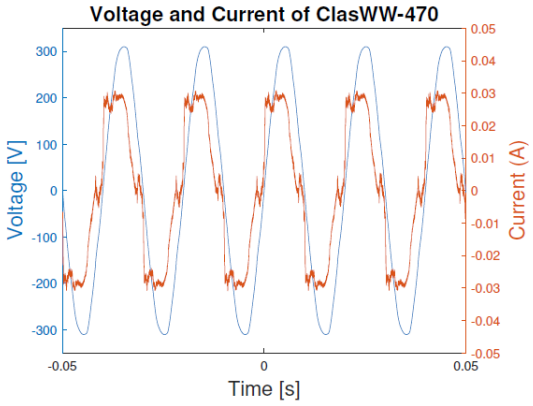
The study has been done in which measurements of retrofit LED bulbs has been taken and analyzed through both Fourier Transform and Short-Time Fourier Transform. It shows through the analysis that time-frequency distributions are necessary when the disturbances in the higher frequency range needs to be characterized.



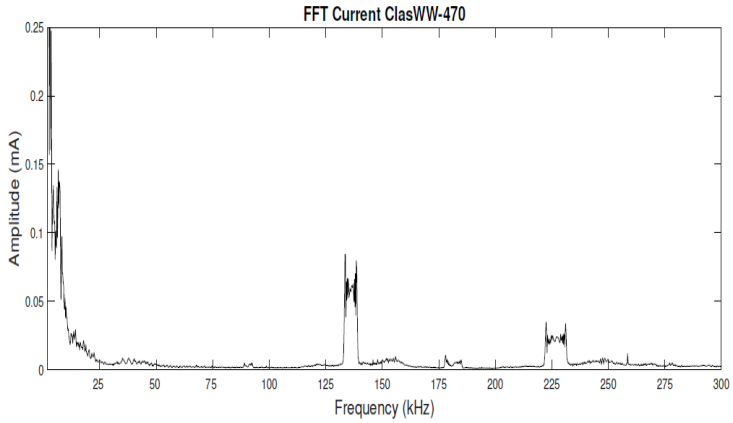
Results:

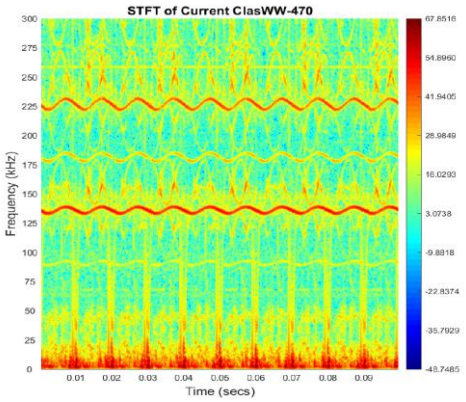
Results of the analysis by FFT of low-frequency disturbances indicate that odd-harmonics are mainly observed from the drawn current by an LED bulb.





High-frequency disturbances are however observable from some LEDs and these are shown as broadband-characteristics in the frequency domain. Time-frequency analysis may reveal these characteristics as frequency-varying components.





Conclusions

Low frequency phenomena emitted by LED consist mainly of harmonic components. FT is therefore effective for analysis of low-frequency phenomena from LED. Disturbances found in the higher spectrum may appear as broadband components in the frequency domain when FFT analysis has been applied. If the analysis is further extended in the time-frequency domain, these broadband characteristics reveal themselves as disturbances of dynamic character. The disturbances are likely introduced from the LED drivers and EMC-standards currently in use, do not account for these high-frequency characteristics. Also, instruments typically used for measuring EMI from lightning appliances cannot provide data for time-frequency analysis. Other measurement equipment and techniques for time-frequency analysis may therefore be needed in future practice for measuring EMI from various electric appliances.

Bruk av fleksibilitet i utformingen av nullutslippsbygninger

Student: **Sandra Annette Haagensen**
Veileder: **Karen Byskov Lindberg**

Problemstilling

Hensikten med denne oppgaven er å undersøke hva som er mest kostnadsoptimalt, og dimensjoneringen av de tilgjengelige energikildene, i en energieffektiv bygning.

Oppgaven

Nullutslippsbygning
Hva er forskjellen på om bygningen har krav eller ikke-krav til null utslipp av CO2 gjennom hele bygningens levetid?

Nullutslippsbygning med batteri
Er det økonomisk lønnsomt å ha et batteri installert i bygningen?
Hva påvirker om batteriet blir ladet/utladet?

Elektriske kjøretøy tilkoblet bygningen
Hvordan påvirker det bygningen når elektrisk kjøretøy er tilkoblet?

Hvordan to lagringsteknologier påvirker bygningen?
Dette skal undersøkes ved å utføre de ni scenarioene i tabellen:

Lagringsteknologi	Varmeteknologi
Varmelager	Varmepumpe Elektrisk kjele Fjernvarme
Batteri	Varmepumpe Elektrisk kjele Fjernvarme
Varmelager og batteri	Varmepumpe Elektrisk kjele Fjernvarme

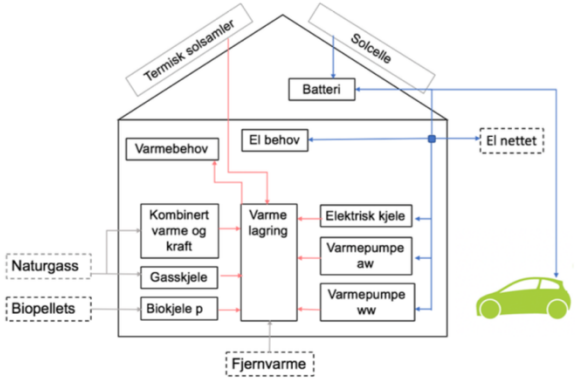
Modell

Om modellen:

- Modellen som brukes har blitt utviklet og løses i FICO Xpress.
- Modellen finner optimal energiløsning for bygningen.
- Den minimere de totale kostnadene gjennom hele bygningens levetid.

Om case studiet:

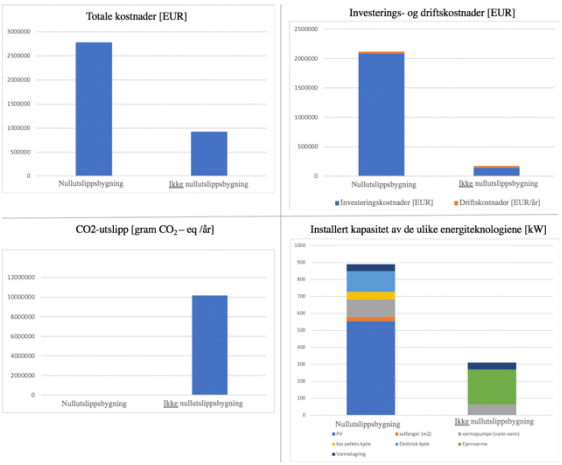
- Lokasjon: Drammen, Norge
- Bygningstype: Skole
- Levetid: 60 år
- Bygningsareal: 10 000 m2
- Energistandard: Passiv



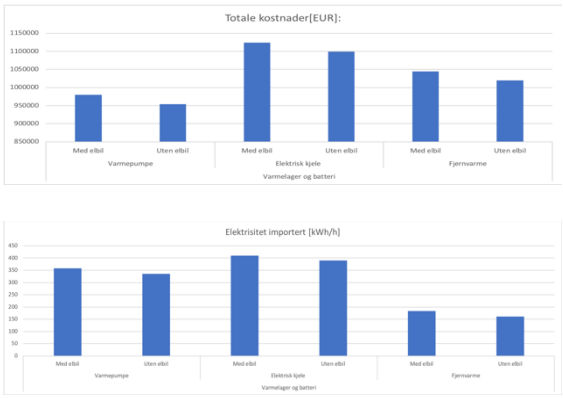
Figuren viser oversikt over alle teknologiene som er implementert i modellen

Beregninger

Nullutslippsbygning
Figurene viser forskjellen på om bygningen har krav eller ikke-krav om null utslipp av CO2:



Elektriske kjøretøy tilkoblet bygningen
Figurene viser hvordan bygningen blir påvirket når elektriske kjøretøy er tilkoblet? Her er det testet med ti kjøretøy.



Nullutslippsbygning med batteri
Det er ikke økonomisk lønnsomt å ha et batteri installert i bygningen.

Det som påvirker om batteriet blir ladet/utladet er variasjoner i prisen på elektrisitet som vist i figuren:

Hvordan to lagringsteknologier påvirker bygningen?
Figuren viser størrelsen på lagringsteknologier ved ulike Oppvarmingsteknologier:

Konklusjon

- Det er store forskjeller i kostnader og valg av energiteknologi om bygningen har krav eller ikke-krav til null utslipp av CO2.
- Det som påvirker kostnadene på batteriet er investerings- og driftskostnadene, levetiden og virkningsgraden.
  Batteriet blir oppladet når prisen på elektrisitet er lav, og utlades istedenfor å importere elektrisitet fra strømnettet ved høy pris.
- Skolebygningen blir i liten grad påvirket om ti elektriske kjøretøy er tilkoblet.
- Bygningen velger den lagringsteknologien som er mest økonomisk lønnsomt.

Enabling Flexiramp Capability in Unit Commitment Formulation

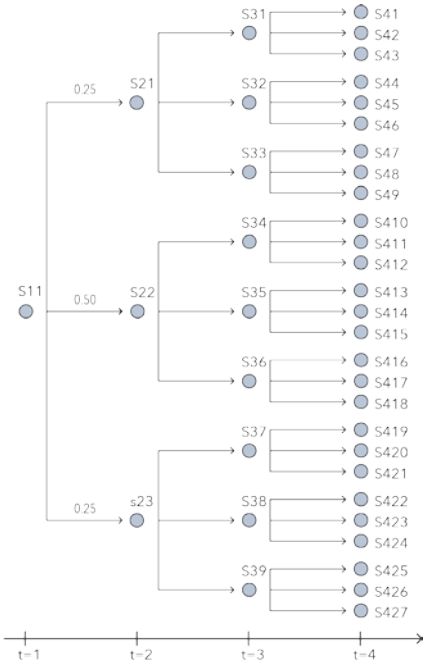
Student: **Magnus Aas Hagebø**
Supervisor: **Hossein Farahmand**

Problem description
Following the climate challenges, large investments have been done in renewable energy sources like wind and solar power. Every indication points to that this trend will continue as the cost of these technologies continue to decrease and become competitive to conventional power production. These intermittent sources introduce more uncertainty in the power system, as they are highly dependent on the weather conditions. Power systems needs to adapt to be reliable under these uncertain conditions by including more flexibility.

This thesis focuses on the flexibility resource of fast ramping units. They can be called upon to respond quickly to deviance in weather forecasts. Flexiramp products and markets have been introduced in the US as a mean to pay generating units that can provide this flexibility to the power system. This payment also acts as an incentive to invest more in flexible units.

The task
The aim of this thesis is to investigate and evaluate different approaches of including flexiramp in the Unit Commitment formulations used for electricity market clearing. This is done through implementation of existing formulations, one deterministic and one stochastic, and running case studies on a system of five generators.
The main contribution of the student is a new formulation of the Unit Commitment formulation that includes flexiramp markets and requirements in a stochastic approach.

Model/ measurements
The optimization models were implemented in Python/Pyomo, and a case study consisting of 5 generators during 4 time steps of 15 minutes were carried out. The models aims to maximize social surplus, while the generator operational limits are the main constraints. The stochastic models are based on the scenario tree seen below.



Going from one time step to the next, three different outcomes can occur. The net load of the system have a 50% chance of being equal to the forecast, and a 25% chance of either an overshoot or an undershoot. These possible variations in the net load requires the generating unit to be flexible in order to be able to meet the possible deviance of the forecasts.

Calculation
The models optimize the system in terms of generator dispatch, flexiramp provided, commitment status, etc. The output is a large number of decision variables, one per generator per node in the scenario tree. The main indicator of the performance of the models is the social welfare.

	SUC	DT (change)	SFUC (change)
Social welfare [10^3\$]	1589.3	-94.3	-1.0
Generator cost [10^3\$]	8	+1.4	+1.45

The table above shows the social welfare and generator cost of three different models. The Deterministic model (DT) and Stochastic Model with Flexiramp (SFUC) is compared to the benchmark model, the Stochastic Model (SUC).

Conclusion
The stochastic models perform much better in terms of maximizing social welfare when modelling uncertain systems. The new formulation of the Unit Commitment is able to retain the benefits of stochastic programming while at the same time provide transparent flexiramp markets and products.

Stability Assessment by Grid Impedance Method and Adaptive Control

Student: **Steinar Halsne**
Supervisor: **Gilbert Bergna-Diaz**

Abstract
In the last decades, the amount of power electronic converters in the electrical power grid has been growing rapidly. Increasing amounts of power is also being interfaced to the grid through such converters, as more and more renewable energy generation is included in the grid. The necessary increase in renewable power does, however, pose added challenges to the converters. This is because much of the renewable energy is being installed in a vast variation of grid conditions. There has been several accounts of unexpected instabilities in such systems. It is expected that resonance triggered between the converter and grid impedance is a likely cause of several of these events. Measures should be taken to avoid such unexpected instabilities if the desirable increase in renewable energy installation is to continue in a safe way.

One possible solution to assess this problem is the utilization of the so-called grid impedance method. In this thesis, the theoretical foundation of the grid impedance method is examined and explained. Based on this, a stability criteria is deduced. An important part of this stability criteria is knowledge of the equivalent impedance of the power system beyond the converter. For actual systems this impedance will be unknown and time-varying. Several possible methods for estimating this impedance are reviewed and the maximum length binary sequence method is selected, based on applicable criteria. The theoretical foundation of the grid impedance estimation method is examined and explained, before the method is implemented in both simulations and laboratory experiments. The grid impedance estimates exhibited a close match with theoretical values for simple simulations without constraints on sampling time or data-integrity. Furthermore, it was proven that the grid estimation method in its current form is not suitable for application in setups under the above data-integrity constraints. This does unfortunately also include the laboratory experiment. As a consequence of the former, it was decided that the stability assessment should be done exclusively by the use of theoretical values for the grid impedance to avoid false results. Under testing, the developed stability criteria, with theoretical grid impedance values, showed to be accurate within 16% of a real time simulation model. This was concluded to be acceptable as the simulation model contained elements present in actual systems, but which were not included in the analytical model. An original adaptive control procedure, based on the developed stability assessment, is also proposed in this thesis. The adaptive control is based on a graphical interpretation of the developed stability criteria. The proposed adaptive control performed well under testing as it improved the stability of the converter with minimal changes to its parameters.

Shipboard DC Microgird

Student: **Marius Ulla Hatlehol**
Hovedveileder: **Trond Leif Toftevaag**
Medveileder: **Mehdi Zadeh**
Medveileder bedrift: **Andreas R. Dahl**
Utføres i samarbeid med: **Kongsberg Maritime**

Problemstilling

In this master's thesis, the problem of actively stabilizing a DC Shipboard Microgrid will be addressed by proposing a modified sliding mode controller.
I denne masteroppgaven undersøkes mulighetene for aktivt stabilisere et DC mikronett ved hjelp av en modifisert ''sliding mode controller''. Oppgaven går ut på følgende:

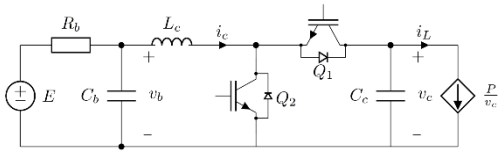
• Gi et kort overblikk over DC skipssystemer og utfordringene relatert til stabilisering av spenningen
• Foreta litteraturstudie basert på nøkkelord knyttet til aktiv stabilisering av DC mikronett ved hjelp av sliding mode control.
• Modellering av det studerte mikronettet
• Foreslå og implementere en modifisert sliding mode controller for the utledede modellen.
Dette inkluderer

1. Utleding av kontroller
2. stabilitetsanalyse
3. simulering

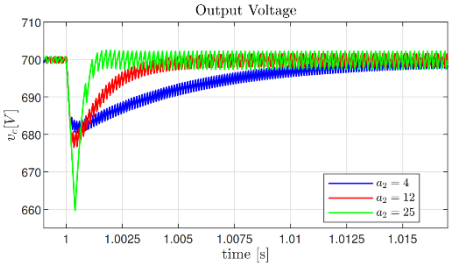
- Evaluere kontrollerens ytelse mot DNV GL's krav til elektriske installasjoner i skip.

Oppgaven

Målet med oppgaven er å aktivt stabiliserte et DC mikronett ved hjelp av en sliding mode controller. Lineære PID kontrollere klarer ikke å stabilisere systemet i det store bildet, derfor trenger en ulineære kontrollere.
Oppgaven går ut på å modellere et forenklet mikronett som på figuren under:



Dette gjøres ved bruken av gjennomsnittsverdi-modellering.
Deretter utledes kontrolleren basert på modellen, og testes ved forskjellige forsterknigsverdier og initalverdibetingelser



Konklusjon

En modifisert sliding mode controller er implementert for den forenklede modellen. Denne har de nødvendige ytelsene satt av systemet som fremkommer i beskrivelsen.
Som det går frem av resultatene, greier den modifiserte sliding mode kontrolleren å stabilisere nettet innenfor regelverket satt av DNV GL.

Dynamic Rating of Power Cables Based upon Transient Temperature Calculations

Student: **Markus Heggås**
Supervisor: **Erling Ildstad**

Problem description

Existing current rating methods are generally based on worst case assumptions of weather conditions (high ambient temperature) and steady-state loading (100% load factor). Due to large thermal masses, variations in ambient conditions and the fact that steady-state loading is seldom applied, it is often feasible to overload power system components to some extent for a certain amount of time. In this sense, the ampacity of power system components, such as power cables, can be considered dynamic.

Scope

The task of the thesis was to investigate:

- How well do transient temperature calculations from an analytical modeling approach compare with a numerical model made in COMSOL?
- For how long and to what extent may the cable be overloaded without violating temperature limits of the conductor?
- How will the cable lifetime be affected by additional aging of the insulation material due to excessive heating caused by overloading?
- How can information about sheath temperature, loading history and ambient temperature be utilized to estimate transient conductor temperature for dynamic rating of a cable?

Modeling

An analytical thermal model was developed according to the IEC standards for rating of power cables. To appraise the results from the analytical modeling approach, a numerical model in COMSOL Multiphysics is developed for comparison.

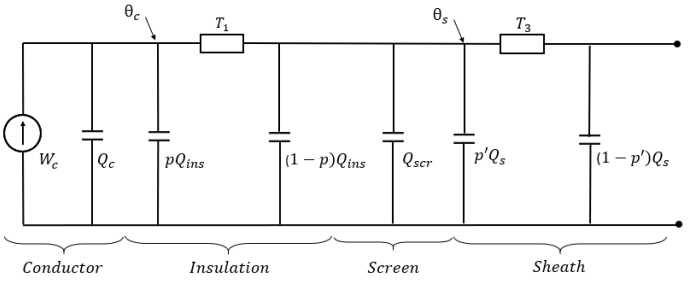


Figure 1 Thermal equivalent for the analytical modeling

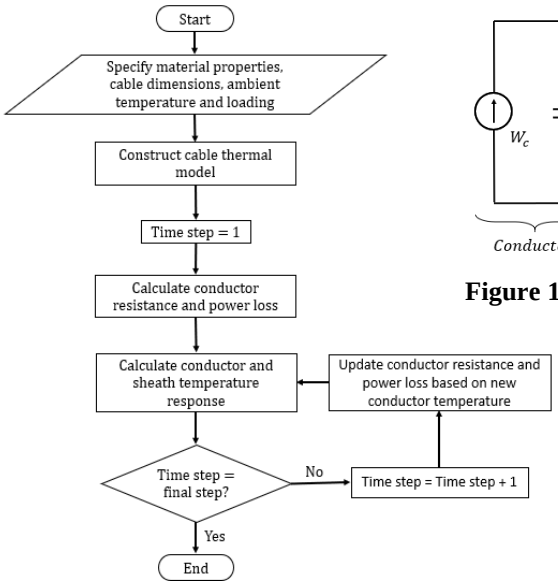


Figure 2 Flow chart for the analytical approach

Results and conclusions

In this thesis, several simulations are performed with an analytical thermal model developed according to the IEC standards for rating of power cables. The key findings of the thesis are:

- Transient temperature calculations from the analytical model compare well with the numerical modeling in COMSOL. In case of a step load of rated current, the largest deviation in computed conductor temperature was only 2 °C. Moreover, the results show that largest deviation occurs approximately 30 minutes after a change in applied current.

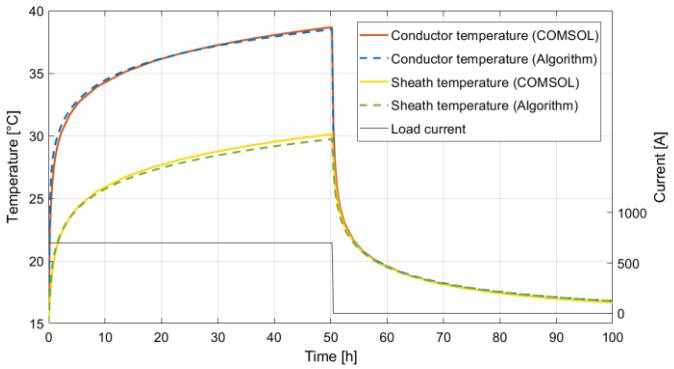


Figure 3 Comparison of analytical algorithm and COMSOL

- Choosing appropriate values for soil properties has larger impact on the accuracy of temperature calculations than the approximations made in the analytical model.
- The analytical algorithm only allows for one current step at a time. To obtain the total temperature rise due to a load profile consisting of multiple current steps, the temperature rise caused by each individual current step is added manually by the principle of superposition. This process could preferably be developed to a more automatic procedure.
- The results show that interpretation of sheath temperature measurements can be useful for estimating conductor temperature. Such information may be obtained by measuring the time derivative of sheath temperature.
- It can be concluded that permitted overloading time period will vary with applied overload current, conductor temperature limit and load history. In the case of an initial load of rated current and a 90 °C conductor temperature limit, an overload current of 60% can be applied for 30 hours. Due to large thermal time constants of the soil, permitted overloading time period will be increased manyfold when the conductor temperature limit is extended to 100 °C and 110 °C.
- Based on the overloading case examples, the additional aging caused by increased temperatures was estimated. In the case of an overload current of 83% applied for 24 hours, the cable lifetime was reduced by approximately one month. This is only 0.2% of the total expected cable lifetime of 40 years.
- Moreover, it is shown that a 10 °C step change in air temperature lasting for 100 hours will only increase the soil temperature at burial depth with 1 °C. This slow impact of air temperature at burial depth justifies that variations in air temperature can be neglected during transient overloading. However, seasonal temperature variations at burial depth should be considered as it is shown that a buried cable can be overloaded for a longer period during winter conditions.

Thermal Design of Solid-State Circuit Breakers for MVDC Grids

Student: **Mikkel Heiene**
Supervisor: **Dimosthenis Peftitsis**
Andreas Giannakis

Problem description

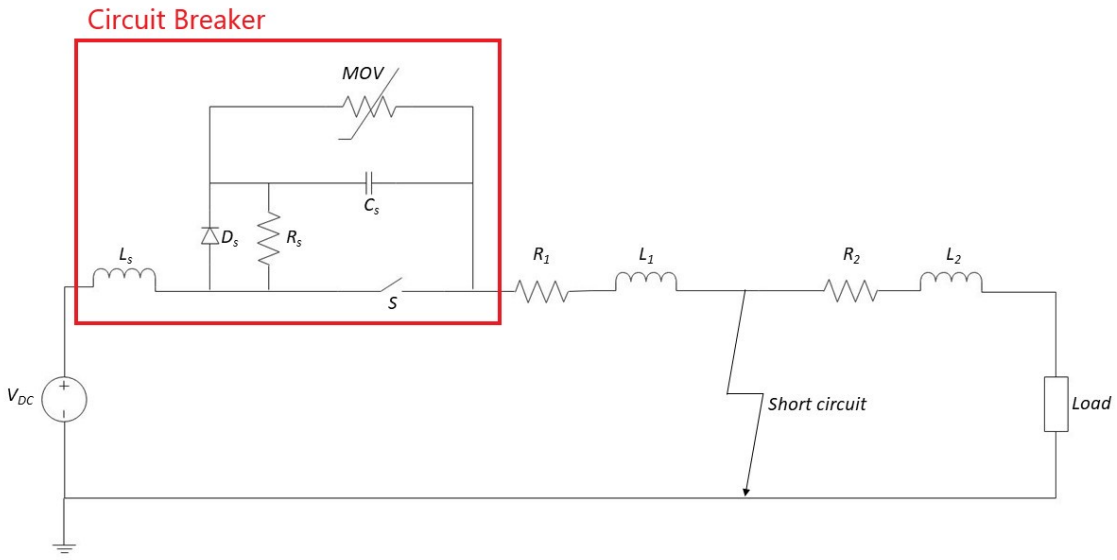
Design and optimization of a MVDC circuit breaker is a critical stage in implementing MVDC grids for future power systems. An important part of this process is the thermal design. Solid-state circuit breakers suffer from high conduction losses and subsequently heat generation, which must be efficiently dissipated to the environment.

The task

The purpose of this paper is to investigate the thermal design of a solid-state circuit breaker for MVDC grid application. The big drawback of the circuit breaker type is the high conduction losses, which in turn complicate the thermal management of the circuit breaker. Different power electronic devices will be analysed for circuit breaker applications, and the specific requirements of cooling systems will be investigated. Additionally, an overview of related aspects of MVDC grids and electrical performance of the circuit breaker will be provided.

Method

The analysis is done through a literature study of current technologies, and MATLAB/Simulink simulations. Below is shown a figure of the studied MVDC grid and circuit breaker.



Conclusion

The superior performance of the Insulated Gate-Commutated Thyristor (IGCT) is shown from a comparative study of the investigated devices under different system operating conditions. The analysis of thermal management considers liquid cooling systems to be the most promising concept, while forced air cooling may be beneficial for certain applications.

Optimal plassering av sekundærreserver

Student: **Elisabeth Haslerud Helgesen**
Faglærer: **Olav Bjarte Fosso**

Sammendrag
For å opprettholde frekvensnivået i kraftsystemet er det nødvendig å kunne regulere produksjon på kort varsel. Reservemarkedet brukes til å utføre denne reguleringen, ved at systemoperatør kan justere produksjon ved kraftverk etter avtale med et kraftselskap.

For vannkraftprodusenter kan det være lønnsomt å inngå en slik avtale med systemoperatør. Kostnader av en slik avtale vil være tapt inntekt fra spotmarkedet ved høye strømpriser, og uønsket forbruk av vann ved lavere priser.

Ved inngått avtale om levering av volum til reservemarkedene er det interessant for kraftselskapet å finne den minst kostbare kombinasjonen av kraftverk å holde av effektvolumet ved. Fordi den tapte inntekten fra spotmarkedet er lik uavhengig av enheten volumet plasseres ved, vil optimal kombinasjon være mulig å finne ved å beregne hvilke kraftverk som gir laveste kostnad basert på vannforbruk og vannverdi ved enhetene. I denne avhandlingen ble dette gjort ved å beregne kostnader per MW som følge av vannforbruk. Aktivering av sekundærreserver (aFRR) på minuttoppløsning er beregnet som et gjennomsnitt av historiske data fra samarbeidsbedrift.

Case som ble utført bestod av tre kraftverk, og totalt åtte enheter. Datoen 13.01.2019 ble benyttet og inputverdier ble basert på data fra samarbeidsbedriften, for produksjonsplan, vannverdier, vannstand og målinger av vannføring.

Resultatet ble å beholde initiell kjøreplan, men å endre magasin ved ett av kraftverkene. Kostnaden som følge av vannforbruk ville ved initiell kjøreplan og ingen aktivering ha et gjennomsnitt på 48,9 EUR/MWh, høyeste kostnad lik 50,4 EUR/MWh og minste kostnad lik 46,8 EUR/MWh. Etter justert plan og medregnet aFRR aktiveringen ble kostnaden beregnet til å ha et gjennomsnitt på 48,1 EUR/MWh. Med høyeste kostnad lik 50,0 EUR/MWh og laveste kostnad lik 45,4 EUR/MWh.

Resultatene viste seg å være sterkt avhengige av initiell spotplan, vannverdi og virkningsgrad.

Effect of SF6-alternative gas on the dielectric breakdown strength in load break switches

Student: **Trygve Helseth**
Faglærer: **Frank Mauseth**

Sammendrag
Det moderne kraftnettet inneholder stadig fler fornybare energikilder. Dette er svært gunstig for klimaavtrykket til samfunnets elektriske energiforbruk, men det gir også noen nye utfordringer. Overgangen til fornybare energikilder krever et mer fleksibelt og kontrollerbart strømnett. Den nøyaktige topologien til neste generasjons distribusjonsnett er fortsatt ubestemt, og ikke innenfor denne oppgavens omfang, men det vil mest sannsynlig inneholde en utbredt bruk lastbrytere. På steder der det allerede er begrenset plass, vil størrelsen på lastbryterne, og generelt for alle elkraftkomponenter, spille en stor rolle. For å oppnå kompakte løsninger har kraftindustrien siden 1970-tallet vært avhengig av bruk av svovelheksafluorid-gass (SF6). SF6-gass har omtrent tre ganger den dielektriske holdfastheten som atmosfærisk luft, dette gjør det mulig å produsere mye mindre utstyr for samme belastningsevne. Utmerkede termiske egenskaper gjør også SF6 til en ideell gass for bruk i brytere. Men dagens utbredte miljøfokus har kastet lys over problemene knyttet til bruken av SF6-gass i elektrisk utstyr. På grunn av et globalt oppvarmingspotensial (GWP) på 22800 ganger CO2, er alternative løsninger til bruk av SF6 svært attraktive. Alternative gasser som tilbyr lignende egenskaper som SF6, men uten den høye GWP, har kommet til markedet de siste årene. Industriselskaper som ABB, Siemens, og 3M tilbyr alle alternative gasser.

I denne masteroppgaven ble den statiske dielektriske holdfastheten til ABBs AirPlus-gass testet på et generisk "pin & cup" kontaktpar. Flere forskjellige parametere ble undersøkt. En økning i luftgap fra 6 mm til 10 mm førte til en økning i U16% holdfastspenningen på 30,87% eller mer for alle oppsettene. For konstant avstand og en trykkøkning fra 1 bar til 1,3 bar var den resulterende økningen i U16% holdfastspenningen 23,60% eller høyere for alle tilfeller. Effekten av AirPlus gass sammenlignet med teknsik luft ga en økning i U16% holdfastspenningen på 55% eller mer for alle konfigurasjoner. Disse resultatene indikerer at AirPlus kan være en viktig faktor i utviklingen av kommende generasjons kompakte lastbrytere.

Eksperimenter ble også utført for å utforske sammenhengen mellom statisk og dynamisk holdfasthet i atmosfærisk luft. Det ble ikke funnet en tydelig og generell sammenheng mellom de to i testene utført under denne oppgaven.

Next Generation High Voltage Subsea Transmission Cables: Influence of electric field, NaCl impurities and thermal cycling rate on insulation lifetime

Student: **Jordan Henry**
Supervisor: Frank Mauseth, Sverre Hvidsten
Contact: **jordanh@stud.ntnu.no**
Collaboration with: **SINTEF**

Problem description

In order to develop dynamic wet power cables with a competitive operational life, a greater understanding of water tree initiation and propagation must be ascertained. The goal of this master thesis broadly speaking has been to shed light on the following areas:

• To find if the rate of thermal cycling experienced by XLPE leads to a degradation in the material's ability to withstand voltage.

• To investigate how the rate of thermal cycling interacts with small droplets of sodium impurities trapped with XLPE, as well as, various voltage levels during material aging.

• To learn how thermal cycling in conjunction with the aforementioned factors influences water tree inception and propagation within XLPE.

Model/ measurements

An experimental setup was developed inside a Votsch Industrietechnil VC 3 4034 climate chamber to age the test objects over a three week period. The experimental set up was capable of cycling the test objects in batches of twenty from 90^{o}C to 50^{o}C. Three sets of aging experiments were performed and within each batch ten test objects were energized to both 10 kV/mm and 3 kV/mm. The first experiment was performed at a cycling rate of 1^{o}C/min and cycled thirty five times. The second, was performed at a cycling rate of 0.1^{o}C/min and also experienced thirty five cycles. The third aging experiment was performed at a constant 90^{o}C/min over the entire three week duration. All other experimental aspects including the test objects themselves were identical. Once the aging experiments had concluded breakdown testing was applied to all sixty test objects. The breakdown testing was done in blind fashion where the aging parameters were unknown to the experimenter until a breakdown had occurred. The breakdown testing was executed with a 50 Hz AC voltage source and a 220 V/100 kV transformer. The voltage was applied in 2 kV steps and allowed a settling time of two minutes between voltage steps

Calculation

The breakdown testing revealed a substantial 29.21 % degradation of the median breakdown voltage in objects cycled at 0.1^{o}C/min compared to those aged at a constant 90^{o}C. Both sets of objects compared were aged at 10 kV/mm with NaCl inclusions. The median breakdown voltage was further reduced when the thermal cycling rate was increased from 0.1^{o}C/min to 1^{o}C/min, however, this time by only 10.02%. All sixty test objects experienced water tree initiation and growth during the aging process. The length of the longest water tree, as well as, the qualitative water tree density were observed to increase

with the rate of thermal cycling. Several large cavities were discovered throughout the samples at the NaCl inclusions points. These deformations were found in samples aged at both thermal cycling rates. Cavities found within samples aged at a thermal cycling rate of 1^{o}C/min were found to be more rigid and abnormal in structure with a higher rate of water tree inception and propagation. Four out of ten test objects, charged at 10 kV/mm with NaCl inclusions, suffered a breakdown before the aging duration had culminated. Upon inspection of the affected objects water trees were discovered around where breakdown had occurred. This has led to the assertation that water is likely to have completely bridged the 700 μm insulation.

Conclusion

Therefore it has been deduced from experimental observations that increasing the rate of thermal cycling allows for increased water tree inception and propagation rates. This in turn has been observed to lead to higher maximum bow-tie tree lengths of up to 97 % when thermal cycling is increased from 0.1^{o}C/min to 1^{o}C/min. Additionally, increasing the thermal cycling rate has been qualitatively linked to increased water tree densities. Which greatly diminishing the insulation's serviceable lifetime as seen by the degradation of median BD voltage in thermal cycled test objects. Finally, it was observed that in test objects cycled with sodium chloride inclusions at 0.1^{o}C/min compared to those held at a constant 90^{o}C experienced a decrease of the median breakdown voltage level of 29.21% a much more significant degradation than the 10.02% decrease between 0.1^{o}C/min to 1^{o}C/min. This lends weight that any thermal cycling activates the wetting of the sodium chloride while the cycling speed enhances the rate at which it is dissolved

Energy Storage for Reinforcement of a High Voltage Distribution Grid

Student: **Vebjørn Hjelle**
Supervisor: **Trond Toftevaag**
Collaboration with: **Stryn Energi AS**

Problem description

The objective of this project is to investigate if energy storage is a viable option to traditional grid reinforcement of the 22 kV distribution system in a rural area consisting of cottages. To do this, a simulation model of a given power system is developed in PowerFactory. Further, relevant reinforcement alternatives are added to the model, including a battery energy storage system which provide peak-shaving. The model is used to analyse the reinforcement alternatives for different load situations. Then an economic assessment of the reinforcement alternatives is conducted.

The task

The area consisting of cottages have the last couple of years experienced rapid expansions, and the consumer mass is expected to continue its growth. As the grid connection is considered to be weak, the growing load demand might become a problem for the supply. Some kind of reinforcement is expected to be necessary at some point. This project investigates the possibility of using a battery system for decreasing the loading of the supply lines and compares this to refurbishment of the lines and adding an additional supply connection.

Model

A model of the 22 kV power system was developed in PowerFactory based on the real data of the area. Four alternatives were implemented, including doing nothing to the grid, refurbishing the existing connection, adding a connection, and adding energy storage. The energy storage facility was implemented with a peak-shaving algorithm. It therefore discharges when the load demand is high, and charges during low-demand periods. Two load scenarios were simulated in the model. One where a planned expansion stage of the area was implemented, and one where the existing supply became critically loaded.

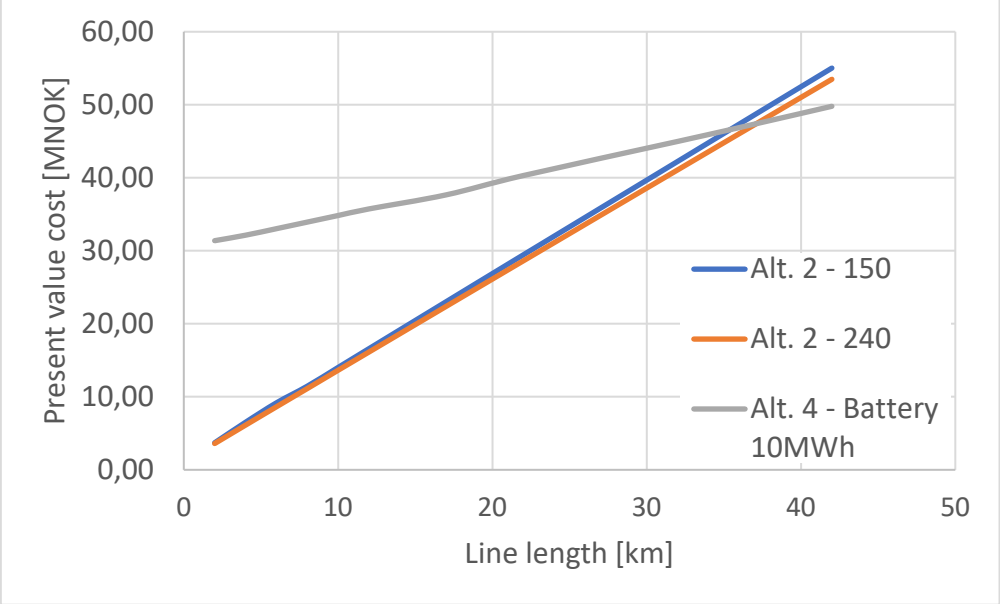
The economic analysis is done for a 30-year analysis period, where investment cost, cost of losses, and O&M costs are included for all alternatives.

Calculation

The simulations show that energy storage is able to provide the necessary power during peak demand to mitigate congestion in the grid, but that a large energy capacity is required due to the prolonged high-demand period. When the load demand incurs a maximal loading of 97% in the existing supply, a battery of 1.2 MW/10 MWh is able to reduce the loading to 80% during the entire simulation period. Lower loading, and losses, are however obtained when the supply lines are replaced, or a new cable connection is constructed, implying that these alternatives might be technically more robust than a battery alternative.

For the critical load scenario, the total discounted cost showed to be lowest for the alternative of replacing the existing supply with new cables. This had a present value of 3.61 MNOK, while the battery alternative had a discounted cost of 31.55 MNOK for the analysed system. The large cost of the battery is due to the very high investment caused by the 10 MWh

necessary energy capacity, which amount to 28.97 MNOK based on a total battery system cost of 331 $/kWh. The cable replacement in this specific case is only 2 km, making the alternative cheap. Therefore, a sensitivity analysis is done where the length of the supply connection is increased. With current battery costs a battery investment is shown to be economically beneficial when the length of cable needing replacement exceeds 37 km, while it is found to be 17 km when using an estimated future cost of batteries of 155 $/kWh.



Conclusion

For the given power system, a traditional reinforcement technically seems like a more reasonable alternative than installing battery storage. This causes both lower losses and a decreased loading of the lines. The simulations do, however, show that battery storage is a technically viable alternative in special cases for peak-shaving. By adding other services, such as e.g. backup power and voltage support, the battery alternative might prove to be more appealing.

During the economic analysis it is found that a battery installation is not an economically viable alternative for the given system, due to the energy capacity resulting in an expensive capital investment. The huge capacity is needed because of the long high-demand period that occurs for the cottage consumer group. For areas having a very long supply connection that needs to be replaced, the battery alternative might show to be economically desirable. This study has, however, only investigated the peak shaving benefits of the battery, meaning that additional services may increase the economic benefit also for shorter supply line lengths.

Optimal PV Inverter Active and Reactive Power Control in Distribution Grids With High Amounts of Solar PV

Student: **Hjelme, Oda Andrea**
Supervisor: **Korpås, Magnus**
Co- Supervisor: **Zaferanlouei, Salman**

Abstract

Photovoltaic solar panels are being installed in low voltage distribution networks at an increasing rate. This brings new challenges to the power system operators. In particular, large amounts of distributed generation give rise to technical issues such as overloading of the power network cables, overvoltages and thus lower power quality. In hours of high generation, overvoltage problems can be avoided by curtailment of active power generation or by reactive power absorption in the photovoltaic inverters. In turn, smart utilization of photovoltaic inverters can increase the distribution network's hosting capacity for distributed active power generation.

In this thesis, control of photovoltaic inverters for overvoltage mitigation in a low voltage distribution grid in Steinkjer, with high amounts of photovoltaic power generation is studied. An optimal power flow optimization model is built and simulated using GAMS (The General Algebraic Modeling System). Optimal set-points for photovoltaic inverter active and reactive power outputs are found by minimization of four different objectives: (i) network active power losses, (ii) voltage deviations, (iii) photovoltaic active power curtailment, and (iv) overall active power losses (network and curtailment).

The main results reveal that control of photovoltaic inverters is effective for overvoltage mitigation and for increasing the distribution grid's hosting capacity for distributed generation. Active power curtailment for overvoltage mitigation results in the lowest network active power losses. Reactive power control eliminate the need for active power curtailment. The network losses are increased compared to active power curtailment due to the reactive power absorption and higher active power generation. The distribution grid can tolerate higher amounts of active power generation with regards to overvoltages compared to overloading of the power cables. The overloading is increased by adding reactive power control to the inverters. This is due to increased reactive power line flows.

Sensitivity analysis on upper voltage limits show that reductions in overall active power losses (network and curtailment) can be obtained by accepting higher voltage variations. This is because by allowing higher voltages, the reactive power line flows and the required amount of curtailed active power generation can be reduced. Thus, one should carefully consider the consequences when setting absolute voltage boundaries.

Advanced gate drivers for next generation high power converters

Student: **Håvard Lefdal Hove**
Supervisor: **Dimosthenis Peftitsis, Ole Christian Spro**
Contact: **Giuseppe Guidi**
Collaboration with: **SINTEF Energy Research**

Problem description

Compared to traditional semiconductor materials such as silicon (Si), new wide band-gap (WBG) devices such as the silicon carbide (SiC) MOSFET offer higher blocking voltages, lower on-state resistance, faster switching transients and operation under higher temperatures. This increases the requirement for the gate driver design as high precision and low parasitics are vital to be able to act on the fast switching transients. This master thesis investigates advanced gate driver topologies for WBG semiconductor devices with focus on the SiC MOSFET.

Modeling and simulation is an important tool when designing power electronic converters employing WBG devices. Therefore, simulation models must provide accurate and reliable results and converge easily. However, the manufacturer of the SiC MOSFET that is used in this master thesis provides a non-continuous SPICE model for the device that often tends to run into convergence errors. Improvements are therefore suggested.

Model/ Method

A new gate driver topology that aims for delay time minimization, termed the multistage driver, is proposed and validated through laboratory work. The multistage driver is voltage controlled, which is more robust than timing-based gate drivers for fast switching devices. The obtained reduction in delay times are transferred to a simulation case of a motor drive application to investigate the impact from delay time minimization gate drivers.

For the SPICE model, improvements to the internal model structure is proposed to provide a continuous behaviour.

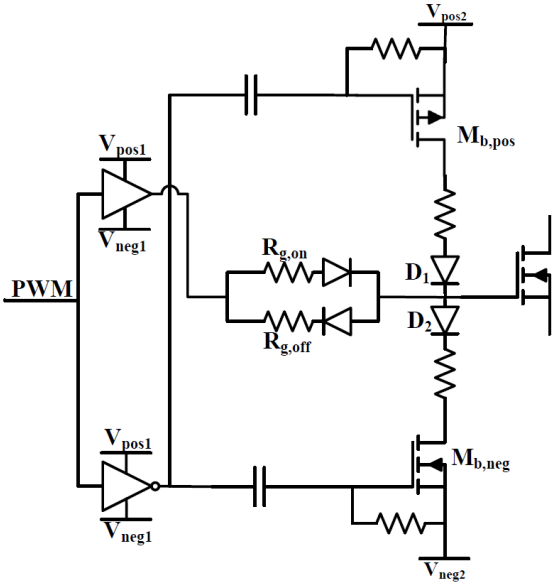


Fig. 1: Multistage driver

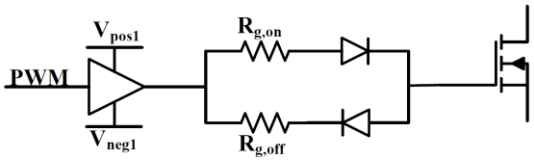


Fig 2: Conventional gate driver

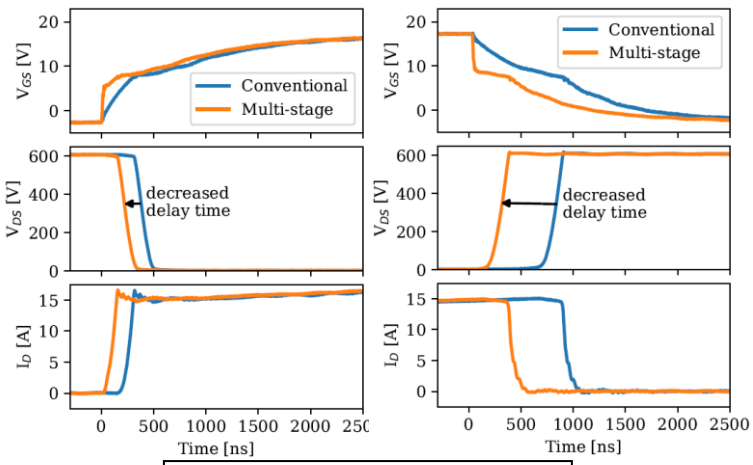


Fig 3: Switching waveforms

Calculation/Results

The delay times obtained with the different gate drivers are shown in figs. 4 and 5 for turn-on and turn-off transients respectively.

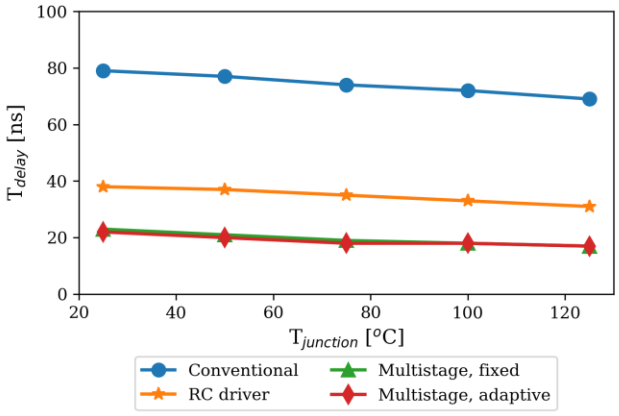


Fig 4: Turn-on delay times

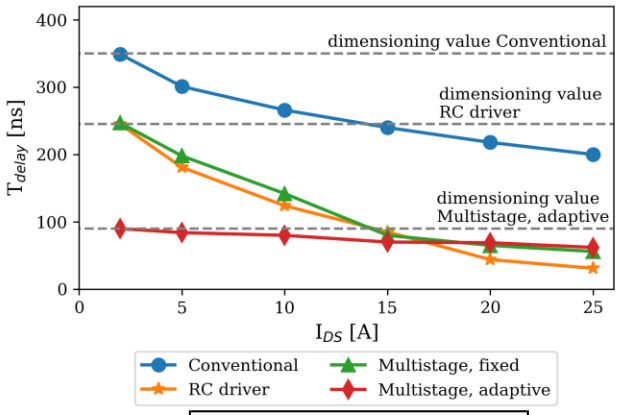


Fig 5: Turn-off delay times

Fig. 6 shows the transfer characteristics for the initial and the proposed SPICE SiC MOSFET model. The initial model is non-continuous while the proposed model is continuous, hence improving convergence.

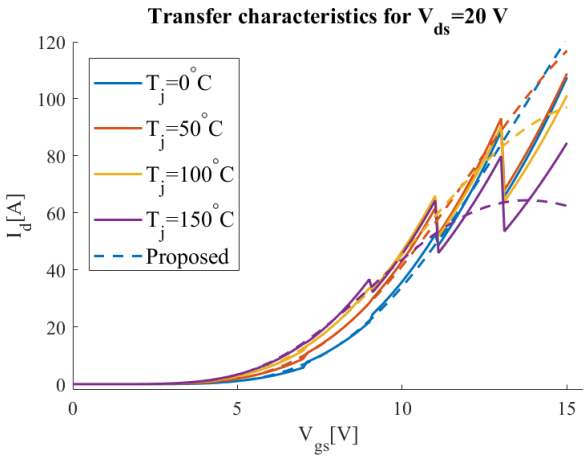


Fig 6: Improved SPICE model

Conclusion

By making the multistage driver adaptive based on load current and junction temperature, the best possible reduction in delay time can be obtained. Compared to a conventional gate driver (CGD), the adaptive multistage driver reduces the turn-on delay time by 72 % and turn-off delay time by 74 %.

By using a delay time minimization gate driver in a converter bridge leg, the requirements for dead time and minimum pulse width can be reduced. A motor drive application is simulated. When using the multistage driver, compared to CGD, the simulation results suggest that the linear modulation region can be increased by up to 3.8 %, and the current THD in the linear region reduced by up to 7.7 % when switching at 15 kHz.

Algorithm for efficiency support

Student: **Eivind H. Hovland**
Supervisor: **Trond Toftevaag**
Contact:
Collaboration with: **Kongsberg Maritime**

Problem description

Enhanced efficiency in the operation of marine vessel power systems promises reduced environmental impact and economical cost. However, uncritical operation of the system may not give optimal total efficiency across the full operational profile. Flexibility in configuration, in vessels with several producers and consumers, offers possibilities to adjust the system to the operating condition. Calculating the overall efficiency may be tedious to a human operator but feasible for computers. Such algorithms can both increase operator awareness and facilitate autonomy

The task

- Giving a brief introduction to marine power system with emphasis on system composure and energy production
- Give a detailed explanation to the marine EMS with emphasis on problem definition, objectives like energy reduction and generation scheduling.
- Build a new optimization model based with the objective of minimizing the power delivered to load.
- Simulate the system operation with the proposed optimization algorithm in system without ESS and where propeller dynamics are included
- Simulate the system operation with the proposed optimization algorithm in system with ESS with 24 hour varying load demand.

Conclusion

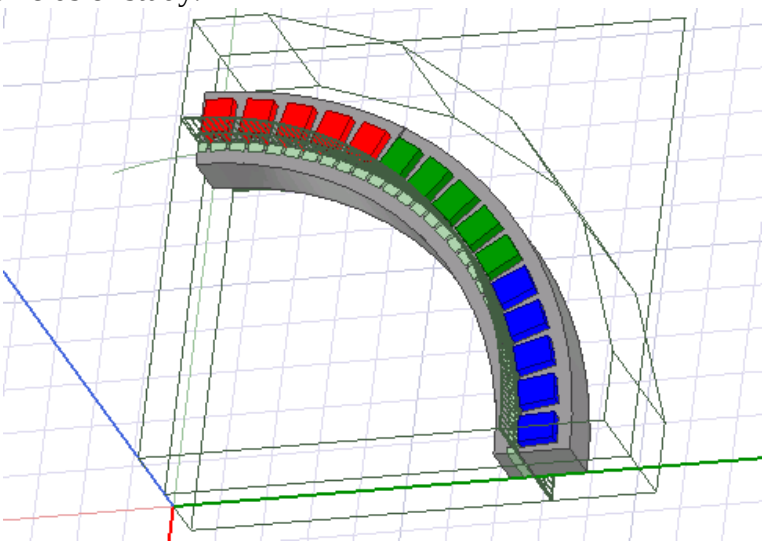
Shipboard power system efficiency improvements include various aspects and a wide range of disciplines. Implementing energy storage systems(ESS) into the modern power system, make the marine vessels highly depended on having a robust control system which can ensure efficient and sustainable system operation.

Segmented Stator of a PM Machine with Concentrated Windings

Student: **Marta Karoline Husebø**
Supervisor: **Robert Nilssen**

The energy sector is in transition. More renewable energy sources are integrated in the existing transmission grid and new large transmission lines are built to increase the flexibility of the network. HVDC is considered as one of the options for new international transmission in Europe. A modular HVDC, ModHVDC, generator is suggested as an option for better integration with the potential future HVDC grid or existing networks. A modular generator differs from conventional ones by having the stator divided in to modules, with air gaps between them. Each segment is connected to the DC potential of the power electronics, providing a higher induced voltage than conventional machines. The ModHVDC generator has several environmental and economic benefits, making it a good candidate for future applications. However it might have some electromagnetic drawbacks that are looked into in the thesis.

As a part of a European project at NTNU, a modular generator is going to be designed and build. To start, the electromagnetic properties of modular machines are going to be investigated in the thesis. Three types of modularity are going to be compared in terms of the magnetic field, torque ripple and losses. The machines are a conventional non modular machine, the same machine divided into two segments of the stator, and one with four segments as well. FEM software is used to simulate the machines at no load and loaded conditions to obtain comparable results. The modeling was done in 3D due to cooperation between different fields of study.



An increase in the magnetic flux density of the stator tooth with the air gap was found. Modularity also lead to an increased torque ripple of the machine, however the ripple was still small compared to nominal torque of the machines. The core losses were higher for the segmented machines, and the rotor and permanent magnet losses were higher for the non-modular machine. The unsegmented machine had the highest total loss at loaded conditions. Generally it was concluded that the majority of the results were not accurate enough to be confident about the findings, especially for the generator with two segments. The 3D modeling software provided too many limitations to obtain results of sufficient accuracy.

Development and testing of a Home Energy Management System control structure for a Norwegian household prosumer during high-demand conditions

Student: **Jens Høen Hval**
Supervisor: **Eilif Hugo Hansen**
Co-supervisor: **Kjell Sand**
Collaboration with:

Abstract

As the peak power consumption is expected to gradually increase during the next decade, electricity grid operators must invest in order to guarantee the grid's ability to handle the increasing power peaks. These investments are costly, and it is therefore expected that the grid tariff imposed on electricity consumers will increase. To facilitate this, the Norwegian Water Resources and Energy Directorate (NVE) proposed in 2017 to change the grid tariff structure, going from an energy-based tariff to a capacity-based tariff. By this tariff, electricity consumers will subscribe to an amount of power capacity, and if exceeding this capacity, this over-consumption will be extra costly for the consumers. If this tariff is being put into place, Norwegian households might want to invest in Home Energy Management Systems that can control the household demand as not to exceed the limit given by the subscribed capacity. This is also facilitated by the installation of smart energy meters in Norway, which provide data on electricity use as frequent as every 2.5 seconds.

The work in this thesis involves the development of a Home Energy Management System control structure, or algorithm, that can perform load controlling actions to avoid over-consumption. The time of year when over-consumption is most likely to happen is during winter, when the demand for heating is largest. By utilizing the demand flexibility offered by electric space heating loads, the household's demand can be reduced for a period of time when the non-deferrable load is large. The control structure is dependent on controllable/flexible loads, that all are prioritized by the user. By the priority selection, the user can determine which space heating loads should have the highest priority, and which should have the lowest. If the household demand exceeds the demand limit, the Home Energy Management System will try to turn off the space heating loads, starting with the lowest prioritized loads, until the demand no longer exceeds the limit. The load control development also emphasizes to minimize the loss of comfort associated with the decrease in room temperature. The load control will, by pre-determined comfort conditions, always ensure that the temperature is over a specified minimum temperature, which is determined by the user. The control structure is also able to utilize any distributed generation assets combined with battery energy storage to use this energy to maximize the comfort for specific rooms that are pre-defined by the user.

An elementary Simulink model of an apartment is developed, giving the ability to simulate how the indoor temperature changes with respect to the status of the space heating loads in the apartment. Combining this with a typical load profile for a Norwegian household, an electric vehicle load and associated photovoltaic panels and battery energy system storage, the simulations are carried out for a cold winter day in Norway. The simulation results indicate that the control of space heating loads alone is not sufficient for shifting demand on an hour-to-hour basis. The control of space heating loads can reduce the demand for shorter periods, and if the measurements of power are averaged over shorter intervals than 1 hour, like 15 minutes or 1 minute, the economic savings by the developed load control can magnify

significantly. In addition to this, utilizing larger flexible loads can also reduce the 1-hour-measurement-based capacity-based grid tariff cost. This is demonstrated by scheduling the electric vehicle charging, and the results show that the grid tariff cost may be reduced by over 30 \%, while preserving a sufficiently comfortable temperature indoors.

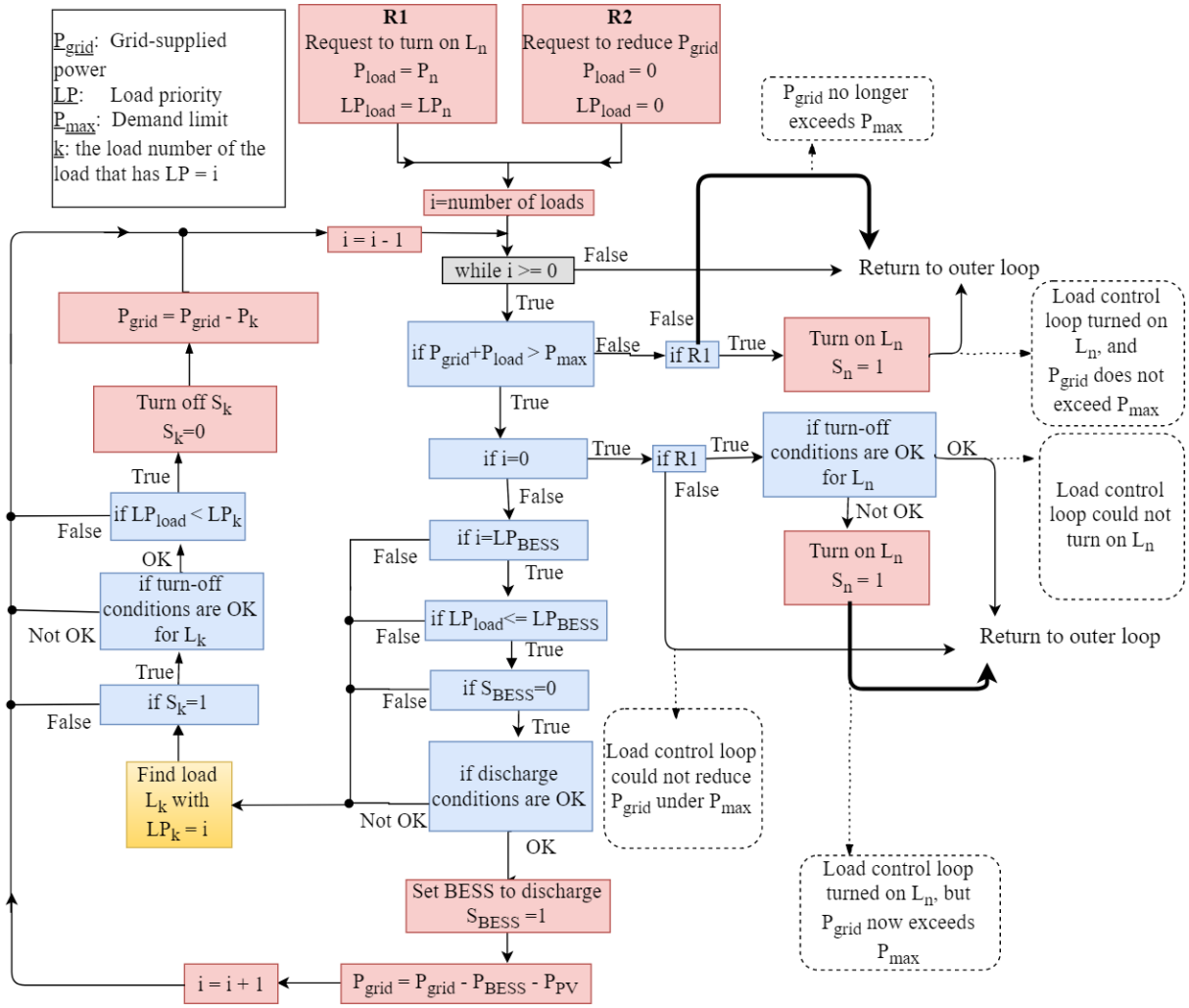


Figure 1: The load control loop, which is the inner loop of the load control

Design of a High Speed Permanent Magnet Radial Flux Outer Rotor Generator for a Hybrid Electric Aircraft Application

Student: **Marius Persson Hårdnes**
Supervisor: **Robert Nilssen**

Abstract

Implementing electric power systems for propulsion in aircraft is seen as an enabler for future air travel with reduced carbon emissions. The path towards fully electric aircraft requires the development of enhanced electrical components with respect to efficiency and weight. As storage of electricity remains a challenge due to low energy density in relevant mediums, hybrid electric power systems are considered an intermediate step towards emission free operation. Motivated by the development of this type of system, a high speed permanent magnet synchronous generator for power production with direct coupling to a gas turbine is designed. With a rated performance of 2.5 MW at the high speed 15 000 rpm, the machine experiences large centrifugal forces whose effects should be mitigated. Therefore, the study of an outer rotor machine is selected.

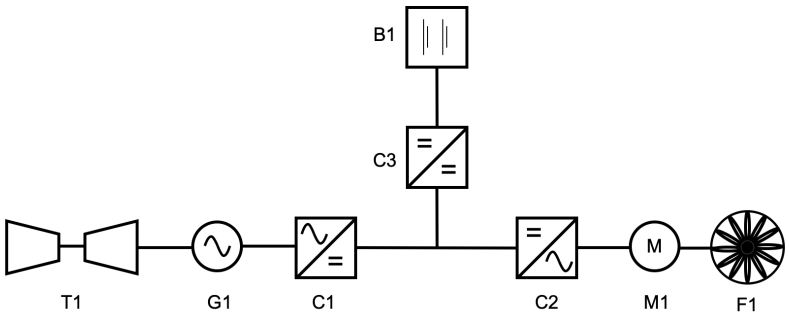


Figure 1: Hybrid electric power system for an aircraft.

With an initial analytical approach of a feasible geometry, followed by implementation in a software for finite element computations, the model of a generator is obtained. Its rated conditions are studied with emphasis on the general output of torque, voltage and power. Necessary improvements for the design are selected based on the FEM results. Due to high speed operation, the machine is required to have small radial extension in order to omit losses.

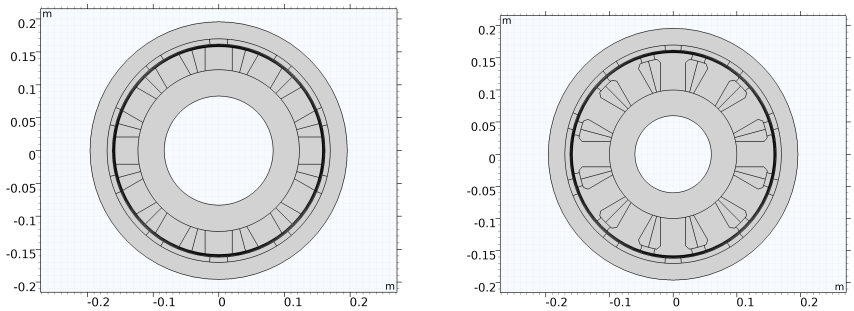


Figure 2: Initial and improved design geometry.

Parameter identification of Synchronous generator using Standstill Frequency Response (SSFR) test

Student: **August Jaros**
Supervisor: **Trond Toftevaag**

Abstract
This Master's thesis serves as the starting point in the work with parameter identification of the Siemens-Schuckert machine at the National Smart Grid laboratory at NTNU in Trondheim, and acquiring experience in use of Standstill Frequency Response (SSFR) test for identification of synchronous machine parameters. The motivation is future collaboration studies between NTNU, HydroCen and SINTEF Energy Research regarding the development of hydropower technology.

The Siemens-Schuckert synchronous machine was tested with the Open-Circuit Characteristic (OCC) test and Short-Circuit Characteristics (SCC) tests. The machine's SCC and OCC was constructed. A retardation test was also conducted to determine the machine's inertia. The inertial time constant was calculated to be H = 2.67s.

The Rudolf-Dietze synchronous machine was tested using the SSFR-test in order to validate the test as an alternative to the traditional, but more demanding, sudden short-circuit tests. The SSFR-test attempts to obtain the operational parameters of the machine. The operational parameters can be expressed as rational functions in the frequency domain which are related to the fundamental parameters that describe the electrical characteristics of the machine. The machine is tested in order to construct the different parameters' frequency responses. Using curve-fitting tools, the rational form operational parameter functions can be obtained. The SSFR-test is the main focus of this thesis.

A laboratory set-up and method of measurement for the SSFR-tests was developed based on available laboratory-instruments. The frequency response of the operational parameters Ld(s), Lq(s) and G(s) was constructed from the SSFR test-results. The oscilloscope used for the measurements was not able to conduct measurements for the required frequency range of 1mHz-1kHz, and measurements below 0.1Hz was omitted from the tests. An estimation method based on the MATLAB System Identification Toolbox was used to estimate the operational parameter expressions. However, due to incomplete test-data, the estimates obtained should be regarded as approximate at best. In order to accurately estimate the complete set of the machine's parameters with this method, accurate SSFR-measurements for the whole range of frequencies are required. Thus, for future SSFR-studies, measurements should be conducted with instruments enabling accurate measurements for the complete frequency range.

Weather Models for Capturing Wind Related Failures in Probabilistic Reliability Analysis

Student: **Jensen, Amalie Gjerdingen**
Supervisor: **Kjølle, Gerd H**
Co-Supervisor: **Sperstad, Iver Bakken**

Abstract

As the occurrence of extraordinary weather events such as major storms increases due to global warming, it is important to include weather data to probabilistic reliability analysis methodologies. To do so, a suitable model for implementing weather effects must be developed.

This thesis is based on the OPAL methodology and prototype which is an analytic contingency enumeration method for meshed power systems. Contingencies are chosen based on the Minimal Cut Set Method. First and second order transmission line outages are studied.

Two methods are developed to generate reliability indices from a time-series of hourly probabilities of failure for transmission lines based on historic weather data and wind-related contingencies. The aim of the methods is to reproduce results from a more complex benchmark method, while reducing computational complexity and capturing failure bunching effects.

The first method is a three weather state approximate equations method. This is an extension of a previously developed method which was based on a fictional case. This is altered and adapted to handle historic failure data. The second method is a timestep method. Similar to the benchmark method, the timestep method calculates unavailability at every hour of the input data-series. A MATLAB implementation to calculate reliability indices, both with and without weather impact, is developed as a part of this work.

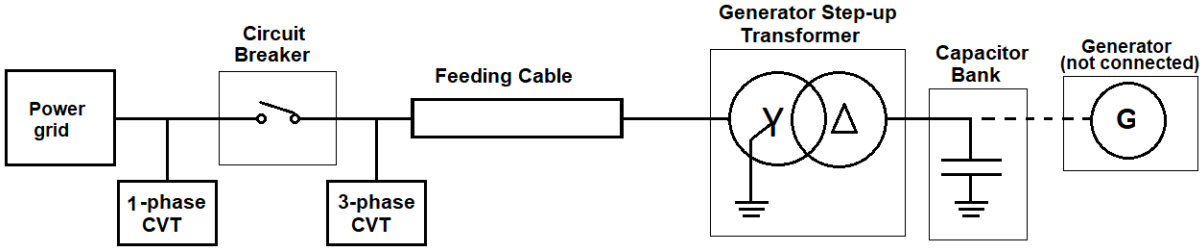
The focus of the thesis is the effect on ENS when including weather. The studies show that the approximate equations method is most suitable for the task. A deviation to the benchmark method of 0.15 MWh/year is acheved for the system as a whole, and a deviation of 7-9% at cut set level when only studying weather-related ENS. This corresponds to a deviation of 0.3-2 % at each cut when including both weather and non-weather related ENS. The timestep method is not suitable due to overestimation increasing with weather impact.

Transients During Energization of Unloaded Generator Step-Up Transformers

Student: **Lars Eivind Jensvoll**
Supervisor: **Hans Kristian Høidalen**
Contact: **Ronny Goin**
Collaboration with: **Statkraft**

Problem description

When connecting a hydropower station to the electrical grid, the station sometimes must be energized from the power grid before the generators are started. This includes energizing the generator step-up transformer from the high voltage side, which represents an abrupt change in the circuit conditions. The transformer terminals experience a voltage change from zero voltage to system voltage in an instant. High and harmonic rich inrush current are associated with uncontrolled energization of unloaded generator step-up transformers. The first current peak can be in the same order of magnitude as the transformer short circuit current, thus result undesirable events such as severe dynamical stress in the transformer windings, false operation of protective relays, and voltage dips that can influence the electrical grid's power quality. Furthermore, energizing unloaded transformers via a feeding cables may create high voltages on transformer terminals. This can occur if resonance frequency of the cable and transformer match, or if one of the harmonics of the inrush current is close to the resonant frequencies. The focus of my master's thesis is to study both the inrush current and the overvoltages that occur on the transformer high voltage side, when energize as explained. The figure shows the generic outline of a typical Norwegian hydropower station, and how it is energized from the grid.



Method

- Statkraft's hydropower plant Nedre Røssåga is modelled using ATPDraw, a pre-processor to the Alternative Transient Program (ATP).

- Transformer inrush currents and terminal overvoltages are simulated for varying energizing times, energizing strategies, power grid configurations and feeding cable lengths.

Conclusion

- The optimal time to energize a transformer is at voltage peak. The optimal energizing time of a cable is at zero voltage. High inrush currents can therefore be avoided, but at the cost of high energizing voltages at the transformer terminals.

- The model in ATPDraw is seen to reproduce the voltage waves up to a certain accuracy. The voltages of the model have too low damping and does not replicate the highest peaks.

Undersøkelse av hvordan fleksibilitet, inkludert smart lading og Vehicle-to-Home, kan påvirke investeringsbeslutningene av en nullutslippsbygning (ZEB), inkludert produksjon på lokasjonen og fasilitering av lading av elektriske kjøretøy

Student: **Sondre Moe Knudsen**
Faglærer: **Karen Byskov Lindberg**

Sammendrag
Nullutslippshus er et viktig steg på veien til en grønn fremtid. Med et fokus på å minimere energiforbruk samtidig som elektrisitet produseres av huset selv er målet å betydelig redusere klimagassutslipp som følge av oppvarming og drift av bygninger. Elektriske kjøretøy er også et viktig redskap i forsøket på å bevege seg bort fra fossile brennstoff. En prosjektoppgave gjennomført høsten 2018 viste at å inkludere lading av elbiler i den årlige utslippsbalansen økte kostnadene drastisk grunnet en voldsom økning i nødvendig PV investering. Disse resultatene ble funnet gjennom en optimaliseringsmodell skrevet i Mosel-språket hvis objektfunksjon var å minimere kostnader samtidig som teknologier ble investestert i for å nå et årlig netto utslipp av CO2-ekvivalenter mindre enn null. Denne masteroppgaven har undersøkt hvorvidt et smart ladesystem (kontrollert av Mosel-modellen) og implementeringen av Vehicle-to-Grid og Vehicle-to-Home kan påvirke kostnadene, eksport og import av elektrisitet og graden av selvforbruk av PV-produsert elektrisitet.

Selv om disse funksjonene hadde en synlig effekt på den totale prisen var den minimal, rundt 0 – 2%. Analyse av eksportert og importert strøm samt selvforbruk viste en mer markant effekt, rundt 8%. Den relativt stabile strømprisen, samt effekttapet ved bruk av Vehicle-to-Grid og Vehicle-to-Home funksjoner, fremstår som de fremste grunnene til at resultatene ikke viste store forskjeller fra bruk av konvensjonell lading.

Toolbox for Specialized Power System Analysis

Student: **Hege Bruvik Kvandal**
Supervisor: **Olav Bjarte Fosso**
Collaboration with: **Statnett**

Power system analysis is an integral part of the operation and planning of power systems. As the power system evolves with emerging green technologies and distributed generation, the tools that perform the analyses must adapt. Python is an object-oriented programming language with attributes that can be useful for the purpose of modernizing the tools. Currently, the tools for power system analysis considered in this thesis are written in Fortran, and the goal is to interface them with Python to take advantage of the functionalities the language provides. In this thesis, the DC optimal load flow analysis will be updated. The modernization is achieved by first translating the Fortran codes to C and then interfacing them with Python using Ctypes. In the translation process, the differences between the languages must be accounted for, and replacements for the Fortran optimization routines must be chosen. The linear programming solver Lpsolve is suggested as the optimization tool for the C codes. After the initial interfacing and testing, it can be concluded that even though the new version of the DC optimal load flow is not yet complete, and many tools remain to be interfaced, the information provided in this thesis can be used to continue the project and eventually lead to a toolbox designed for the future.

Simplified Loss Model for Offshore Wind Farms

Student: **Eivind Nervik Lea**
Supervisor: **Pål Keim Olsen**
Contact: **Pål Keim Olsen**
Collaboration with: **Equinor**

Problem description

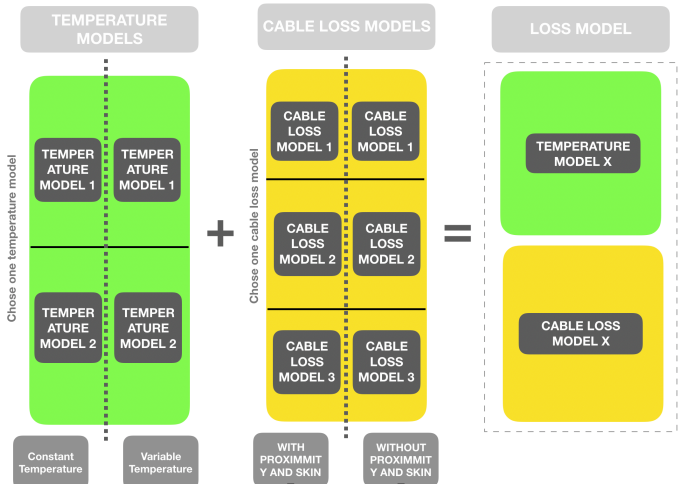
When investing in energy facilities, e.g offshore wind farms, one has to know the minimum price at which electricity must be sold to recoup the lifetime costs of the system, known as the Levelized Cost of Energy (LCoE). Electrical losses are important in LCoE calculations as it effects the annual production in an offshore wind farm. One trend in the offshore wind market is longer distances from shore. This requires longer cables and in most cases it will increase the losses in the wind farm and thus estimating these cable losses accurately will contribute to more accurate LCoE calculations.

The task

Develop a standardized loss model to analyze electrical losses in array cables for HVAC offshore wind farm grid, and validate that loss model with real data from an operating offshore wind farm for a full month.

Model/ measurements

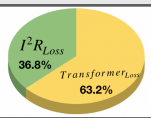
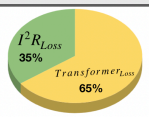
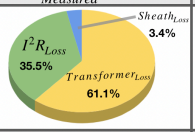
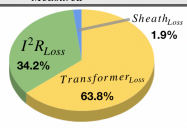
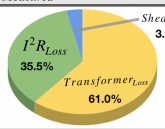
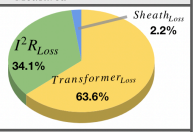
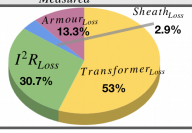
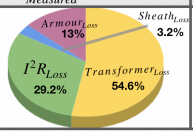
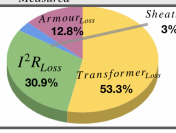
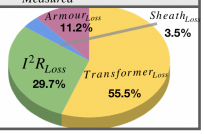
The presented loss model below is divided into levels of abstractions/complexity. There are 2 main abstractions, temperature and cable losses. Each abstraction is divided into different levels of complexity, see figure below. A combination of temperature model and cable loss model form the Loss Model. The idea is to build a model, from the simplest of models to the more complex. In addition the Loss Model is divided into constant and variable temperature and between resistance with and without proximity and skin effect factor.



Calculation

Accuracy of the Loss Model for one string in the wind farm is shown below.

RESISTANCE **WITH** PROXIMITY & SKIN EFFECT

	Temperature Model 1		Temperature Model 2	
	Constant Temperature	Variable Temperature	Constant Temperature	Variable Temperature
Cable Loss Model 1	$\frac{Loss_{Simulated}}{Loss_{Measured}} = 8.84\%$	$\frac{Loss_{Simulated}}{Loss_{Measured}} = 11.51\%$	-	-
			-	-
Cable Loss Model 2	$\frac{Loss_{Simulated}}{Loss_{Measured}} = 5.8\%$	$\frac{Loss_{Simulated}}{Loss_{Measured}} = 9.82\%$	$\frac{Loss_{Simulated}}{Loss_{Measured}} = 5.74\%$	$\frac{Loss_{Simulated}}{Loss_{Measured}} = 9.55\%$
				
Cable Loss Model 3	$\frac{Loss_{Simulated}}{Loss_{Measured}} = -8.63\%$	$\frac{Loss_{Simulated}}{Loss_{Measured}} = -5.41\%$	$\frac{Loss_{Simulated}}{Loss_{Measured}} = -8.03\%$	$\frac{Loss_{Simulated}}{Loss_{Measured}} = -3.61\%$
				

Conclusion

Results shows that suggested model is able to simulate the losses with an accuracy of 3.6%. However there are are too many uncertainties to validate the model presented with confidence. The biggest uncertainties have to do with measured data where wind turbine transformer losses and cable losses had to be included in the model. Further work has been suggested in order to validate the loss model with more confidence.

Lyset sin påverknad på rognkjeks i oppdrettsanlegg

Student: **Lundehaug, Silje**
Veileder: **Hansen, Eilif Hugo**
Medveileder: **Nilssen, Kjell J.**

Sammendrag
Fiskearten rognkjeks (Cyclopterus lumpus) blir brukt i oppdrettsnæringa for avlusing av atlanterhavslaks (Salmo salar). Oppdrett av rognkjeks er nytt innan havbruk. Til no har ein hatt svært avgrensa kunnskap om korleis rognkjeks nyttegjer seg av lys og kva for kunstig belysning som kan bidra til trivsel for arten i produksjonsanlegga.

Rognkjeks har to lyssensitive organ: Auge og pinealkjertel. Pinealkjertelen ligg inne i kraniet og regulerer mellom anna produksjonen av hormonet melatonin. Dette hormonet styrer biologiske rytmar, blant anna søvn. Denne oppgåva presenterer spektrale transmisjonsmålingar gjennom skalletaket til rognkjeks for å bestemme kor mykje lys som når inn til kraniet og dermed kan påverke melatoninresponsen i pinealkjertelen. Det har også blitt utført åtferdsforsøk med rognkjeksyngel og lysmiljøet i to rognkjeksanlegg har blitt kartlagt.

Transmisjonsforsøka viser at stråling i bølgelengdeområdet 300-350 nm har spesielt stor transmisjon gjennom rognkjeksskallen, og at transmittert stråling varierer lite mellom stor fisk og yngel. Åtferdsforsøka viser at både karfarge og lysfarge vil påverke åtferda til rognkjeks, når dei får velje mellom to alternative lysmiljø. Kartlegginga av lysmiljøet i rognkjeksanlegg viser behovet for å utvikle retningslinjer for kunstig belysning i desse anlegga.

Analyse av forbruksmålinger fra smarte nettstasjoner for planlegging og drift av distribusjonsnett

Student: **Tonje Leine Lunden**
Veileder: **Eivind Solvang**
Utføres i samarbeid med: **SINTEF Energi**

Frem til i dag har nettselskapene hatt lite detaljert informasjon om belastningsvariasjoner i distribusjonsnettet. Smarte nettstasjoner og AMS på kundenivå kan gjøre det enklere for nettselskapene å dimensjonere ulike nettkomponenter. Lyse Elnett har i forbindelse med prosjektet Smarte nett Stavanger bistått med kvantitative forbruksdata fra ulike nettstasjoner i Stavanger sentrum. Nettstasjonene er utstyrt med nytt måleutstyr og fjernstyrte brytere, som kan overvåkes og fjernstyres fra driftssentralen. Formålet med denne oppgaven har vært å se på hvilket potensial forbruksmålinger fra nettstasjoner har for planlegging og drift av distribusjonsnettet.

I denne oppgaven har det blitt beregnet timesforbruk for tre ulike nettstasjoner basert på generelle lastprofiler på kundenivå. Beregnet forbruk har blitt sammenlignet med målt forbruk fra nettstasjonene. Det er innhentet temperaturdata fra Meteorologisk institutt for å tilpasse beregnet forbruk til målt forbruk i 2018. Resultatene viste for to av nettstasjonene at beregningene ikke klarer å gjenskape variasjonene i det målte forbruket. Derimot viste beregningene et godt bilde av forbruksvariasjonene for den siste nettstasjonen. Mer nøyaktig kundeinformasjon vil føre til at beregningene kan bli mer presise.

Videre er det beskrevet en metode for automatisk oppdatering av forbruksprofiler fra ulike nettstasjoner. Her vil inngangsdata være temperaturmålinger og forbruksmålinger fra nettstasjonene. Unike forbruksprofiler for hver enkelt nettstasjon kan bli generert. Å implementere et verktøy for en slik automatisering i nettselskapene vil medføre økt kunnskap om forbruksvariasjonene for nettstasjoner med gitte kundesammensetninger.

Tap ved ulike delepunkt i et ringnett har blitt undersøkt, med utgangspunkt i timesmålinger av forbruk fra de ulike nettstasjonene. Årlig tapskostnad ved å kjøre samme delepunkt hele året sammenlignet med å velge delepunktet med minst tap i ringnettet hver time utgjorde minimale forskjeller. Sett opp mot hvor ofte bryterne må kobles om for å realisere den sistnevnte strategi vil det føre til stor slitasje på bryterne og dermed store investeringskostnader for nye brytere. Det er derfor anbefalt at nettselskapene vurderer alternative strategier. Dette kan for eksempel være et delepunkt for ukedager og et for helg, eller spesifikke delepunkt for ulike sesonger.

Muligheter og utfordringer med elektriske veier i Norge

Student: **Joakim Gotheim Lønset**
Faglærer: **Eilif Hugo Hansen**

Sammendrag
Denne studien undersøker muligheter og utfordringer med elektriske veier i Norge. Til å svare på dette, studeres hvordan elektriske veier kan være tilpasset å forsyne trafikken i Norge. Det er sett at elektrisk forsyning på veien kan supplere den konvensjonelle stasjonære ladeteknikken på en slik måte at behovet for batterier reduseres. Mellom annet gir det muligheten for at flere kjøretøy kan utnytte elektrisk energi i framtiden. Vurderingene som er gjort tilsier også at et samspill mellom elektriske veier og batteri – trolig er den mest klimavennlige og energieffektive drivstoffløsningen som er mulig å få til i Norge i dag.

Videre er det sett nærmere på ulike elektriske veisystemer, og forsøkt å gi en status på disse systemene i dag. Her er det funnet et bredt spekter av løsninger, hvorav samtlige er vurdert å ha klare fordeler og ulemper til hverandre. Siden ladesystemene distribueres på veien medfører det at systemene må ha stor utstrekning, og følgelig blir de derfor også dyre løsninger. Det skjer ennå stor utvikling på området, og det er vanskelig å tro at dette kommer på norske veier innen få år. Studien viser imidlertid svært mange fordeler med elektrisk forsyning på veien, og tilsier at det likevel kun er spørsmål om tid før elektriske veier kommer til Norge. Med dette som utgangspunkt, vurderes også hvordan man kan planlegge og legge til rette for elektriske veier i framtiden. Erfaringen er at svært mange faktorer har betydning for hvordan man distribuerer elektriske ladestier i veinettet. Derfor er det vanskelig å finne en generell framgangsmåte for alle strekninger sett under ett. I en tidlig startfase synes det hensiktsmessig å planlegge elektriske ladestier for hver enkelt veistrekning, framfor å tenke på veinettet i en helhet.

Et viktig punkt i planleggingen er tilmed å forsøke og utnytte eksisterende elektrisk infrastruktur langs veien slik det er i dag. I et konkret eksempel er det derfor sett på konfigurering av elektrisk forsyning til godstrafikken gjennom Rogfasttunnelen. Det er tatt utgangspunkt i planlagt elektrisk infrastruktur i tunnelen, samt at tidligere arbeid beskriver forbruket av elektrisitet til godskjøretøyene som befinner seg på denne strekningen. Enkle beregninger og vurderinger, tilsier at Rogfast skal være kapabel til å forsyne ventet godstrafikk på strekningen i mange år framover.

Continuous-Time Unit Commitment using spline interpolation

Student: **Andreas Rise Mathisen**
Supervisor: **Hossein Farahmand**

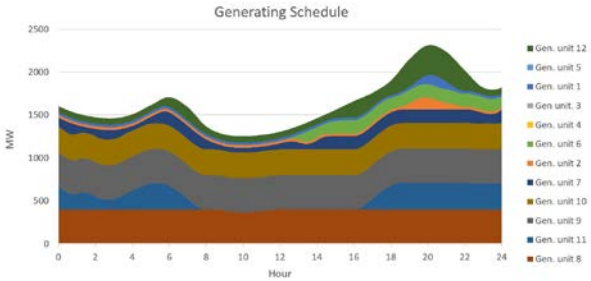
Abstract

Power system operators are facing increasing challenges with both scheduling and real-time (RT) operation of generating units. The day-ahead unit commitment (UC) is a well-established and essential part of today's power system operation, where forecast load data is used to schedule the next-day commitment and operation of generating units. A well-formulated UC problem formulation, where ramping and generating constraints are incorporated is crucial to ensure an effective power system operation. This translates down to both economic and stability aspects, where the aim is to reduce operating costs and ensure that sufficient ramping and generating reserves is available in power systems at all times.

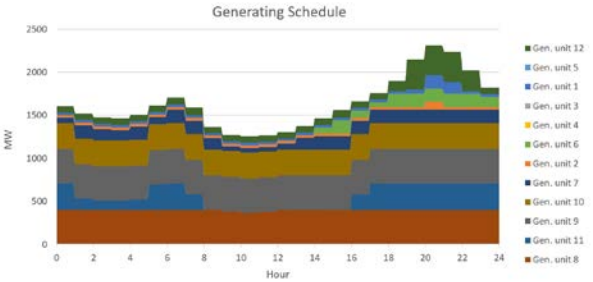
The current day-ahead UC problem models load forecasts as constant in hour-intervals, where load change between hours is modelled as step functions. There are several reasons why this formulation is so well-established. It is simple and effective. However, it has some major weaknesses. It is effective when load forecasts are accurate and when sub-hourly variations in load are low. In power systems with high penetration of variable renewable energy sources (VRES), two main problems are: 1) Power output from VRES is highly intermittent and hard to predict, and 2) large and steep variations in output from VRES require large ramping reserves. The current day-ahead UC formulation does not capture sub-hourly variations and sharp ramping events, which can lead to ramping scarcity during RT operation.

In this thesis, a continuous time day-ahead UC problem formulation is considered by using spline interpolation. The model uses the same day-ahead load data as the current UC model but will use this data not only to schedule generating output profiles but also ramping profiles. Hence, sub-hourly variations will be considered and incorporated into the UC problem. Furthermore, two modifications will be assessed and applied to the UC model, and they are namely to 1) formulate robust generating constraints and 2) introduce energy storage (ES) units in the system. The proposed UC model is formulated as a mixed integer linear programming (MILP) problem and will be compared to the traditional UC problem through simulations based on historical load data.

Calculations



a) Bernstein UC model



b) Traditional UC model

Submodel	Model	DA cost	RT operation	Net costs	Diff.
Standard	Bernstein	$257,121.14	$25,294.65	$282,415.79	
	Traditional	$255,959.33	$57,674.80	$313,634.13	+$31,218.34
Robust	Bernstein	$264,531.34	$20,305.59	$284,836.93	
	Traditional	$262,630.74	$32,588.52	$295,219.26	+$10,382.33
Std. w/ES	Bernstein	$254.256,56	$38,683.79	$292,940.35	
	Traditional	$253,276.61	$269,932.70	$523,209.31	+$239,268.96
Rob. w/ES	Bernstein	$255.047,25	$25,042.53	$280,089.78	
	Traditional	$254,155.21	$56,976.97	$311,132.18	+$31,042.40

These figures show the results from the simulations of the UC problem on CAISO load data from June 2nd, 2018. Costs are calculated both in terms of day-ahead scheduling costs and RT economic dispatch costs.

Results
Simulations are based on load data from California ISO (CASIO), simulated on the IEEE 24-Bus Reliability Test System, and show that overall, the proposed Bernstein UC model outperforms the traditional UC model in terms of both operating costs and scarcity events. The models perform similarly when day-ahead load forecasts are accurate, but for load data with large forecast errors, steep ramping and large sub-hourly load variations, the Bernstein model performs significantly better. RT operation costs are kept much lower with the Bernstein model, much because the traditional model relies more heavily on auxiliary generation during RT operation due to ramping and generating scarcity.

Conclusion
The results of the simulations in this thesis show that the Bernstein UC model performs much more consistent than the traditional UC model, and its main advantages are shown in the case studies where day-ahead forecast errors are large, when there are large sub-hourly load variations in load and when there is large load ramping. The robust nature of the Bernstein UC model yields lower RT operational costs and fewer ramping scarcity events than the traditional UC model.

An important takeaway from the simulations in the thesis is that the continuous time Bernstein UC model, schedules generating unit commitment in one-hour intervals, just as the traditional UC model. Hence, it is shown that it is possible to effectively incorporate ramping trajectory functions into a UC model while maintaining the same one-hour scheduling structure as before. This means that the MILP commitment structure from the traditional UC model is preserved.

Flow-Based Market Coupling in Short-Term Hydro-Thermal Scheduling

Student: **Torbjørn Røed Meberg**
Supervisor: **Arild Helseth**
Co-supervisors: **Hossein Farahmand & Christian Øyn Naversen**
Collaboration with: **SINTEF Energy Research**

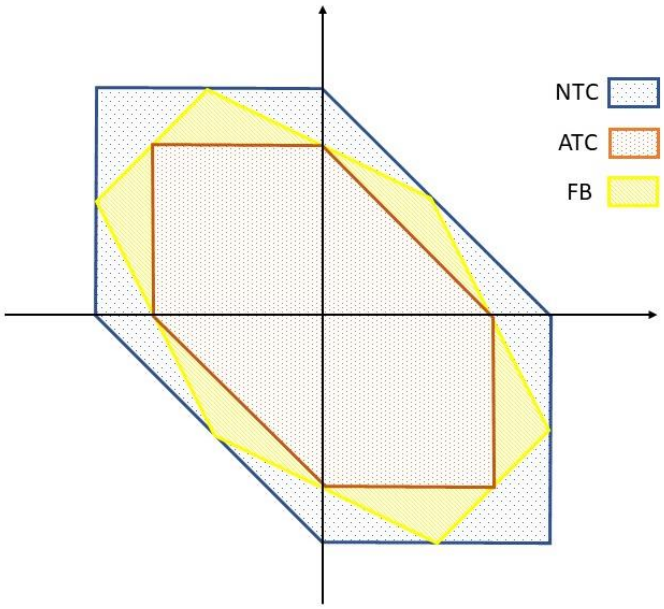
Problem description
The scope if this master thesis is to continue the development of SINTEF's model PriMod. Currently the model is using a transport model for transferring power between the areas. The work will focus on how to incorporate flow-based market coupling to the model, and how the concept affects the behaviour of the simulated system compared to the present transmission modelling.

The task
Flow-based market coupling is implemented in the model, prior to an analysis of the results of the simulation. The analysis will try to discover changes in flow of power, and the associated effects in the pricing structure between the original model, and the modified version with FBMC.

Model/ measurements
The work was performed with Pyomo, a Python-based optimization modelling language. The optimization model is presented. Below, the constraint for physical flow of power is presented. The flow of power is dependent on the PTDF-matrix and net injected power in the areas.

$$f_{i,j,k} = \sum_{a \in \mathcal{A}_{\mathcal{H}}} a_{i,j}^{a} \cdot \left(\sum_{h \in \mathcal{A}_{\mathcal{H}}} f_{a,h,k} + \sum_{l \in \mathcal{A}_{\mathcal{T}}} t_{a,l,k} - t_{l,a,k} \cdot (1 - \mathcal{T}_{l,a}^{loss}) \right)$$
$$i,\ j \in \mathcal{A}_{\mathcal{H}}, \quad k \in \mathcal{K}_{l}$$

Flow-based market coupling have different domain of power than the conventional ATC market coupling, as illustrated in the figure below.



Conclusion

Key findings:

- The level of congestion in the lines is somewhat lower with FBMC, and the most congested line have changed.
- The structure of the pricing has changed significantly. The prices converge in 80.45% of the steps, compared to 15.61% in the base case.
- Due to an improved allocation of power, the median and average prices are lower for the FBMC than the base case.
- The system acts "non-intuitive" in a significant amount of time-steps. One area imports power in 6.85% of the simulated time-steps despite a higher market price in the exporting area.

Comparison of virtual oscillator control and droop control in an inverter-based stand-alone microgrid

Student: **Mathias Melby**
Supervisors: **Olav Bjarte Fosso and Marta Molinas**

This thesis is about controlling DC/AC inverters. More specifically is the goal to compare the recently introduced virtual oscillator control (VOC) with the better-known droop control. The control methods are analysed under different conditions to uncover their limitations and their strengths. It also presented how the selection parameters could make the methods equivalent. This is used as a criterion to give a fair comparison. During the analysis were some improvements of the VOC discovered, and the method was optimized to improve its performance.
To compare the controllers, they were both implemented on parallel connected inverters in a simulation model of a stand-alone microgrid. The model, seen in Figure 1, consisted of two inverters supplying one common load with either virtual oscillator control or droop control applied. Both methods were set to function similarly in steady-state to ensure fair comparison on equal terms. The comparison was performed by developing timestep simulation models in MATLAB/Simulink as well as equivalent small-signal state-space representations. This way, both the steady-state behaviour, the transient characteristics, and the robustness of the control methods were investigated.

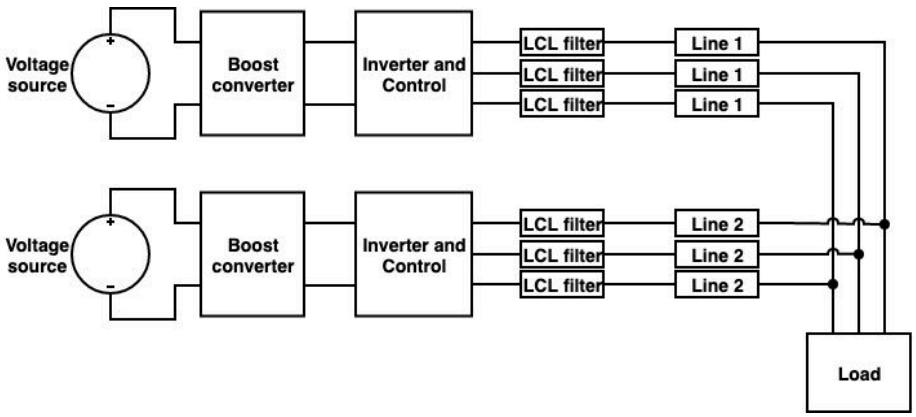


Figure 1: Topology of the microgrid model

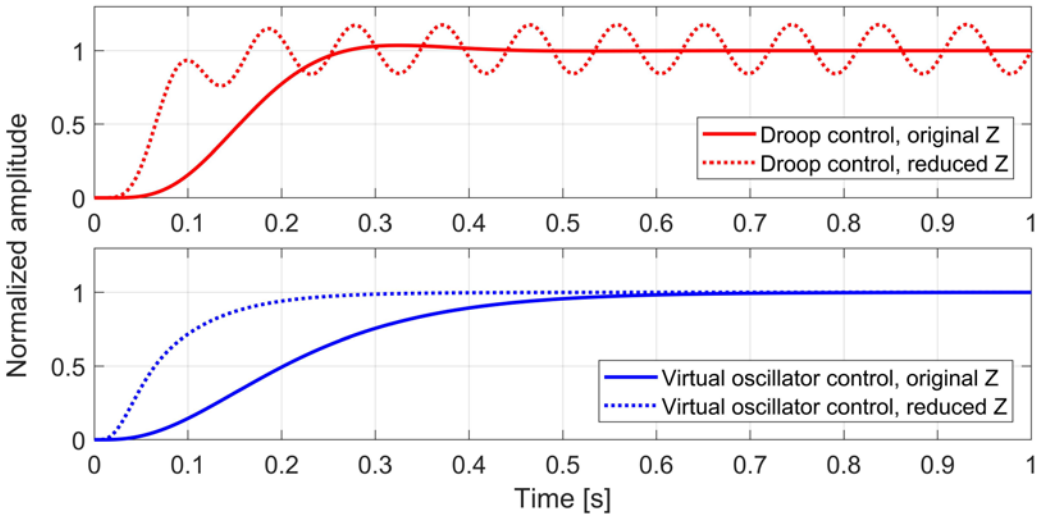


Figure 2: Step response of the overall system with both control methods

One of the main differences between the control methods is related to the coupling strength between the inverters. This factor is inversely proportional to the impedance between the inverters and determines how strongly they affect each other. The analysis show that the droop controller is at its best when it is operating without the inverters having a large influence on each other. When the line impedance was reduced, the stability margin decreased, and the droop-controlled system became unstable when the impedance was close to one-tenth of the base value. The VOC, on the other hand, benefits from a tighter coupling as the system's stability margin increases with a reducing line impedance. This can be seen in Figure 2 where the step response for each system is shown. Furthermore, the virtual oscillator-controlled system was stable for all operating conditions tested in this work. Hence, the virtual oscillator control is a more robust method.

The increased robustness entails a lower voltage quality. Whereas the droop controller provides a pure sinus waveform as a reference voltage, the virtual oscillator control gives a slightly deteriorated voltage shape as well as an oscillating instantaneous frequency. Even though the VOC was tuned to optimize its performance, the droop controller would still be a smarter alternative for the simulated microgrid as the voltage quality and the preciseness of the control were better.

Therefore, if the microgrid has a high impedance grid, either due to a long distance between the units or because of a large impedance per unit length, there is not enough grounds to choose the virtual oscillator control over the droop control. On the other hand, if the coupling is tight, the virtual oscillator control would be the better alternative.

Sensorless Control of Synchronous Machines used in ASH

Student: **Håkon Laaveg Mjell**
Supervisor: **Roy Nilsen**

Problem description

For some high-power applications, as for instance in Adjustable Speed Hydro (ASH), synchronous machines are used for power generation.
In this master thesis, sensorless control methods for such a Synchronous Generator with damper windings have been developed. This means developing flux-models to be able to operate such machines without speed- and position- sensors. The performance of the control system depends on the accuracy of the parameters of the flux model.

The main focus of the thesis is:

- Sensorless control at low-speed operation
- Parameter sensitivity of the flux model

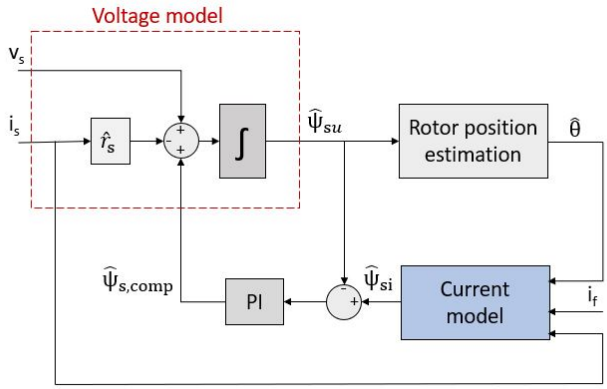
The task

The main goal of this master thesis was to investigate sensorless operation at low speeds, and the parameter sensitivity of the flux model. The three-phase synchronous machine has been emulated by a Simulink model. A closed-loop observer combining the voltage model and the current model has been used, with a PI controller in the feedback loop. The PI controller was tuned by symmetrical optimum.

How estimation errors of the stator resistance, inductances in the d- and q-axis and damper winding resistances affected the sensorless performance was tested and analyzed. The simulations showed that the combination of the voltage and current model estimated the stator flux linkage accurately, except at low speeds. It was revealed that an erroneously estimated stator resistance and a voltage offset were the most critical sources of error. However, the errors could be reduced to some extent by using a PLL. The PLL was used to filter the rotor position input of the current controller, and was able to improve the performance when the stator resistance was underestimated. When a DC offset of 2V was applied to one of the stator voltages, the flux model performed better without the PLL at low speeds. At higher speeds, the PLL was able to reduce the errors slightly.

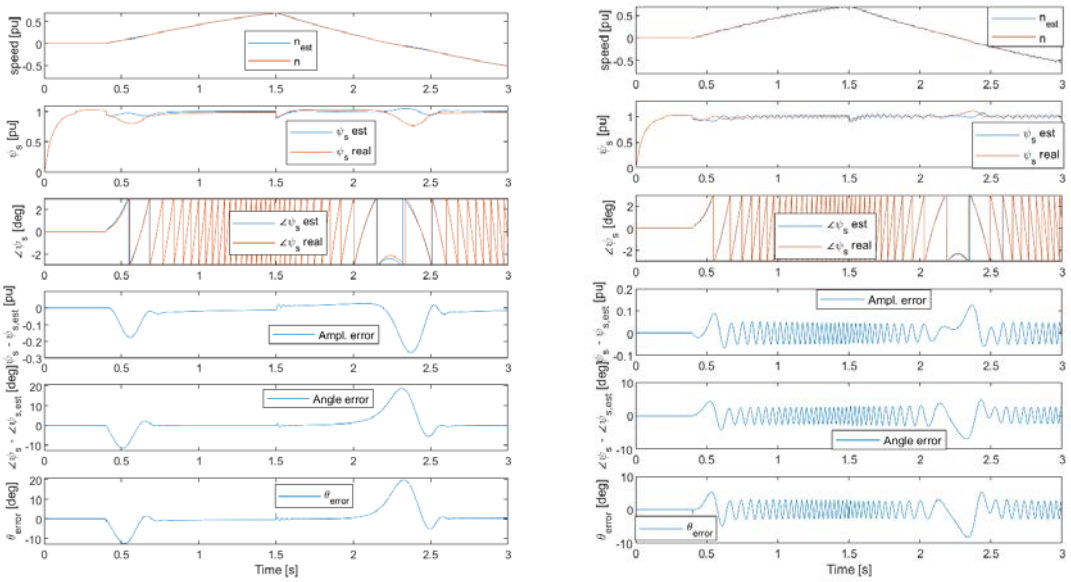
Model/ measurements

The figure below shows an illustration of the combination of the voltage model and current model, with a PI controller in the feedback loop.



Calculation

The figures show the stator flux linkage and rotor position estimates when the stator resistance is underestimated (left), and when a DC offset of 2V is applied to one of the stator voltages (right).



Figur 1: Underestimated stator resistance **DC offset of 2V**

Conclusion

The largest estimation errors were found in the low-speed region. The most prominent errors were caused by an erroneously estimated stator resistance, d-axis inductance variation and a DC offset applied to the stator voltages. At higher speeds, the stator flux linkage and rotor position were accurately estimated by the combination of the voltage model and current model. The PLL was able to improve the performance when the stator resistance was underestimated, but when a DC voltage offset was applied, it caused larger errors at low speeds.

Interaction Strategies for an Optimal Grid Integration of Microgrids

Student: **Stine Fleischer Myhre and Jonas Riseth**
Supervisor: **Olav Bjarte Fosso, NTNU Elkraft**
Co-supervisor: **Bendik Nybakk Torsæter, SINTEF Energi AS**
Collaboration with: **CINELDI, SINTEF Energi AS**

Abstract:

A microgrid is a power system with clearly defined electrical and geographical boundaries which consists of loads, energy generation units and energy storage units. It is expected that if microgrids are operated appropriately, they can increase the reliability of the power system, postpone some grid investments and facilitate more renewable energy production. There are no clear guidelines regarding which role microgrids are going to have in the Norwegian power system. Many questions regarding how microgrids can be integrated into the present power system, how the interaction between microgrids and the system operator is going to be and which regulation strategies that must be implemented are unanswered.

Several elements regarding the integration of microgrids are studied in this master's thesis. A microgrid has the possibility to contribute with different ancillary services to the system operator. This thesis investigates which services that are suitable for microgrids and how they can be performed. Demand response programs are applicable for systems where the system loads can be controlled and can contribute to demand curve changes. Two different demand response programs, where the microgrid participates, are investigated in this thesis. Furthermore, regulatory challenges regarding different types of microgrid owners are addressed with some proposed solutions.

A model of a fictional 22 kV distribution power system is developed in Python by using the Pandapower package. A representation of a microgrid including energy generation from PV modules and wind turbines, a battery energy storage system, household loads and a hospital load is made and can be connected to the distribution system on a selected bus. Seven different scenarios chosen based on the findings in the literature study are established to test the impacts a microgrid can have on the distribution system with different strategies. The scenarios are;

- **Base case:** The microgrid is not connected to the distribution power system.
- **Microgrid generation:** The microgrid is connected to the distribution power system without using the battery.
- **Microgrid generation and storage:** The microgrid is connected to the distribution power system using a simple battery strategy.
- **Microgrid generation and battery regulation:** The microgrid is connected to the distribution power system using a voltage regulation strategy on the battery.
- **Microgrid regulates with all units:** The microgrid is connected to the distribution power system using a voltage regulation strategy on the battery and the generation units.
- **Microgrid with PBP strategy:** The microgrid is connected to the distribution power system using a price based demand response strategy.
- **Microgrid with Peak shaving strategy:** The microgrid is connected to the distribution power system using a peak shaving demand response strategy.

The simulations are conducted with weather data from three different days and with the microgrid connected to three different placements in the distribution network. A load flow is performed for every hour through those days for all the cases. This thesis examines and compares how all these different cases affect the voltage and line loading levels in the distribution system. The results indicate that the operation of a microgrid can have a significant impact on a distribution power system and that an appropriate operation strategy can be essential to integrate a microgrid successfully. A voltage

regulation strategy performed by a microgrid based on reactive power can have both positive and negative impacts on the voltage curves in the system. For lines with low R/X ratio, the voltage regulation will result in increased voltage profiles, while for high R/X ratios, the voltage regulation strategy will result in decreased voltage profiles. The voltage regulation strategies result in a negative impact on the line loading in the system for lines upstream of the microgrid. Furthermore, demand response can both benefit a microgrid and improve both the voltage and the line loading in systems when appropriate price signals are implemented. On the other hand, it can have a negative impact if local aspects are not considered in the price signals.

Hydro-thermal multi-market modelling - Economic surplus

Student: **Siri Hartvedt Nordén**
Supervisor: **Arild Helseth**
Collaboration with: **SINTEF Energy Research**

Problem description

Fundamental modelling of the power system is essential to provide decision support for investments and optimal system operation. With increased penetration of intermittent generation and the outfacing of coal and nuclear power, it is expected that more dispatchable capacity will be held out of the energy market to provide balancing services. With more generation reserved in capacity markets, the fundamental market models need to be re-visited as they mostly consider the product of energy. This thesis further develops a prototype for fundamental hydro-thermal multi-market modelling named PriMod.

The task

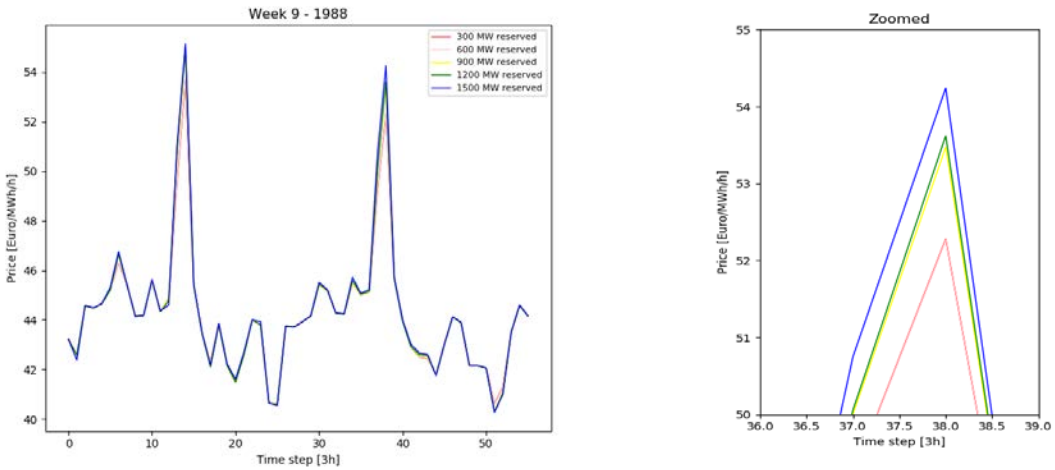
The main objective of this thesis has been the implementation of constraints regarding up and down regulation and to investigate the impact different allocation methods and reserve volumes has on the power system. Both reservation of capacity within the entire Nordic power system and within each price zone is tested. In addition, a tool to analyse how the economic surplus distributes has been created.

PriMod

The model concept (which PriMod is a part of) basically comprises two steps. First, it utilizes FanSi, an existing long-term fundamental model to provide valuation of water. Then a short-term operational model under development re-optimizes the power system with a higher level of details. This enables PriMod to provide fundamental analysis for short-term modelling. To include reserve procurement of up and down regulation, different constraints regarding the required regulation capacity are added in the operational model.

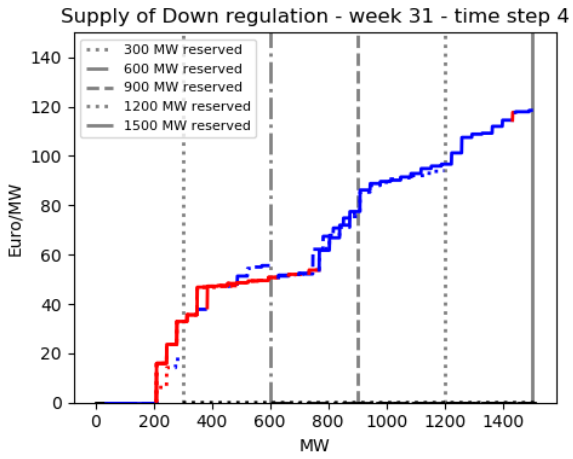
Results

The results show that increased volumes for up regulating reserves increase the area prices as illustrated by figure 1. The effect is most prominent at the price peaks during winter when the load is high. Contrarily, increased volumes of down regulating capacity decrease the area prices, mostly during summer when the load is at its lowest. This underlines that for increased volumes of reserves procured in balancing markets, the price impact in the energy market is significant, highlighting the need for a fundamental multi-market model.

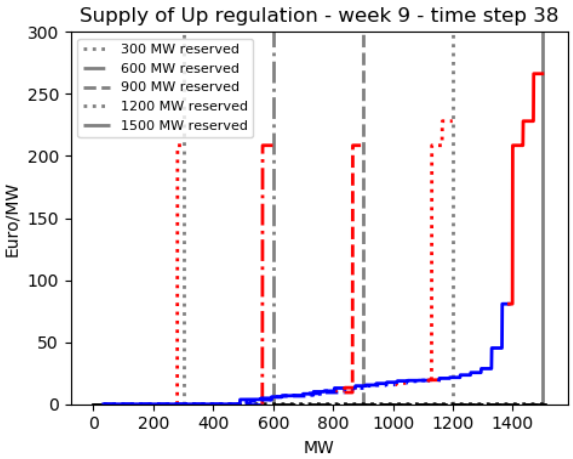


Figur 1 - Average area price

Moreover, as illustrated by figure 2 and 3, the results show that up regulating prices increases during winter as expensive thermal units (red lines) supply up regulation at expensive costs. In the summer, the down regulating prices increase with increased reservation volumes as hydro power stations (blue lines) are forced to produce energy at lost profit. The lost profit achieved by forcing production for down regulating or holding back capacity for up regulation will be compensated by the TSO. Individually, the reservation costs for up regulation in week 9 are more expensive than the down regulation costs in week 31 for the same amount of reserved capacity. However, combined the total reservation costs are higher in week 31 as both up and down regulation becomes costly.



Figur 2



Figur 3

Regarding the welfare calculations, increased reserve procurement decrease the consumer surplus during winter as the area prices increase and increase the consumer surplus during summer when the area prices decrease. The producer surplus follows the opposite trend. However, in the calculations of surplus from hydro power, there are some irregularities as the producer surplus depends on the water values and the future costs of water. Since the different simulations handles reservoirs differently, the costs of hydro power are different in the simulations. Further investigation of the producer surplus from hydro power is therefore needed. Resultingly, the total surplus does not decrease for increased reserve procurement as would be expected.

Conclusion

The thesis results indicate that PriMod shows great potential in serving as a fundamental multi-market model, but still lacks some details in the handling of reserve units to obtain realistic modeling.

Multi-Period AC Optimal Power Flow for Distribution Systems with Energy Storage

Student: **Line Nyegaard**
Supervisor: **Vijay Venu Vadlamudi**

Battery energy storage systems are increasingly considered as a flexible resource in the power system providing a wide range of technical, economic, and environmental advantages. Deployed in the distribution grid, as a community energy storage (CES), the unit can have multiple purposes. It can prevent congestion problems on the network by participating during peak consumption hours, resulting in local energy balance. Besides, it can facilitate a higher amount of renewable generation. The integration of decentralized renewable production is increasing and must continue to rise for the world to achieve a more sustainable power system. However, renewable energy sources are generally unregulated and have a low contribution to power flexibility. Thus, the need for balancing service will become critical in operating the future power system.

In planning and operating of the power system, Optimal Power Flow (OPF) has an undeniable role as a technical and economical tool. Broadly speaking, the OPF optimizes the power system operation according to an objective while meeting all system constraints, including the power flow equations. In line with technological developments and trends in the power system, there is a need for new models and solution methods for the OPF problem. The increasing deployment of energy storage requires that the OPF captures the couplings between different time-steps that are introduced, giving rise to multi-period AC OPF.

This thesis work is emphasizing on providing pedagogical clarity of the fundamental and methodological aspects of multi-period AC OPF. A literature survey is conducted with the purpose of elucidating the current state of research on the relevant study. The aim of this master has also been to create a multi-period AC OPF model. The model is tested on various test-systems. The case studies have been kept simple and illustrative with the purpose of showing the characteristics of system operation strategy when energy storage is deployed. Another intention of the case studies is to demonstrate some applications that can be performed by the proposed solution strategy. From the thesis work, it has become evident that multi-period AC OPF has proved to be a powerful tool in power system analyzing when optimization over a time horizon is favorable.

Metode for automatisk generering av optimale bryterkoblinger ved feil i distribusjonsnettet

Student: **Pettersen, Fanny Moen**
Veileder: **Kjell Sand**

Sammendrag
Feil i distribusjonsnettet står i dag for mellom 70 − 80% av total årlig ikke levert energi. I årene som kommer står distribusjonsnettet overfor en rekke utfordringer, slik som økte krav til pålitelighet, økt energibehov og implementering av distribuert energiproduksjon. I tillegg til dette vil økt sannsynlighet for ekstreme værsituasjoner, i kombinasjon med et aldrende infrastruktur, øke sannsynligheten for omfattende strømbrudd. Samtidig utvikles det stadig ny teknologi som kan benyttes til å effektivisere nettdrift. Ulike metoder, komponenter og informasjonskilder som kan benyttes til å redusere KILE-kostnader ved avbrudd er redegjort for i oppgaven.

Det er utviklet en metode for automatisk generering av optimale koblinger ved feilsituasjoner i distribusjonsnettet. Metoden tar utgangspunkt i nettdata tilgjengelig i nettselskapets DMS-system, samt informasjon om feiltype og eventuell feilindikasjon. Metoden er delt i fire, ut fra hvilke informasjon som er tilgjengelige i det spesifikke feiltilfellet. De fire ulike kategoriene er ukjent feilsted, kjent feilsone, kjente feilsteder og kjent feilsted. De fire metodene er testet ut på en avgang i BKKs nettområde. To feiltilfeller ble simulert, og sammenlignet med koblingssekvensen ved reelle feiltilfeller. Simuleringer er utført i Powels DMS-system, iAM DMS. Alle simuleringer er gjennomført hos BKK i Bergen.

Resultatene viser at foreslått metode ga reduserte KILE-kostnader sammenlignet med de opprinnelig koblingssekvens i hvert feiltilfelle, og for alle de fire kategoriene. Den prosentvise forbedringen varierte mye utifra hvor i nettet feilen inntraff. Dette knyttes opp mot fordelingen av forventet KILE i det aktuelle nettet. Resultatene av følsomhetsanalysen bekrefter at fordeling av forventet KILE i nettet vil ha stor betydning på resultatene.

Active Front End Converter Used in Adjustable Speed Hydro

Student: **Jose Armando Romero Amaya**
Supervisor: **Roy Nilsen**
Collaboration with: **Hydrocen**

Problem description

This Thesis is related to the controls used by the Active Front End Converter (AFE), also called Grid Side Converter (GSC) which is part of a full frequency converter used to control a variable speed generator available in a pump storage power plant.
The control of the AFE is a cascade control, which includes a hysteresis current control loop, resonant voltage control loop, AC voltage and frequency droop, and other dynamic features as virtual damping and synthetic inertia.
At present, the tuning of the resonant controllers, i.e. the obtention of K_{P_T} and K_{Vh} is approached using formulas for simplified models. However, actual systems also include filters, active damping loops, virtual impedance, and other control features. In addition to that, the model discretization also has an impact on the tuning values, causing an error in the resonant frequency and the phase lead produced by the delay compensation.

The task

The current and voltage controllers of the LCL-type grid side converter have been studied. The focus of this thesis has been the development of a tuning methodology of voltage control loop considering the PI control, resonant control and active damping by means of the Nyquist diagrams and robust control theory guidelines applied to the open loop transfer function. Also, a delay compensation method has been developed and tested in a simulation environment.

Model/ measurements

A maximum K_{P_T} is obtained to limit the interference of the commutation harmonics with current control by means of classical control theory. The delay compensation angle ϕ_h is based on the properties that the resonant controller locus has in the z plane, where it forms a circumference and the way the resonant controllers interact among them in that plane. The impact of the most important variables has been evaluated.

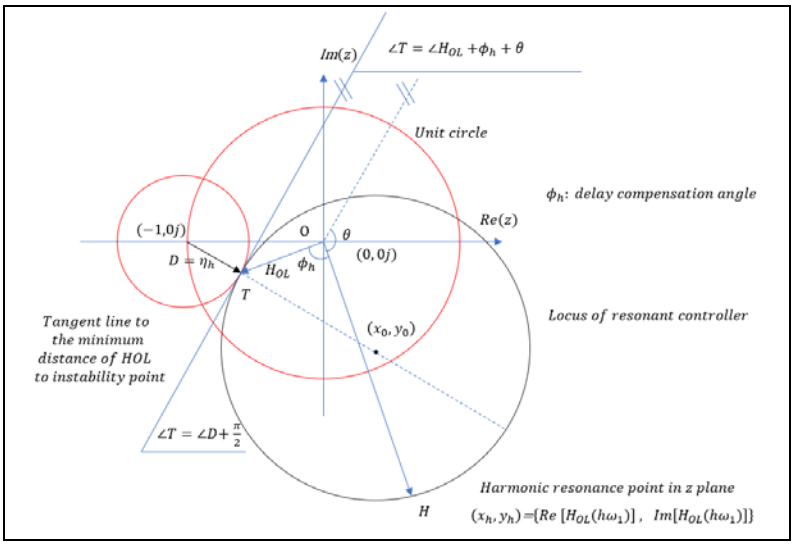


Figure 1: Optimum asymptote to maximize the minimum distance $D(z)$ for one generic resonant controller in the z plane at frequencies around $h\omega_1$ and delay compensation angle ϕ_h

Calculations

The delay compensation angle ϕ_h relationship obtained from Figure 1 has been calculated for each harmonic frequency, as shown in Figure 2 and the recommended values for the K_{P_T} and K_{Vh} of the resonant controller have been obtained, getting a stable solution that can be appreciated in the Nyquist diagram shown in Figure 2.

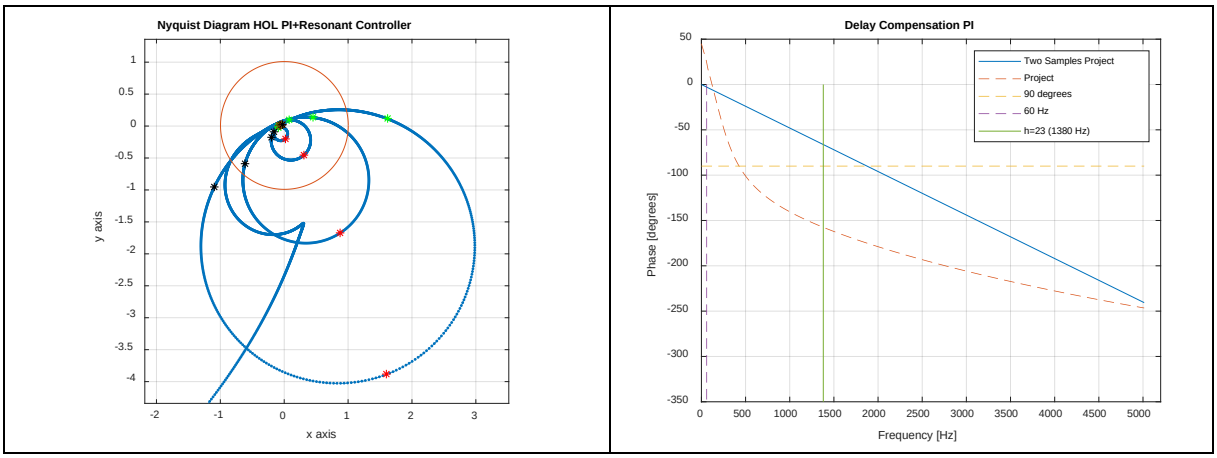


Figure 1: Nyquist diagram and delay compensation angle proposed for the R.C.

Results

All parameters calculated have been used to tune the resonant controllers, obtaining a very good transient response. The difference or error between the capacitor voltage reference and the actual capacitor voltage value become very close to zero in approximately two cycles, which is very good. The current produced by the inverter follows the reference as expected. A voltage drop is observed in the capacitor voltage due to the large rated inverter current, which is an expected behavior considering that the inverter is connected to a strong grid, which keeps its voltage constant.

Conclusion

The resonant controllers with damping have a better performance than resonant controllers without damping regarding frequency adaptability and they should be considered whenever possible.

The delay compensation method for resonant controllers with damping becomes very similar to the method proposed by Yepes for resonant controllers without damping when a very small relative damping factor is used. In this sense, it could be said that the method proposed by Yepes for resonant controllers without damping is a special case of the method proposed. Delay compensation is more important for lower values of K_{P_T} than for higher values of K_{P_T}.

K_{P_T} is the most important factor when tuning P+R controllers and its maximum value is dependent on the crossover frequency ω_{cr}. Once the maximum K_{P_T} is obtained, it should be adjusted to make sure that the current controller follows the reference. Then K_{Vh} can be obtained. It is observed that a high K_{P_T} reduces stability and a low K_{P_T} hinders performance.

Harmonic resonant gains K_{Vh} is not critical regarding tuning provided their values are not high but, it impacts in the Total Harmonic Distortion factor (THD). The harmonic resonant gain should be considered proportional to the harmonic percentage of the total THD in the system to minimize them and at the same time guarantee stability.

Adaptive Protection of an Inverter-Dominated Microgrid and Testing at the Smart Grid Laboratory at NTNU

Student: **Kjersti Lunde Runestad**
Supervisor: **Hans Kristian Høidalen**

Problem description

The connection of microgrids in the existing distribution system affects the magnitude of fault currents due to their two operation modes, i.e., grid-connected and islanded mode. Additionally, the type of distributed generation units and the status of distributed generators dynamically change the fault current level. Generation sources based on renewables will rapidly change its operation mode due to their intermittent behavior. Moreover, several renewable energy sources utilize power electronic converters which represent different characteristics based on their converter control schemes. Thus, the integration of distributed energy resources complicates the protection strategies and the handling of short-circuits.

The task

The general objectives of this master thesis are to:

- Investigate an adaptive protection scheme with digital relays applicable to microgrids.
- Investigate the control strategies of power converters in AC microgrids.

The general objectives are achieved by:

- Implementing an inverter-dominated microgrid system with adaptive digital protective relays at the Smart Grid Laboratory at NTNU.
- Conducting experiments to investigate the influence of inverter-interfaced distributed generation on microgrid protection.

Model

The investigated microgrid system consists of three converters with their respective transformers. Converter B and converter D in *Figure 1* represent two distributed generation sources, whereas converter C represents the main utility. The grid emulator supplies the DC voltage to the converters. Additionally, the microgrid system also consists of a load, a short-circuit emulator, and line inductance. In short, the protective relay adapts its protection function based on the breaker status of the STS, which indicates if the microgrid is grid-connected or islanded. The present operating state of the microgrid is communicated via the relays through IEC61850 GOOSE messaging. The contactor on the DQD bus-bar is remotely controlled in order to isolate short-circuits, so the rest of the system can operate as an active island.

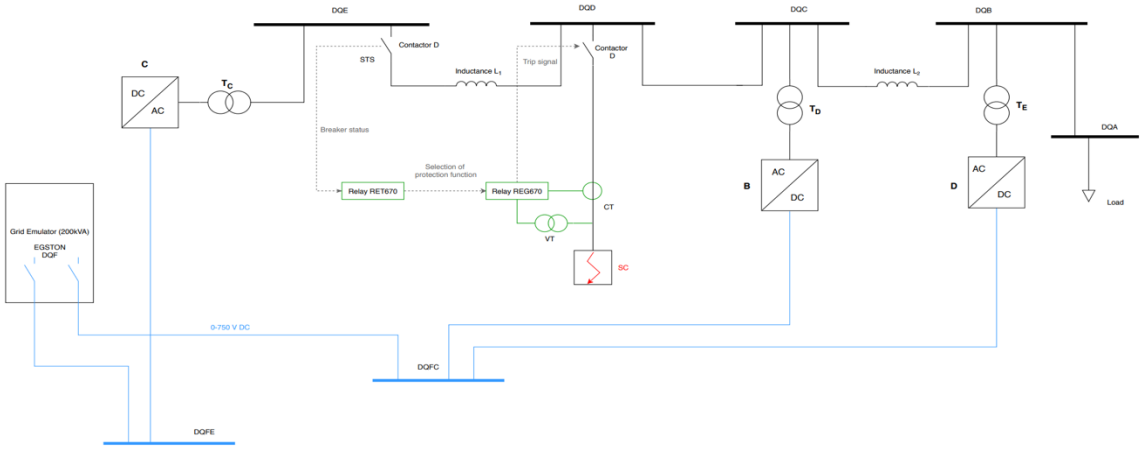


Fig 1: Illustration of the laboratory setup at the Smart Grid Laboratory at NTNU

Results

One of the main findings from the laboratory testing is that the fault current level differs in grid-connected and islanded operation. Consequently, the over-current relay does not operate in islanded mode because the pick-up setting in the over-current relay is configured based on the short-circuit contribution from the utility grid. The fault current level and the operation of the over-current relay during grid-connected and islanded mode is illustrated *Figure 2* and *Figure 3*, respectively. Thus, the need for an adaptive protection scheme is demonstrated, and the digital relay switches to the under-voltage protection function in the event of islanding. In this testing, the under-voltage relay operates on every short-circuit during islanded mode because the voltage always drops below the threshold limit during faults.

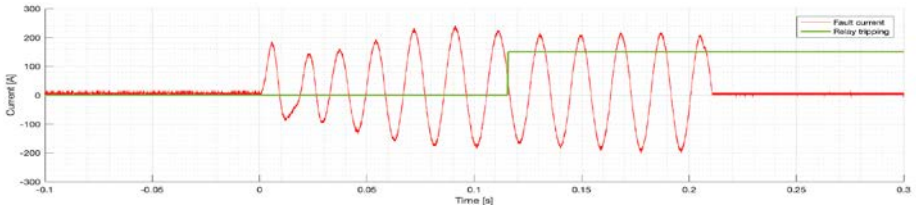


Fig 2: Fault current during grid-connected mode where the over-current relay trips after approximately 0.116 s and the short-circuit is disconnected at approximately t = 0.212 s.

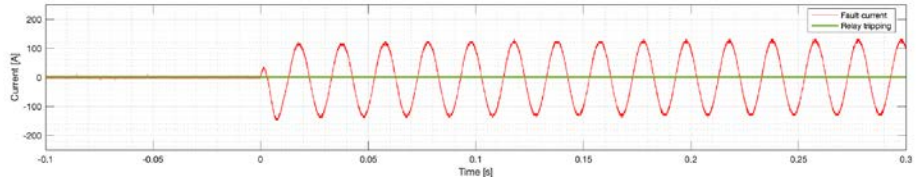


Fig 3: Fault current during islanded mode where the over-current relay does not operate.

Another important finding is that the fault current and voltage level depend on the implemented converter control. The control strategies are based on different active and reactive controllers that affect the current and voltage in different ways. Additionally, the control settings within each control strategy influence the converter behavior during faults.

Conclusion

The implementation of microgrids affects the reliability of conventional protection, so adaptive protection schemes which consider the dynamic changes in microgrids are needed. The laboratory testing showed that the fault current levels depend on the microgrid operation mode. Moreover, the converter control may affect the behavior of inverter-interfaced distributed generation units during short-circuits. Subsequently, the converter control and the impact on fault current and voltage level must be strongly considered when designing microgrid protection schemes.

Blockchain Technology Implementation for Electric Vehicle Charging within the Smart Grid Architecture Model

Student: **Mina Bergerøy Ryssdal**
Supervisor: **Irina Oleinikova**

Summary

This thesis investigates the potential of implementing the novel blockchain technology as a tool in smart grids. Traditional energy systems are currently facing new challenges and undergoing a transition towards smarter and more complex energy systems. Energy and climate policy and interrelated trends are driving the power system towards smart grids. Smart grids integrate new solutions and services and are characterised by extensive utilisation of information and communication technologies (ICT). The Smart Grid Architecture Model (SGAM) is introduced as a framework to increase the understanding of smart grid concepts. The SGAM methodology is used as a standardised approach to developing the smart grid use case "electric vehicle charging". One of the focal points in smart grids is to fully integrate the growing electric vehicle fleet into the power system.

Blockchain technology is gaining attention in the energy sectors, as a promising tool in the increasingly complex system. The novel technology has the potential to transform operations and markets by reducing friction and reducing roles in a system. By analysing the blockchain technology characteristics, it is recognised the technology can support the energy transition, and contribute to the ICT needs of a decentralised and dynamic power system with consumers at heart. The decentralised architecture of electric mobility, with multiple actors is as a promising application area for blockchain in smart grids. By considering the use case "electric vehicle charging" developed according to the SGAM methodology, functions and interactions involved are revealed. Here blockchain technology can be applied as an information technology to provide interoperable and innovative charging systems. Blockchain can reduce interaction and information frictions in a charging process while securing information and transactions. A specific application scenario is developed, where a blockchain-based system connects the actors and processes functions in electric vehicle charging. Additionally, the solution can integrate information flow for the provision of services to the power grid operation through demand response. The blockchain-based charging system is implemented on the Ethereum blockchain platform for proof of concept. The implementation and simulation prove a feasible solution by the use of smart contracts.

Energy Storage Emulation in Low Voltage Grid

Student: **Nora Sagatun**

Supervisor: **Elisabetta Tedeschi & Santiago Sanchez**

Problem Description

The work of this thesis concerns the grid integration of a battery energy storage system. The components involved in the system is described theoretically. Moreover, the battery pack is designed to fulfill the set requirements and tested computationally. A DC-DC converter is presented with an outline of the inner current control and outer voltage control. The battery and converter are implemented in the MATLAB/Simulink environment and the results are presented. Further, the power hardware in the loop (PHIL) methodology is explained. The battery pack and DC-DC converter is combined with a physical grid connection using a physical voltage source converter by employing the PHIL technique. The emulation of the energy storage system is presented through the laboratory results.

The Task

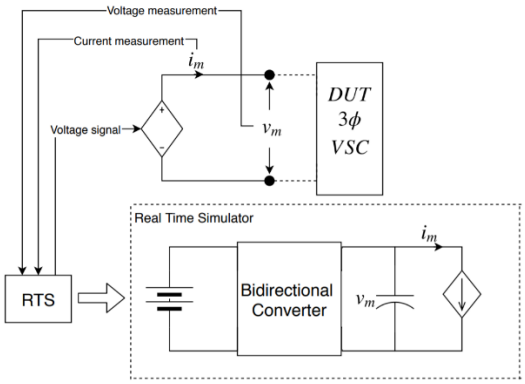
The aim of this thesis is to develop an emulation of an energy storage system in a grid connection conducted with a power hardware in the loop methodology. This will be achieved by reaching the following objectives:

1. Design and study a battery energy storage system.
2. Investigate and describe a DC-DC converter and design its current and voltage control.
3. Review the power hardware in the loop concept and create a structure suitable for an energy storage system emulation.
4. Develop a computational simulated model for testing of the battery pack and DC-DC converter to review the design and control setup.
5. Implement the power hardware in the loop structure with the simulated model in a real time simulation connected with physical laboratory equipment to obtain an energy storage system emulation for a low voltage grid

Model

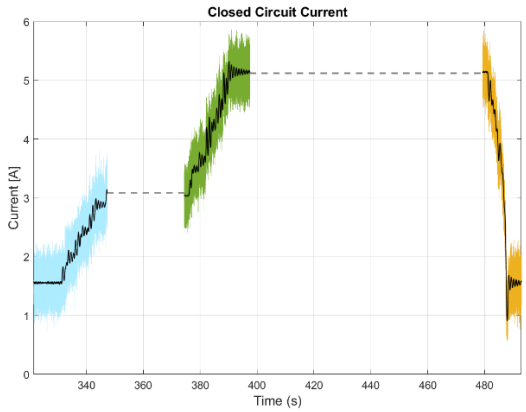
The system outline is defined in the figure below. The DC-DC converter circuit is included in the real time simulator (RTS). The converter is based on an average model of a boost converter. It can be observed that the physical equipment sends voltage and current measurements to the RTS, which is the corresponding voltage v_m over the capacitor in the RTS as well as the controlled current i_m of the circuit. The RTS is connected to the real device under testing (DUT) which is a physical three-phase voltage source converter. From there, the measurements of voltage and current are signaled to the RTS. The RTS simulates the energy storage model of the battery pack

and bidirectional converter and a load. As illustrated in the figure, the RTS sends a voltage signal to the physical equipment to a controlled voltage source.



Calculation

The figure below presents the resulting current from the laboratory test. This graph contains two different measurements. The black line represents the current i_k, the signal from the real time simulator which represents the simulation. The gray dashed line represents a constant estimated average between data logs. The blue, green and orange lines are the output current data logs from the physical laboratory equipment, i_{out}.



Conclusion

The laboratory results from the current signal depict an acceptable outcome where the current from the physical signals and the current from the simulated model follows the same values. However, the noise of the physical equipment is significantly larger than the noise in the simulation. This is due to the use of sensors at the laboratory rated to much higher currents, leading to a sensitive low current operation. The voltage signals from the physical laboratory equipment and simulation model responds identically throughout the entire simulation, which describes a successful PHIL test of an emulation of an energy storage system.

Investigation of Contact Erosion and Arc-Welding in a Medium Voltage Switching Device Using COMSOL

Student: **Martin Sanden**
Supervisor: **Prof. Kaveh Niayesh**

Problem description

In this master's thesis, a basic model for the material transport in medium voltage contacts during closing will be developed. Two contacts will be examined, a fixed and a moving contact, making it necessary to implement a moving mesh. In addition, phase change from solid to liquid state is included. For this purpose, the multi-physics simulation tool, COMSOL, will be used.

The main goals of this master's thesis is to examine the influence pre-strike arc has on the contacts during closing operation. Further, the aims is to investigate the welding behaviour of the closing contacts, and study the contact erosion at different short-circuit currents and arcing times.

The task

The task were to find the effect pre-strike arc had on a medium voltage switching devices during making operation. The main aims were to find the amount of contact erosion and arc-weld strength after the making operation had occurred.

Model/ measurements

Three base models were developed in the simulation program COMSOL. One for each contact material simulated: copper, tungsten and copper-tungsten. Each base model consisted of a fixed and a moving contact. There were two changing parameters: Short-circuit current and arcing time. Figure 1 presents the geometry used when simulating the different contact materials.

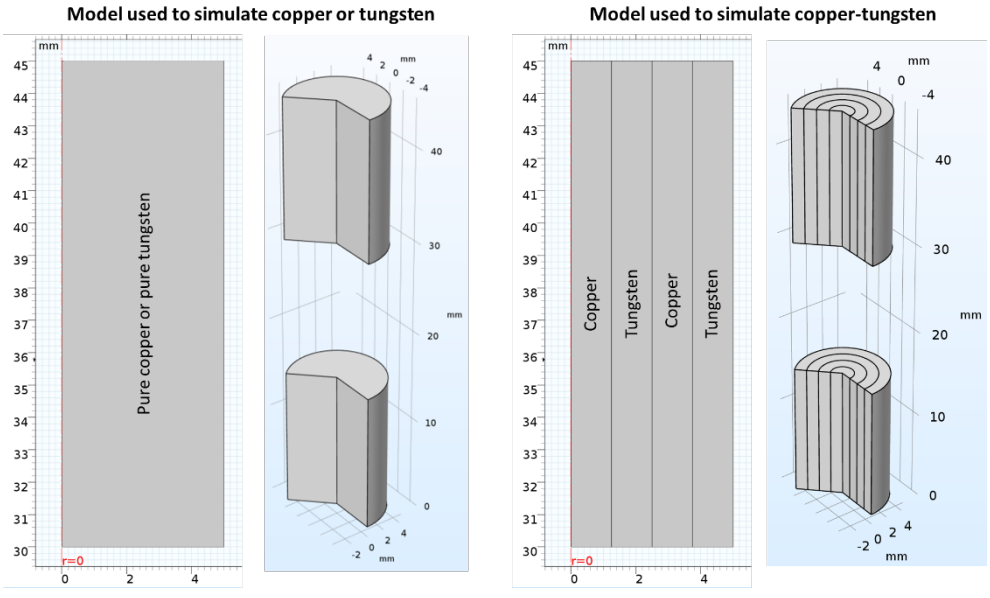


Figure 1: Geometry used to simulate the different contact materials.

The COMSOL model made it possible to examine both the temperature distribution and contact erosion after closing operation had occurred. Contact erosion were simulated by applying a deformation to the geometry after the temperature exceeded the vaporisation temperature. The arc weld strength were calculated by examining the contact temperature at mechanical touch. It was assumed that the liquefied material, from both contacts, in close proximity to each other fused together and made a weld. S

Calculation

It was found that pure copper had the lowest strength toward contact erosion and arc welding. Additionally, the results showed that copper-tungsten tolerated these thermal stresses best. At maximum short-circuit current and arcing time, the contact erosion for the contact materials copper, tungsten and copper-tungsten were 26.88 mg, 17.37 mg and 15.45 mg, respectively. Figure 2 shows the simulation with copper-tungsten.

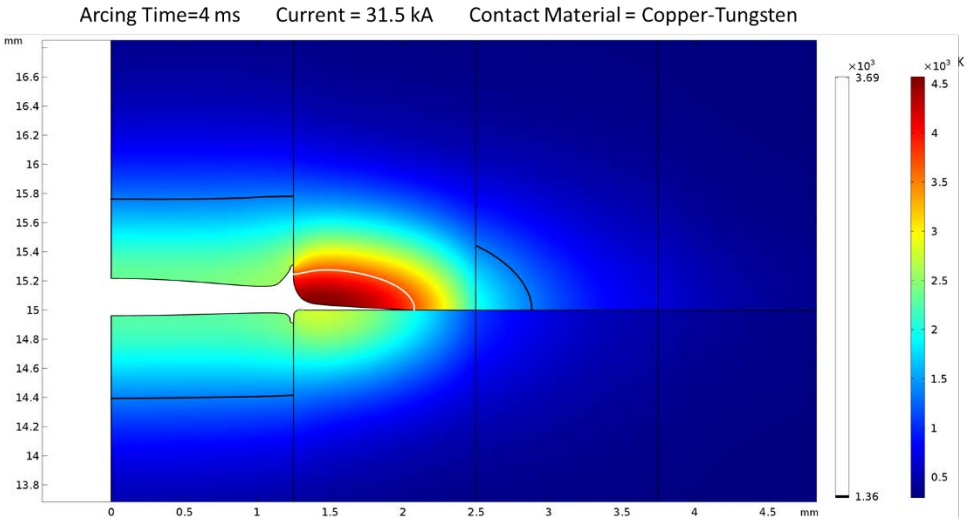


Figure 2: Simulations of the contact material copper-tungsten.

The contact material copper-tungsten were further examined, to see the impacts material distribution had on contact erosion and arc welding. The results showed that the contact material with high tungsten density performed the best.

Conclusion

Altogether, when examining copper-tungsten, it was found that increasing the amount of tungsten particles present at the contacts, reduced both contact erosion and arc welding strength. These results indicates that the contact material copper-tungsten is good with regards to thermal stresses during making operations.

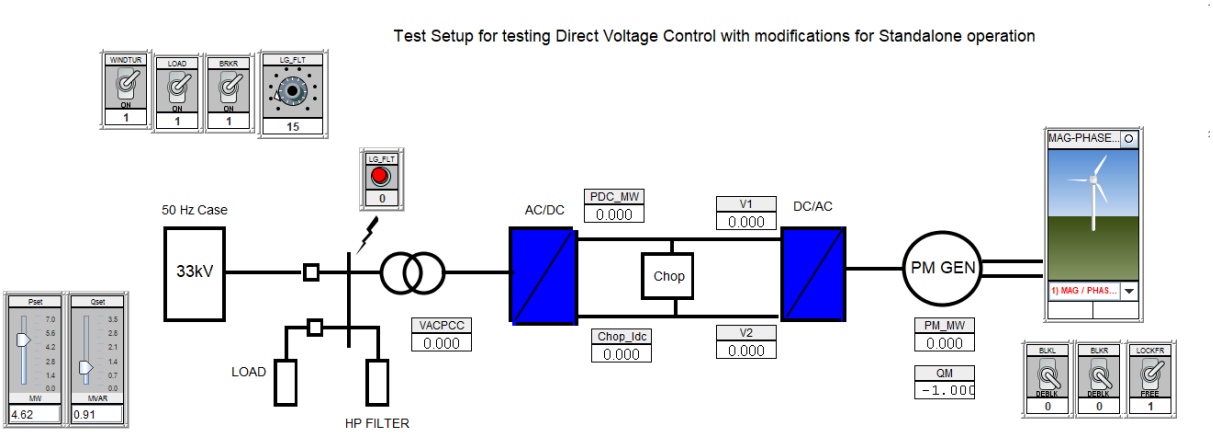
Real-time implementation for Grid-forming of type-4 wind turbine to mitigate voltage and frequency instabilities in high renewable penetration

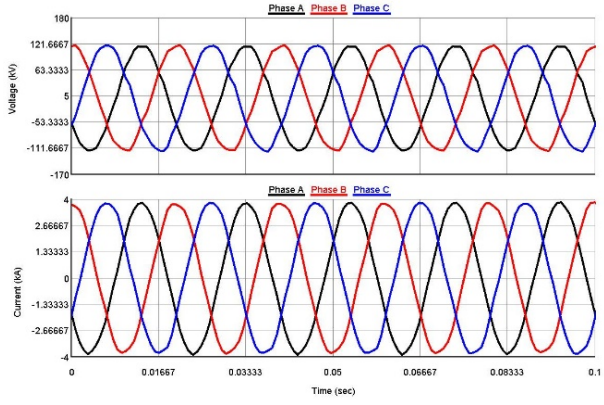
Student: **Shubham Sethi**
Supervisor: **Irina Oleinikova**
Collaboration with: **TU Delft**

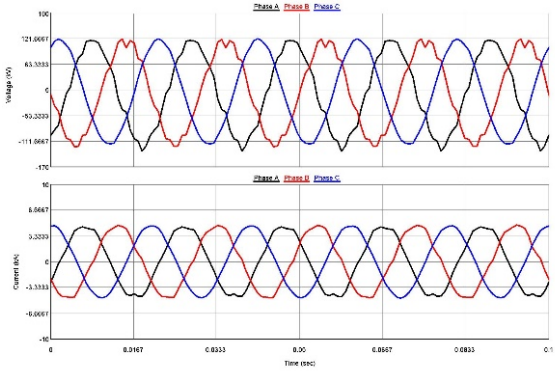
The increasing penetration of PE converter interfaced generation units in electrical power systems have given rise to many challenges in the power system operation. Two of the most important challenges are the voltage control and frequency control in the absence of conventional generation units. Furthermore, the PE converters can interact with the power system elements causing the power system to become unstable.

In this thesis, the effect of the wind turbines modified with grid-forming capability is analysed on the transmission networks as well as on the Offshore VSC-HVDC converter station. The dynamic response of the WTs is studied considering the high share of the power electronic converter interfaced generation. It is shown when the wind turbine power converters are equipped with the implemented control strategy, they can provide voltage and frequency stability to the system and further upgrades can be added to enhance the system response. The control strategy implemented employs the direct voltage control which is upgraded with voltage dependent active current control for improving the transient voltage recovery of the system. The inertial response based on modifying the machine side converter is also added which extracts kinetic energy from the wind turbine rotor that improves the frequency response of the system following load change.

In the end, an offshore wind farm network is modelled which includes the offshore wind park connected to an offshore MMC HVDC converter station for delivering bulk power to the DC source connected via the HVDC cable. The developed wind turbine model is employed for integration in the offshore wind farms which has shown to eliminate the transient overvoltages occurring in the offshore network during the blocking of the HVDC converter.







Automotive Drive for a Formula Student Racecar

Student: **Håkon K. Skeie**
Supervisor: **Roy Nilsen**
Collaboration with: **Revolve NTNU**

Problem description
The scarce amount of available drive systems for Formula Student racecars creates an opportunity to increase vehicle performance with the introduction of purpose-built, in-house systems. For the 2019 season, Revolve NTNU wanted to implement its very own drive system, thus replacing an off-the-shelf solution featuring four inverters, motor controllers and motors.

Model/ measurements
The inverter gate driver circuitry was validated using a double-pulse test setup to verify that the parallel configuration of SiC MOSFETs did not feature erroneously setups or compromising circuit layouts. As the system was not developed for testing, but for the final implementation, any proper current measurement through the transistor was impossible. The configuration was verified by the synchronous operation of the gate signals and the drain-source voltages across the transistor which operated to a satisfactory degree. A Simulink model of the control system for the IPMSM was developed from an existing model within the institute. It was used to verify that the proposed algorithm controls the motor with regards to its torque-speed curve.

The implementation of the same control system on the existing hardware platform was done using Atmel Studio for programming the Arm Cortex M7. A test bench was built to enable the verification of the system ahead of vehicle implementation. These tests included module verification, such as PWM modulator testing, low-range torque verification and field weakening assessment through no-load motor acceleration runs. The final drive was implemented on the intended vehicle to perform dynamic tests which was not feasible on the test bench due to mechanical limitations.

Abstract
Based on the characteristics of the new motors for the 2019 season, this thesis presents the proposed solution of an inverter and motor controller design, as well as the process of testing and validating these systems, for the implementation of a complete drive on the 2019 Formula Student electric racecar. An initial assessment was undertaken to produce the system requirements based on previous competition data, with analytical approximations of the effects of changing to an interior permanent magnet synchronous motor with a much wider field weakening range than the previous motor. The requirements developed specifies current handling capabilities for the inverter, and control requirements for the controller relating to the obtainable speed under current constraints.

The final inverter design features SiC MOSFETs in parallel to handle the on-state ohmic losses of the individual component, resulting in a successful current handling test, from the initial assessment, with a temperature rise of only 12 degrees under the harshest transient load at a switching frequency of 12 kHz.

Simulating the control system in a Simulink environment as an assessment of the viability of the controller designs showed satisfactory results. The chosen approach features a current reference calculator employing maximum torque per ampere (MTPA) strategy considering ohmic losses, and a maximum torque per flux (MTPF) strategy analytically estimating the effects of the voltage constraint and solving for stator flux angle by the Newton-Raphson method. Simulation results show a torque-speed curve encompassing the theoretical datasheet values, with a field weakening range of 33.75% of the motor maximum speed.

This approach was implemented on an existing hardware platform in C and was tested both on test bench and on the intended vehicle with the inverter. Even though test bench facilities limited the DC-link output voltage under load, the capabilities of the field weakening algorithm were deemed satisfactory when relating the voltage dependency to the maximum attainable speed, thus isolating the capabilities of the algorithm. Furthermore, the vehicle implementation showed satisfactory behaviour when moving between strategies, from MTPA to MTPF, both during acceleration and regenerative braking.

Lågspentforsyning i grisgrendte strøk

Student: **Hermann Skromme**
Faglærer: **Eilif Hugo Hansen**

Samandrag
Forbruksmønsteret hjå straumkundane er i stadig utvikling, og dette kan medføra at nettselskapet får problem med spenningskvaliteten når kunden aukar forbruket sitt. Det har i seinare tid kome til utfordrande laster, som f.eks. elbil-lading, induksjonstopp og direkte varmtvatn. Arvingar oppgraderar ofte elektriske installasjonar ved overtaking av generasjonsbustadar utan å nødvendigvis varsla nettselskapet. Dette fører til at forbruket går opp, noko som igjen medfører eit større spenningsfall. Dersom nettet er for svakt kan ein då få problem med spenningskvaliteten.

I Kvinnherad Energi AS har det sidan 70-tallet vore standard å installera 2x63A eller 3x63A inntaksikringar hjå kundane. Sidan ein ikkje hadde simuleringsverktøy til å sjekka spenningsfall og kortslutingsverdi hjå den einskilde kunden, har ein forhaldt seg til etablerte standarar.

Denne oppgåva ser på kva laster som skapar problem, samt korleis ein skal fanga opp problem med spenningskvaliteten før kunden tek kontakt. Oppgåva tek for seg både det tekniske og økonomiske aspektet ved å oppgradera nettet for å få tilfredsstillande spenningskvalitet hjå kunden. Hovudfokuset i oppgåva har vore å finna den beste samfunnsøkonomiske løysinga. Oppgraderingar som vert gjort i eksisterande nett utan at kunden har eit behov for oppgradering av inntaksikringen vert dekka gjennom nettleiga. Ved behov for større oppgraderingar i lågspentnettet, vil dermed alle kundane måtta betala.

For å finna den mest optimale oppgraderingsmetoden har eg køyrt NIS-analysar i nettet. Tradisjonelt sett har ein valt å forsterka tverrsnittet ved kundeklagar og mistanke om for dårleg spenningskvalitet. I denne oppgåva ser ein på moglegheiter for forsterking ved auking av tverrsnitt, installasjon av Voltage Booster, ombygging til 400V og bruk av 1000V. Felles for desse oppgraderingane er at ein til ein viss grad kan nytta eksisterande lågspentnett. I jakta på den beste løysinga, må ein og vurdera om utbyggingar i høgspentnettet er naudsynt, noko som normalt vil vera dyrare enn utbyggingar i lågspentnett.

Ved bruk av NIS-systemet kan ein gjera analysar både for spenningsfall og kortslutingsyting, og slik finna ut kor lang utstrekking av lågspentnettet ein kan ha før ein kjem under grenseverdiane. Ved å samanlikna verdiar frå NIS-systemet og data frå AMS-målarar kan ein få eit bilde av korleis kart og terreng stemmer overeins.

For å finna den beste tekniske og økonomiske løysninga på korleis ein skal oppgradera nettet, må ein samanlikna fleire metodar. For å trekkja rett slutning er det også viktig å ha ei formeining om korleis bruksmønster og lastsituasjonar vil utvikla seg i tida som kjem. Dersom ein gjer ei oppgradering av nettet slik at ein akkurat overheld noverande krav, kan ein komma i ein situasjon der ein må gjera ei ny oppgradering om få år.

A Method for Planning a Fast Charging Station -Applied to the distribution grid of Eidsiva Nett

Student: **Nathalie Skyttermoen**
Supervisor: **Gerd Kjølle**
Collaboration with: **Eidsiva Nett**

Summary
This master thesis presents a suggestion for a planning method for fast charging stations. A new way of thinking when planning new, large connections in the grid will be necessary for the future distribution grid to be socioeconomic beneficial. Cooperation between the owner of the charging station and the distribution system operator will be crucial to obtain a better utilization of the existing power grid. The need for establishing new load profiles, especially one for fast charging stations was found to be important, as the peak load of a fast charging station occurs during the summer while the existing load profiles are calculated with a peak load in the winter. Besides, a large load such as a fast charging station will require a finer resolution in the load variation in the grid simulation software than it is today. Based on traffic counting, one can see that there is a significant difference between the traffic on a Monday evening compared to a Friday evening. The same applies for the weekends, when there is a lot more traffic on the road on Sunday evenings than Saturday evenings.
One cannot always elect a location based on the available capacity in the grid, but the location does also need to be a logical place to stop, have some basic facilities and enough space to establish a charging station.

There is a need for a standard for the requirements of the security of supply, removing that question from the planning process and making the charging stations more predictable for the end-users.
This thesis has looked at different alternatives in addition to traditional reinforcements of the grid to cover the increased power demand from a fast charging station. A solution with a battery without any grid upgrades can be beneficial if the total price of the battery system is low enough, it can also be a good temporal solution if the power demand is expected to increase further in the following years. A solution that combines reinforcements of the grid and a smaller battery will probably not be that beneficial, as the price difference between upgrading two different cross-sections is not very large compared to the installation cost. Both the solutions with a battery in the grid will require a lot from the battery, which will be very costly with many charging cycles during the year for this application. The batteries need to have enough storage capacity to cover the demand in all the hours it shall be used, and it requires large enough power capacity to recharge in the possible hours.
The second alternative to traditional reinforcement is smart power management which utilizes the existing grid to the maximum. Such a solution will reduce the power to the charging station in the busiest hours of the year, according to the simulation done in this thesis. There may be exceptions somewhere in the grid, making that alternative worth to consider, as it will be the most economically beneficial alternative if the supplied power can be tolerable.
Technical and economic analysis for different alternatives and locations have been performed in this thesis, where the alternative with traditional reinforcement was the best alternative for all locations, given that the total price of a battery system is higher than 1030 kr/kW.

Prosesstøtte og visualisering i neste generasjons asset management

Student: **Torbjørn Slinde**

Veileder: **Eivind Solvang**

Utføres i samarbeid med: **SINTEF Energi**

Problemstilling
I dag står kraftselskapene i et veiskille. Den teknologiske utvikling har på kort tid ført til stor omvelting i kraftbransjen. Samtidig blir komponentene i kraftnettet eldre som fører til svekkelse av komponentenes tilstand. Videre skal det investeres svært mye i nettanlegg i Norge de neste ti årene. Nettselskapene er nødt til å balansere planlagte investeringer med blant annet drifts- og vedlikeholdskostnader. Dette kan knyttes til begrepet asset management eller anleggsforvaltning, som er et begrep som brukes i mange ulike bransjer. Generelt gjør asset management en organisasjon mer rustet til styring og drift, og omhandler balansering av kostnader, ytelse og risiko. Asset management dekker spesielt to områder: forvalting av anleggsområdet og det mer organisatoriske. I denne oppgaven er det valgt å fokusere på det første området, med hovedvekt på vedlikehold og reinvestering/fornyelse

Oppgaven
Målet med oppgaven er å vise hvordan visualisering kan gi bedre beslutningsstøtte for vedlikehold og reinvestering i det høyspente distribusjonsnettet. Hovedfokuset ligger på hvordan ulik informasjon kan visualiseres for at nettselskapene får et bedre grunnlag for beslutningstaking. Denne masteroppgaven er tilknyttet pågående arbeid i arbeidspakke 1 (WP1) Smart grid development and asset management i FME CINELDI.

Oppgaven deles inn i de tre følgende delaktivitetene:

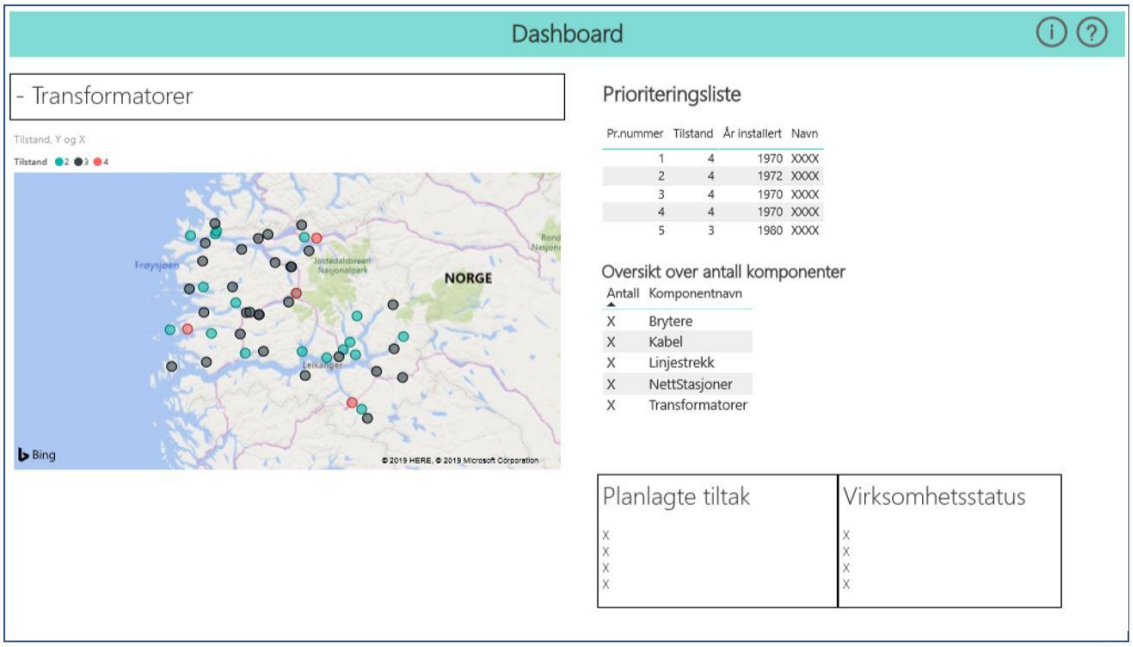
1. Utvikle skisser og eksempler i verktøyet Power BI av noen utvalgte vindu fra et tenkt dashboard.
2. Vise hvordan visualisering kan gi bedre beslutningsstøtte for vedlikehold og reinvestering ved hjelp av casestudier.
3. Sende ut en spørreundersøkelse til ulike nettselskap. Undersøkelsen skal berøre dagens praksis for asset management, samt gi nettselskapene mulighet til å komme med kommentarer til resultater fra de to delaktivitetene nevnt over.

Resultat
Hovedfunksjonen til et tenkt dashboard vil være at selskapene får en oversiktlig plattform som støtter beslutninger for vedlikehold og reinvestering av ulike komponenter. Et dashboard er avhengig av god datakvalitet og tilgjengelig inngangsdata. Dashboardet deles inn i flere vindu og gir ulike brukere informasjon for å bedre kunne planlegge handlinger. Utvalgte skisser tilknyttet et tenkt dashboard er utarbeidet i visualisering- og analyseverktøyet Power BI utviklet av Microsoft. Eksempel av en hovedside er vist i Figur 1.

Videre er det presentert tre caser. Alle tre casene er viktig for visualisering i form av informasjonsgrunnlag for strategier og metoder for beslutningstaking. I case 1 er det sett på hvordan miljø- og komponentdata kan brukes til å plukke ut høyspentmaster. Dette er master som er forventet at skal skiftes ut basert på alder og ulike grunnforhold. Selskapene får på denne måten en oversikt over forventet utskifting de neste årene. I case 2 visualiseres resultatene fra prosjektet REPLAN, hvor det er utført tilstandsvurderinger med tilhørende økonomiske analyser for ti ulike fornyelsesalternativ. Det er flere faktorer som spiller inn ved valg av alternativ, og faktorene kan visualiseres for å gi et bedre grunnlag for beslutningstaking. Beslutning er ofte knyttet til risikoaspektet, og spesielt konsekvenskriteriet personsikkerhet. Dette blir sett på i Case 3, hvor det er presentert ulike måter for å

prioritere tiltak basert på risiko. Det å sammenligne ulike konsekvenskriterier er utfordrende, da det blir en kombinasjon av både kvalitative og kvantitative vurderinger. Det er vist at personsikkerhet bør vektes høyest for beslutningstaking, mens risikoen for de andre kriteriene bør fungere som supplement til å bestemme rekkefølgen for ulike tiltak

For å kunne kartlegge behovet for et dashboard, ble det sendt ut en spørreundersøkelse til 14 nettselskap, hvor syv nettselskap svarte på undersøkelsen. Målet med spørreundersøkelsen var at nettselskap kunne komme med kommentarer til skisser av et tenkt dashboard og resultat fra casestudiene, samt svare på spørsmål knyttet til asset management. Tilbakemeldingene fra de syv nettselskapene har vært verdifull for denne oppgaven.



Figur 1: Hovedside i et tenkt dashboard

Konklusjon

I oppgaven konkluderes det med følgende:

- Visualisering knyttes til grafer, tabeller, matriser, kart og ulike dashboard. Et dashboard knyttes til en prioriteringsliste basert på risiko og tilstand. Verktøyet Power BI anbefales for å sammenstille mindre datasett og presentere enkle analyser. Verktøyet vil gi utfordring ved bruk av kartdata.
- Tre casestudier er gjennomført. Casene underbygger ulik bruk av metoder for visualisering som beslutningsstøtte.
- Spørreundersøkelsen viser at det er stort fokus på digitalisering og at å sammenstille data fra ulike kilder vil kunne forbedre beslutningsprosessen. Erfaring fra personer som har arbeidet med asset management i en årrekke skal ikke undervurderes, og har vært verdifull for denne oppgaven. Spørreundersøkelsen har bidratt til å verifisere resultatene og gitt gode innspill.

Incorporating Demand Side Response in Power System Adequacy Studies

Student: **Anette Solheim**
Supervisor: **Vijay Venu Vadlamudi**

Problem description
Increased amount of intermittent renewable resources, phase-out of flexible coal and gas power plants, in addition to a changing energy demand at the consumer side with increased use of power demanding appliances, challenge the security of supply. Due to these changes, the power system in Europe is expected to observe a rising scarcity of flexibility. Demand side response (DSR) programs are one type of resources that can offer flexibility and thus improve the system reliability. With the introduction of the smart grid regime, smart meters and other smart house technologies, the possibilities for DSR have gained a lot of attention recent years. Smart meters and information and communication technology (ICT) that enable two-way communication between the consumer and the utility, are facilitating the possibility for load shifting at the demand side.

The task
The objective of this thesis is to incorporate DSR in power system adequacy studies. The DSR models consist of two methods for load shifting, referred to as load shifting method (LSM)1 and LSM2, and a model for price-responsive demand, real-time pricing (RTP) model. LSM1 is based on a model found in literature which has a load recovery procedure that can create spikes in the load profile for greater amount of shifted load. Such spikes can illustrate rebound effects that can appear when loads are reconnected after a disconnection period. Thus, in LSM2, a uniformly distributed load level in the valleys is proposed. Effective Load Carrying Capability (ELCC) is chosen as the capacity credit and existing software that calculates the ELCC at hierarchical level (HL)I for other types of resources is extended to handle DSR resources available for load shifting modelled by LSM2 for both HLI and HLII evaluations. The generation- and composite system assessment, and ELCC calculations are performed on two standard test systems, the Roy Billinton Test System (RBTS) and the IEEE-Reliability Test System (RTS).

Methodological approach
The main adequacy indices used in the assessment are Loss of Load Expectation (LOLE) and Expected Energy Not Supplied (EENS). Adequacy indices are calculated either by an analytical method or by Monte Carlo simulation using existing software. Load modifications are carried out in advance of the simulations. LSM1 and LSM2 are utilized for different levels of shaved energy in a yearly chronological load profile. The RTP model considers day-ahead prices where the consumers can reschedule their energy demand over a 24-hour period. Higher prices are triggered by outage cases. Price elasticity matrices (PEMs) are used to model consumer reaction to price differences and PEMs of optimizing consumers that shift load from peak to off-peak hours are used. Figure 1 illustrates original and higher prices observed at a bus in the RTS. Figure 2 shows the original and the corresponding price responsive demand. The ELCC is calculated by obtaining indices for a system without and with DSR resources available for load shifting at increasing load levels. The procedure is illustrated in Figure 3. The horizontal distance between the curves is the ELCC for a specified amount of DSR resources.

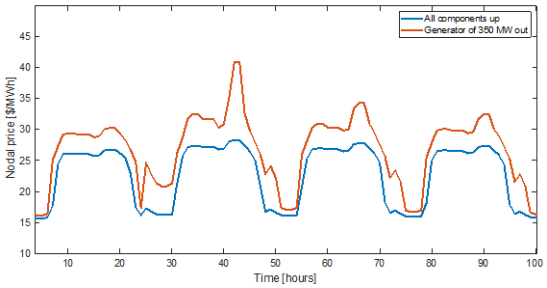


Figure 1: Nodal prices for base case and an outage case.

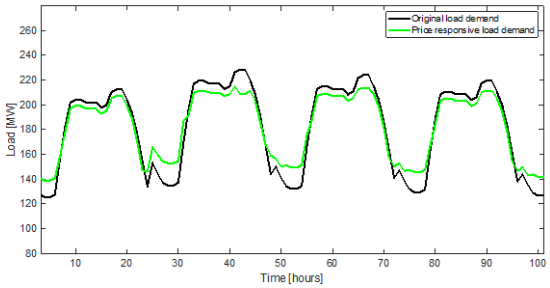


Figure 2: Original and price responsive demand.

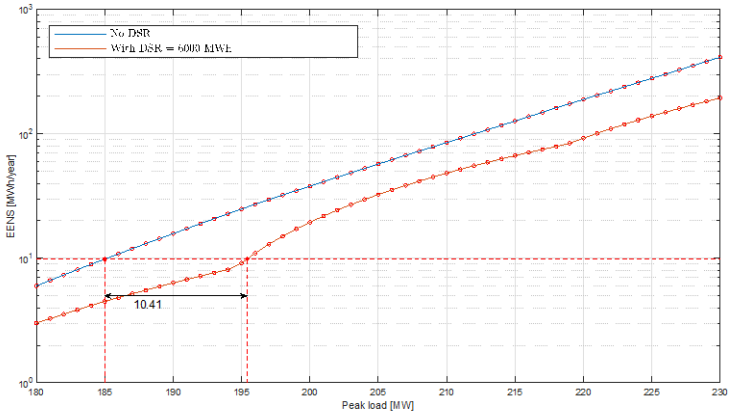


Figure 3: Illustration of graphical solution method for ELCC calculations.

Conclusion

The main results for the assessment reveal that load shifting performed by LSM1 and LSM2 has a positive influence on system indices. Bus indices that experience most improvement in index values are buses with lowest curtailment costs. Bus indices of buses that are less connected, e.g. radial connections, appear to have little improvement with increased amount of shifted load. It is observed that indices obtained with LSM2 are lower than the indices obtained with LSM1 at higher load shifting percentages due to the different valley filling procedures of these methods. The results obtained with the RTP model show that higher price differences, especially in high demand periods, give greater load responses which improve the adequacy indices. Further, increased elasticity coefficients are shown to improve the indices until a self-elasticity coefficient of -0.4 for the case studied. An increase in the index values is observed with this elasticity coefficient since load spikes are introduced in the load recovery period.

The ELCC results show that the procedure is dependent upon the system size and configuration, and which index that is used in the evaluation. The EENS index yields in general higher ELCC values than the LOLE index. The ELCC for increasing amount of DSR resources is investigated and the main observations are a declining increase in ELCC for the RBTS, and little difference between the ELCC at HLI and HLII for the RTS due to a reliable transmission grid in this network. A fixed amount of energy demand available for load shifting is evaluated at each bus in the RTS. The results show that the ELCC is differing among the buses.

Flashover Characteristics for Medium Voltage Insulators.

Student: **Frode Solskinnsbakk**
Supervisor: **Hans Kristian Høidalen**
Contact: **Bjørn Gustavsen**
Collaboration with: **SINTEF**

Abstract

A laboratory experiment has been successfully carried out in the high voltage laboratory at NTNU. Five different pin insulators, all with rated voltage of 24 kV, were subjected to 1.2/50 _s voltage impulses. For each voltage level, five impulses were applied, before the voltage amplitude was increased, and the process repeated. The voltage across the insulators was measured with an oscilloscope, and the flashover voltage and time registered, to obtain the voltage-time characteristics.

Four different flashover models have been investigated. The voltage-time characteristics for the flashover models have been fitted to the experimental results by the use of Matlab. The data obtained during the fitting process was implemented in the simulation software ATPDraw. The performance of the flashover models was tested by simulating lightning strikes to one of the phase conductors of a three phase power line.

One of the four models (No.2) has been suggested for simulation purposes regarding flashover across insulators with a rated voltage of 24 kV. This suggestion applies for two of the insulators tested, which are frequently used in the distribution grid in Norway.

Design Procedure and Cogging Reduction for Coaxial Permanent-Magnet Gears

Student: **Soløst, Ivan**
Supervisor: **Nilssen, Robert**

Abstract
High-performance magnetic gears are no longer a novelty but have yet to attain industrial commercialization. This is despite obvious advantages such as friction-free rotation and inherent overload protection. This, in addition to achieving high torque densities, makes magnetic gears competitive with classical mechanical gears. The aim of this thesis is to take a step closer towards commercialization by systematizing the design process of a coaxial permanent-magnet gear. This includes presenting various techniques to reduce cogging torque, which can be a significant issue.
Simulations were performed using finite-element analysis in COMSOL Multiphysics. The combined cogging reduction techniques gave a 64% reduction in the cogging torque amplitude for a given combination of poles and pole pieces, while reducing the maximum torque transmission by only 35%. An academic prototype was designed, built and tested. The test results were highly deviant from the simulated torque ripple, which was found to be due to manufacturing inaccuracies. A step-by-step design procedure for coaxial permanent-magnet gears is proposed and an important note is made on the simulation method to get a more realistic torque ripple. It is demonstrated that heavy simulations requiring super computers are not necessary to find gear layouts with simulated torque densities in the 100-140 kNm/m^3 range.

Design and Optimisation of Electrical Collectors for a Multi-Rotor Wind Turbine System

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Collaboration with:

Abstract:

The extensive use and fast development in wind power also introduce challenges as the wind turbines keep increasing in size and power rating. The high amount of material required to realise the massive turbine blades and other components makes it hard to keep reducing the Levelised Cost of Energy (LCOE). As a result, new and innovative designs are studied to find other methods to realise high energy density wind turbines.

As a way of realising a large producing unit with material savings, the old concept of multi-rotor wind turbines has been relaunched recently. In a multi-rotor system, several small rotors are connected with small spacing, which in total sweep a large area in order to produce a high amount of power. Since smaller rotors are used, this drastically reduces the material required to develop the system. Promising aerodynamic studies have been performed for the concept. However, thorough studies of the electrical design of the system are still lacking. This work, therefore, concentrates on researching this aspect and proposes different electrical design configurations for the multi-rotor system. The proposed configurations are compared under different scenarios. The proposed configurations are all cluster connections and have been identified in this work as AC cluster, DC cluster and hybrid cluster. It is important to emphasise that these configurations relate to the way in which the power output of the small rotors is collected.

It is noticed from prior work on this topic that to study only power losses is insufficient to compare different design options. In this study, a multi-objective optimisation method is used to obtain several key performance indicators, such as efficiency η, power density ρ, and power-to-mass ratio γ, to compare and to choose the optimal design for a multi-rotor system. Key indicator parameters are defined and studied extensively for the different configurations, as is shown in the thesis work. Moreover, Pareto analysis is performed to locate potential design points and reasonable trade-offs between several parameters and objectives that can be contradictory, such as maximising efficiency and minimising volume and mass.

Extensive analyses have also been performed to establish analytic expressions for the power losses, volume and mass of the components included in this study, as these are needed to evaluate η, ρ, and γ. The components considered include the power electronics, that is, the switch valves, DC-link, and phase reactors.

Various cases have been defined in order to perform solid comparisons. The two first cases use three turbines per cluster, with machines rated at 444 kW, but with changed modulation method. Further, case 3 and 4 study the behaviour of the configurations when the cluster size and the machine size are increased. Finally, case 5 studies a DC series-connection of wind turbines, different from a parallel-connection which has been one of the configurations in the previous cases.

The results achieved have shown significant differences with different modulation methods, so this may influence the overall design. Also, the increase in the cluster size and machine size has been found in this work to be beneficial. However, this also provides challenges regarding control and can reduce the potential gain in aerodynamic behaviour as well as reduced material.

Overall, the DC and hybrid cluster connections perform the best. The hybrid configuration has the highest power density and the power-to-mass ratio at machine power of 444 kW but requires operation at non-optimum speed. The parallel-connected DC cluster performs close to the hybrid cluster, and its topology is worth investigating more. Besides, the series-connected DC configuration, reducing the need for transformers, was promising. However, DC collector grids evidently need more research.

Nonetheless, to make the system compete with conventional turbines, the substantial reduction of components in the DC and hybrid clusters may be necessary. The results obtained help discussing potential advantages for each configuration, but further research, including the control, must be performed to choose a proper design.

An investigation of lithium-ion battery degradation during shallow-, deep- and combined cycles

Student: **Mats K. Sundklakk**
Supervisor: **Trond Leiv Toftevaag**
Collaboration with: **SINTEF Energy Research**

Problem description
This thesis aims to develop a hypothesis on a possible methodology to estimate battery life that are exposed to three different cycle-programs.

Abstract
This master thesis investigates the degradation rate of nine identical lithium-ion batteries. The batteries are the Super B 12V2600P-AC, which is a lithium iron phosphate-type (LiFePO4). Every battery was new from the manufacturer. The experiments were conducted with Chroma 17020 Regenerative Battery Pack Test System situated in the National Smart Grid Laboratory in Trondheim, Norway.

Chapter 4 conducts a Performance and Capacity-test on all nine test objects. The test revealed the battery's actual capacity, voltage-profile, internal development of heat, and internal resistance. None of the batteries had experienced errors during production and performed as expected.

In chapter 5, the nine test objects were distributed across three different Cycle-tests and cycled as much as possible. The chapter describes the construction of the Cycle-tests and how to execute them. Cycling every battery almost 900 hours and 465 full cycles resulted in various levels of capacity fade and degradation. Other parameters, such as internal resistance, maximum temperature, and losses, are also presented in this chapter.

Figure: Chroma 17020 Regenerative Battery Pack Test System

Conclusion
Estimating battery life is an intricate procedure that is dependent on many factors. The results from the Cycle-tests show that the higher the depth of discharge, the higher the rate of degradation.

Pedagogisk forbedring av undervisningen på NTNU med emnet Elektriske kraftsystemer som eksempel

Student: **Simen Svagård**
Faglærer: **Eilif Hugo Hansen**

Sammendrag

I denne masteroppgaven sees det på hvordan undervisningen av emner på NTNU kan forbedres. Oppgaven beskriver ulike aktive læringsformer og pedagogiske prinsipper som Konstruktiv justering og relasjon, og viser hvordan disse benyttes i emner både på NTNU og andre universiteter. Selv om nye læringsformer er tatt i bruk i noen grad, er hoveddelen av undervisningen på NTNU fortsatt basert på tradisjonelle forelesninger. Aktiv læring handler om at de tradisjonelle forelesningene begrenses til å introdusere de sentrale begrepene i pensum. Deretter er det opp til studentene å ta ansvar og bruke forskjellige læringsformer for å ta til seg utfyllende informasjon for å oppnå identifiserte læringsmål. Oppgaven diskuterer hvordan aktive læringsformer kan anvendes i praksis i emnet Elektriske kraftsystemer og i undervisningen på NTNU generelt. Emnet har ifølge referansegrupperapporter forbedringspotensialer på en rekke områder. På bakgrunn av dette, samt egne erfaringer med emnet, foreslås det konkrete forslag til endringer. De siste årene har pensum primært blitt formidlet gjennom tradisjonelle forelesninger med støtte i lysbildeframvisning og tavleregning. Det foreslås derfor å forsøke en aktiv læringsform kalt Flipped classroom. Det er en moderne læringsform der studentene forbereder seg hjemme før forelesningen. Forelesningen erstattes med gruppediskusjon og oppgaveløsning. Et nytt øvingsopplegg, med faste øvingstimer i uka der øvingene ikke skal leveres inn, bør også prøves ut. Det kan kunne bidra til å løse dagens utfordringer med umotiverte studenter på grunn av lange øvinger, og også redusere juks med løsningsforslag som dessverre synes å være relativt vanlig på NTNU. Dyktige studentassistener er nødvendig hvis disse læringsformene skal fungere. De trenger bedre pedagogisk opplæring for å kunne gruppeundervise og hjelpe studenter som står fast.

Jordfeil i Spolejordet Regionalnett

Student: **Morten Paulsen Særen**
Faglærer: **Hans Kristian Høidalen**

Sammendrag
En forenklet modell av Nordnettet er etablert i programvaren ATP Draw. Modellen er designet for å analysere jordfeilstrømmer, spenning og resonanskurve. Den er bygd opp slik at man selv kan stille inn spoleinnstillingene etter ønske. Modellen fungerer til sitt formål og man kan legge på konduktiv avledning. Modellen kan kjøre transiente grafiske analyser av både feilstrøm i spoler og feilsted. Feilstrømmen er blitt presenter for feil i alle regionene. På bakgrunn av disse feilene er det blitt sett på hvordan feilstrømmen oppfører seg. Det er også sett på spolenes egenskaper før og etter feil.

Det er observert at spolene bruker lengre tid på å stabilisere spolebidraget for feil langt unna. I tillegg vil den transiente responsen ha høy amplitude. Den høye amplituden er avgjørende for hvordan feilstrømmens utforming blir. Har man høyt spolebidrag i et område vil feilstrømmen i feil langt unna dette område få lavt makspunkt på impulsresponsen. Til gjengeld bruker også disse feilene lengre tid på å nå ønsket feilstrøm.

I alle feilsituasjonene simulert vil feilstrømmen i modellen kompenseres ned til et ønsket nivå. Det er ikke noen forskjell på hvor feilen er lokalisert. Strømmene i spolene nærmest feilen vil ha minst svingninger og stabilisere seg raskest for å gi bidrag. Når feilen er i et område med høy spoleytelse vil feilen raskt bli kompensert ned til ønsket nivå. Størrelsene på spolene vil være avgjørende for hvilken kurve man ønsker på feilstrømmen. Det er ikke avgjørende med utformingen på kurven til feilstrømmen, da denne strømmen vil kompenseres ned i alle feilstedene i nettet

I feilstedet vil feilfasen ha null spenning mens de to friske fasene får en spenningsheving på$\sqrt{3}$. Ser man på ende til ende spenningen så vil feilfasen etablere en liten spenning, mens de to andre fasene fortsetter med en lik spenningsheving på ca. $\sqrt{3}$.

Det kan tyde på at konduktans bidrar med å øke feilstrømmen med en reel del i feilstrømmen. Det er absoluttverdien på den komplekse strømmen som avgjør hvor stor feilstrømmen blir. Spoleinnstillingen kan være korrekt, men med økt reel del vil det ikke være mulig å oppnå ønsket verdi på feilstrømmen. Det ble gjort funn av skjevfordelte faser der feilfasen fikk forhøyet spenningsnivå og den ene friske fasen fikk et minsket nivå.

Peer-to-Peer Energy Trading in Combination with Local Flexibility Resources in a Norwegian Industrial Site

Student: **Guro Sæther**
Supervisor: **Olav Bjarte Fosso**

Abstract
With the increasing deployment of decentralized renewable energy sources (DERs) and energy demanding devices, the power system is facing new challenges, such as the need of flexibility options at local level. Meaning that the power system conventional top-down structure might change as consumers are becoming more active entities. Such a restructuring requires new ideas for market designs that considers local energy features. Thus, energy storage systems and peer-to-peer (P2P) energy trading have emerged as new ways to decrease the stress of the grid and foster the deployment of DERs. Another promising solution to incentive consumers to reduce their power demand and forward efficient network utilization, is to implement a peak power charge in the grid utility tariff. Industrial customers are already subject to such a peak power charge, and are billed for the highest peak drawn from the grid each month.

As some local market designs have been proposed for residential communities and smart grids, this study proposes two market designs for an industrial site centered on the role of P2P energy trading. With higher energy demand and a peak power charge, industrial consumers are subject to a considerably cost of electricity. In this study, the value of P2P energy trading in combination with various local generation and flexibility resources are assessed for a Norwegian industrial site. The objective is to minimize the total cost of electricity, while ensuring a fair market design for all participants in the industrial site. In this regard, the system operation of P2P trading subject to the peak power charge is an additional contribution to the existing literature. An optimization model, based on multi-period linear programming, is built and simulated with a time horizon of one year in GAMS. Several analyses are carried out using time series (representing a proxy industrial site) provided by the grid owner, NTE Nett AS, located in central Norway.

The main findings note that P2P energy trading is able to bring economic benefits to the industrial site, as well as to the individual buildings, with yearly net savings of the total cost of electricity of 6.8 \% and 11.0 \% in the two local markets. Further, using P2P energy trading for peak shaving purposes are highly beneficial. The total cost of peak power is reduced 15.0 \% and 25.6 \% in the two case studies, with the substantial peak power charge as key driver, making peak shaving the largest contributor to the net cost savings. Moreover, the industrial site consumes more distributed generation locally, with no power curtailment and reduced grid feed-in. The thesis provides novel results on the benefits of P2P energy trading, especially with regards to industrial customers and the peak power charge.

Stability and Control of a Microgrid

Student: **Roger Thoresen**
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Contact: **roger.thoresen@outlook.com**
Collaboration with: **Siemens PTI and Sunnfjord Energi**

Problem description

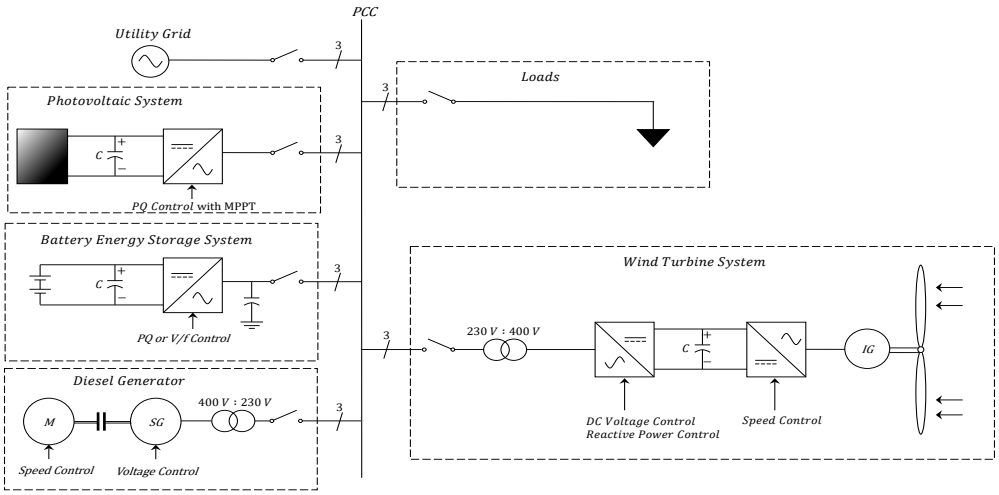
Many of the remote areas connected to the grid today needs an upgrade or replacement of the current connection. For the gird companies, and hence the customers, the reinvestment costs are high compared to the consumption. This provides an incentive for alternative solutions. One of the alternative solutions is to implement a microgrid with local production and storage. Introducing local production, such as wind and solar, in combination with storage solutions, such as batteries and hydrogen, could increase the self-consumption and reduce the dependency of the connection to the distribution grid. Or even remove the need of a connection at all. An initiative actuated by the Norwegian energy company Sunnfjord Energi, in cooperation with Siemens PTI, aims to facilitate a microgrid solution in their concession area.

The task

Through the specialization project the long-term energy balance and cost where considered. In this thesis the aim is to further develop a comprehensive model suitable for analysis of transient events and with a control that ensured stabile operation. The focus is on the transition from grid-connected operation to islanded operation.

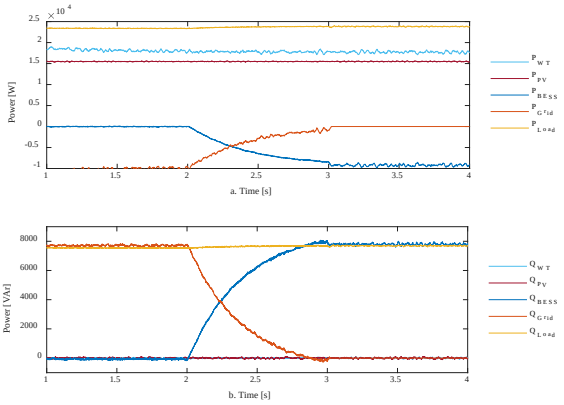
Model/ measurements

The microgrid model and control is developed in the MATLAB/Simulink environment. The existing low voltage grid is modelled with pi-sections and obtained parameters from Sunnfjord Energi Nett, while the distributed generation is based on mathematical representations and parameters given in literature. With each of the electricity generation units connected through two-level voltage sourced converters, a large share of the thesis is devoted to the introduction of the control techniques. The control is mainly derived in the dq-reference frame where the traditional measurements of voltages and currents are transformed through a Park's Transformation. Controller tuning is mainly performed with the use of well-known techniques as Modulus- and Symmetrical Optimum. The Battery Energy Storage System (BESS) functions as a master unit controlling the frequency and voltage during islanded operation.

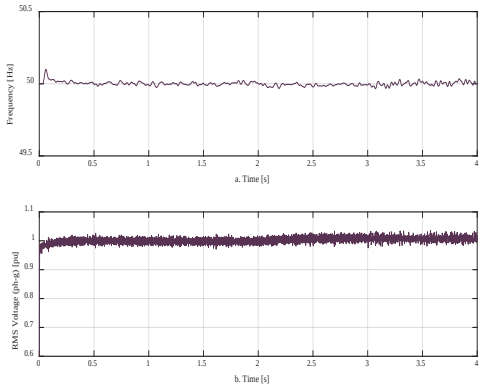


Calculation

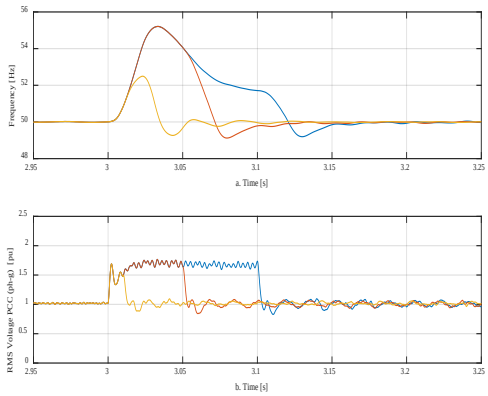
Through a series of simulations of intentional- and unintentional islanding the system's ability to perform a stable transition was considered. With an intentional islanding the power export/import is minimized before islanding, leading to a stable transition without large impacts on the frequency and voltage. The case is rather different for unintentional islanding where either islanding detection time delay is implemented, or islanding without BESS.



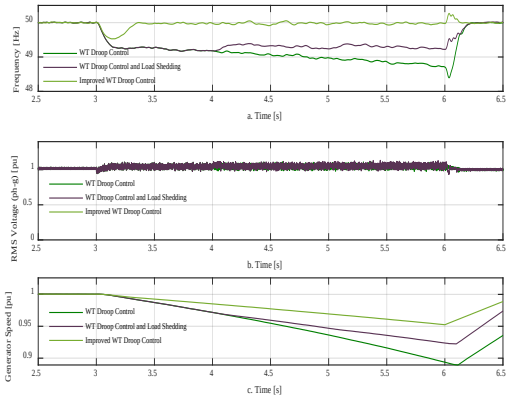
Intentional Islanding: Active- and Reactive Power



Intentional Islanding: Frequency and RMS Voltage



Unintentional Islanding With Time Delay (10ms, 50ms, 100ms): Frequency and RMS Voltage



Unintentional Islanding without BESS: Frequency, RMS Voltage, Wind Turbine Generator Speed

Conclusion

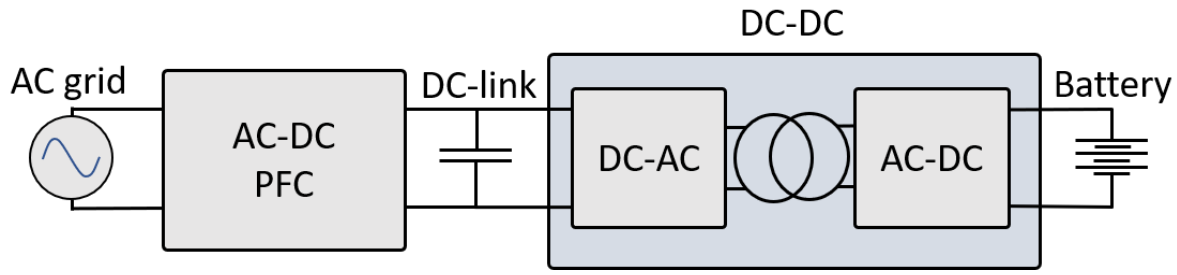
Through model validation for each of the subsystems were considered to perform as expected at varying conditions. Simulations of intentional islanding showed that the microgrid could perform a stable transition to islanded operation. The same was found for unintentional islanding where an assumption of no time delay for the islanding detection was made. However, for unintentional islanding with time delay, or without the BESS, the transition from grid-connected to islanded operation was not satisfactory as both frequency and voltage deviated substantially from their respective nominal values. Measures to enhance a stable transition was either implemented or discussed for further work. An alternative to unintentional transition, in form of a black start, was also performed with the BESS and diesel generator system with promising results.

Bidirectional DC-DC converter for an Electric Vehicle On-Board Charger

Student: **Mathias Winther Thorsen**
Supervisor: **Dimosthenis Peftitsis**
Co-supervisor: **Torbjørn Sørsdahl**, **Valeo Siemens eAutomotive**

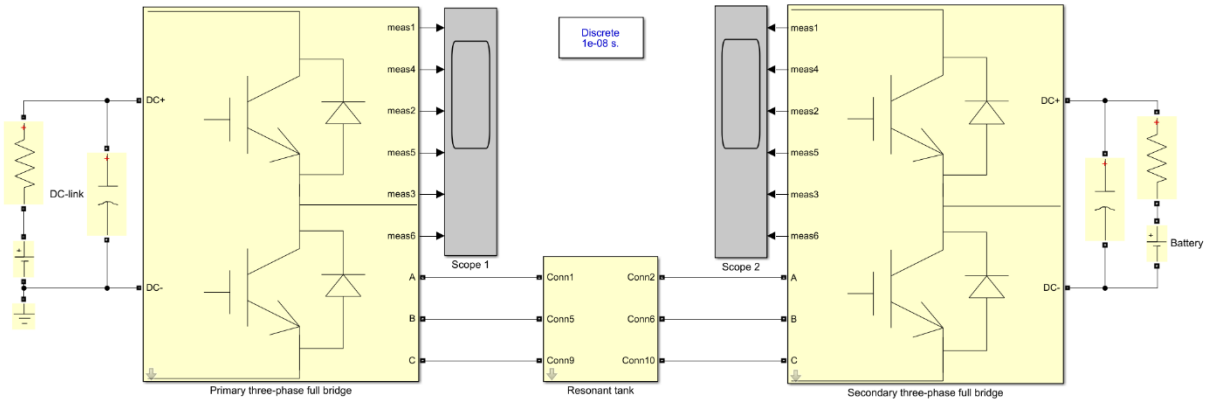
Problem description
The increasing number of EVs on the roads play an important part in decarbonizing the transport sector, but charging them causes strains on the electric grid. This thesis aims to determine if Vehicle-to-Grid (V2G) technology can be part of the solution to this problem, and to design a converter for use with V2G using new technology.
V2G means that the EV can communicate and deliver electricity back to the grid. For the EV to be able to participate in a regulating market it needs to be compatible with the market. It also needs to provide sufficient resources for the extra investments and complexity to be worth it.
A DC-DC converter for the On Board Charger (OBC) of an electric vehicle is to be designed. The converter should provide isolation and allow bidirectional power flow for V2G capability. The converter should have efficiency over 97.6%, compact size and low electromagnetic noise. The suitability of new WBG technology for such applications is to be investigated.

The task



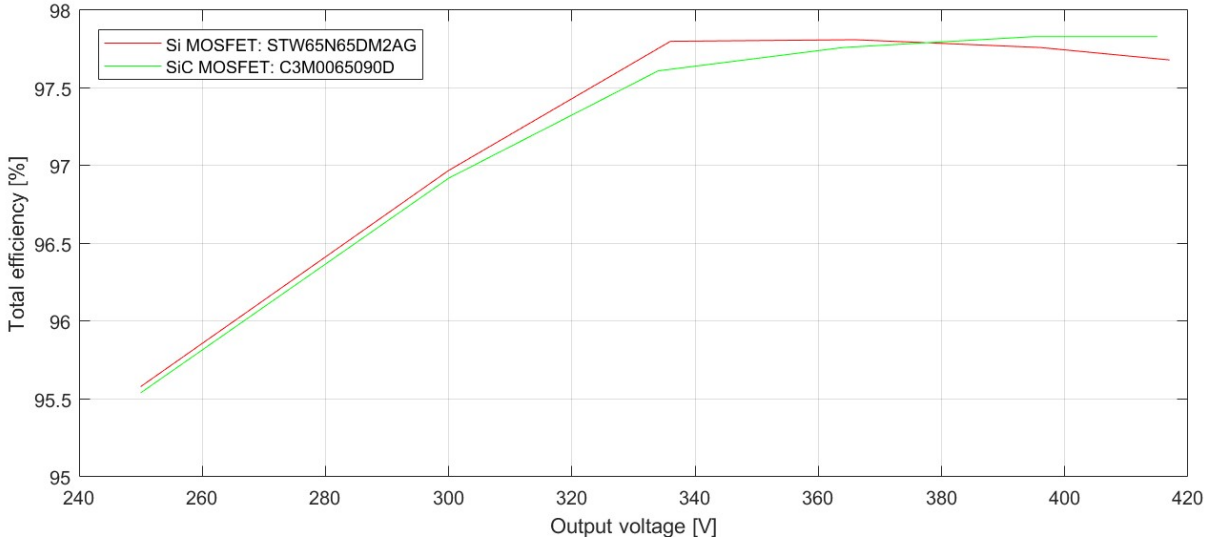
The converter to be designed is the DC-DC converter between the DC-link and the battery which includes a high frequency AC-link for isolation. A symmetric resonant CLLLC three-phase converter topology was chosen for high performance for both directions of power flow.

Model/ measurements
The main circuit was modelled in Simulink, while the switching transients of the MOSFETs was modelled in LTSpice. The Simulink model included the DC-link modelled as a constant voltage source and the battery modelled as a resistive load. The primary three-phase full bridge is frequency controlled with 50% duty cycle while the secondary bridge uses synchronous rectification. No control structure was designed, so steady state operation was investigated.



Results

The converter achieved over 97.6% efficiency at full load at series resonant frequency, with unity gain, over the whole voltage range of the DC-link voltage. For battery voltage below 340V the DC-DC converter must increase the frequency to regulate the gain, giving lower efficiency. Still, the efficiency is relatively high and with a limited time spent in this mode of operation the overall efficiency of the converter is high.



Conclusion

Several studies and projects show that V2G can provide an important resource to the grid while producing income for the EV owner. V2G can take part in many different regulating markets due to the fast response. The most cost effective means of implementing V2G capability is in the OBC of EVs.

Within the field of power electronics, WBG technology is maturing, enabling significant benefits over Si devices, but at a higher cost. Other interesting development includes integrating several magnetic components into a transformer, enabling efficient soft-switching topologies with few components.

A novel high frequency 7kW isolating bidirectional DC-DC converter is designed for use in an OBC. With a symmetric CLLLC three-phase resonant topology operating frequencies over 250kHz is achieved with over 97.6% efficiency over a wide operating range. The topology gives low amplitude and high frequency on input and output voltage ripple, simplifying filtering.

Modeling MMC Energy Dynamics in Offshore HVDC Systems Using OpenModelica

Student:	**Erling Vatn Tranulis**
Supervisor:	**Elisabetta Tedeschi**
Contact:	**erling.v.t@gmail.com**
Collaboration with:	**DNV GL**

Our need for clean, renewable energy causes offshore wind to constitute an increasing fraction of our energy mix. Due to considerations of maritime spatial planning and higher wind speeds, the distance to shore increases. This makes modular multilevel converter (MMC) based HVDC systems the superior transmission choice. Because these transmission systems are often large and complex, analyses of the dynamics characterizing them are necessary. Such analyses must be conducted by the use of specialized software that can reproduce the system behavior with sufficient precision.

This thesis uses the open source OpenModelica tool to investigate the power dynamics related to the MMC in offshore HVDC systems. The thesis also demonstrates the suitability of the software for such purposes in two regards. Firstly, it is shown that the software can accurately model systems that are characterized by relatively high-frequency dynamics. This is done by modeling a 10kHz two-level voltage source converter (2L-VSC) in OpenModelica and a benchmark software, MATLAB Simulink. The comparison showed that OpenModelica accurately captured all dynamics of interest as well as provide insight into its trustworthiness and computational resilience. Secondly, it is demonstrated that models developed in OpenModelica can be integrated into systems which are modeled using real-time simulation software (ePHASORsim) and real-time simulation hardware (OP5700). How this integration must be executed is described in this thesis.

Using OpenModelica, the thesis aims to investigate how the energy storage capability of the MMC can improve the power dynamics of an HVDC system. This is investigated in two scenarios that differ in duration and energy

requirement. In doing so, it is attempted to demonstrate the characteristics of the MMC's storage capability, which might provide guidelines for determining how this energy should be appropriately used. The first scenario studies the MMC's impact on turbine dynamics caused by wind speed fluctuations around the turbines rated wind speed. It is attempted to smoothen out power fluctuations that arise from the acceleration and deceleration of the turbine rotor upon crossing the rated wind speed. It is demonstrated that the improving impact of the MMC in this regard is almost always negligible, but that the relative impact improves with fluctuation brevity, ideally lasting no longer than two seconds. In the second scenario, it is attempted to reduce the response time of the HVDC system to a step in power reference by utilizing the stored MMC energy. Here, it is shown that the response time is reduced (by a factor of 32) down to a couple of milliseconds. These characteristics demonstrate that the MMC's energy storage capability is best used to counteract power fluctuations in the range of milliseconds to two seconds when the magnitude of the variations are in percent of the rated MMC power. Moreover, because of the coupling between the stored energy in the converter and the DC voltage, a controller is developed to reduce this coupling by using a feed-forward term in the voltage controller. It is showed that when this control is implemented, the step response time of both the DC voltage and the zero-sequence energy sum is reduced by a factor 3 and that oscillations are almost perfectly removed.

In the spirit of joint academic and industrial progress without socioeconomic borders, all models developed in this thesis have been made publicly available.

Beregning av avstand til enpolte feil i direktejordet transmisjonsnett

Student: **Thomas Treider**
Veileder: **Hans Kristian Høidalen**
Medveileder: **Christian Sundal Melaaen**
Utføres i samarbeid med: **Statnett SF**

Sammendrag
I denne oppgaven er det gjennomført testing av to ensidige og tre tosidige impedansbaserte algoritmer for beregning av avstand til enpolte feil i direktejordet transmisjonsnett. De to ensidige algoritmene som ble vurdert er to ulike varianter av algoritmen Modifisert Takagi, som benyttes av Statnett i deres applikasjon AutoDig i dag. I tillegg ble tre tosidige algoritmer valgt. De fem algoritmene som ble studert ble testet med hensyn på ledningslengde, feilsted, feilmotstand, målenøyaktighet i strøm- og spenningsmålinger, og med hensyn på unøyaktige verdier av ledningsparameterne. De tosidige algoritmene ble i tillegg vurdert med hensyn på usynkroniserte målinger.

Enpolte feil ble simulert ved å modellere en generisk 420 kV ledning i programmet ATP Draw. Hovedfunnene i denne oppgaven er at AutoDigs nåværende algoritme presterer dårligst bant de algoritmene som er vurdert. Ved å anta lav feilmotstand, lave omsetningsfeil i måletransformatorer og presise ledningsparametere er den observerte presisjonen i overensstemmelse med den presisjonen som er rapportert ved reelle hendelser.

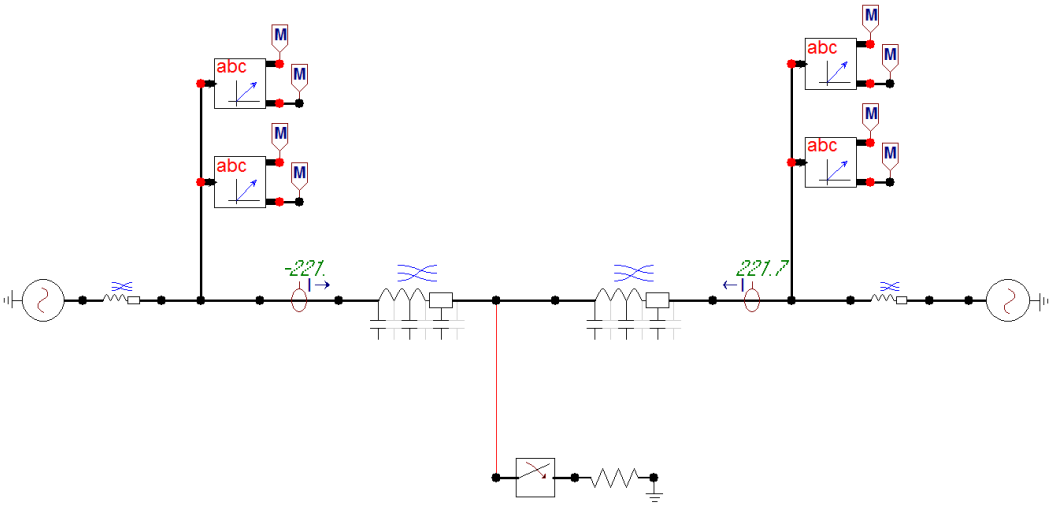
Videre ble det observert at de tosidige algoritmene var betydelig mer presise enn de ensidige algoritmene, og at disse også var mindre påvirket av variasjoner i samtlige av parameterne som ble variert. Det konkluderes med at det med stor sannsynlighet er mulig å oppnå en betydelig økning i presisjon ved å gå bort fra dagens algoritme til fordel for en av de tosidige algoritmene, men det har ikke vært anledning til å teste ut dette i praksis.

I tillegg til dette har det basert på resultater underveis i arbeidet blir foreslått to modifikasjoner av den allerede eksisterende algoritmen Modifisert Takagi. Disse to modifikasjonene innebærer en ensidig og en tosidig metode for å estimere feilstrømmens vinkel. Begge disse representerer betydelige forbedringer av AutoDigs algoritme, men resultatene er basert på simuleringer og er ikke verifisert i praksis.

Videre anbefales det å ta i bruk en algoritme for beregning av synkroniseringsvinkelen mellom målinger foretatt i hver ende av ledningen. Denne algoritmen er testet og funnet å være betydelig mer presis enn dagens metode benyttet av AutoDig. Dersom AutoDig skal benytte en tosidig algoritme basert på synkroniserte målinger foreslås det å benytte metoden beskrevet over for synkronisering av målinger i kombinasjon med den valgte algoritmen.

Modell

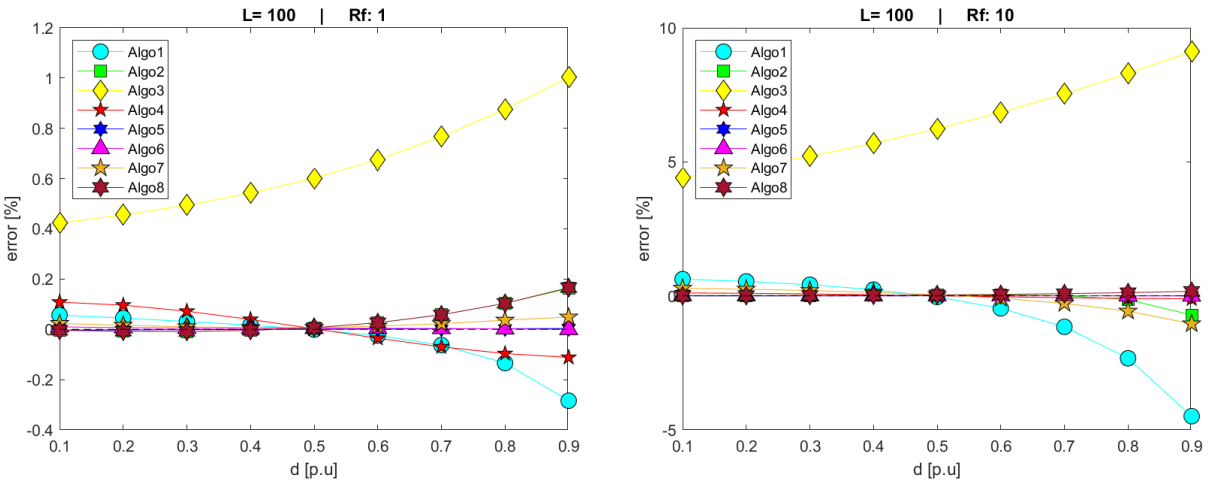
Transmisjonsledning med omkringliggende nett ble modellert i ATP Draw.



ATP Draw-modell for simulering av enpolet feil på kraftledning

Beregninger

AutoDigs algoritme (Algo3) er minst presis, og er særlig påvirket av feilmotstanden. De tosidige algoritmene gir best resultat i alle tilfeller.



Prosentvist avvik for alle algoritmer, L=100 km. Algo1, 2, 3, og 7 er ensidige algoritmer, Algo4, 5, 6, og 8 er tosidige.

Changes in the European energy system, resulting from increase in Norwegian transmission capacity and hydropower development

Student: **Marta Ulvensøen**
Supervisor: **Steve Völler**
Co-supervisor: **Magnus Korpås**

Problem description

This thesis has analysed the European energy system, with focus on more development of hydropower and reservoir capacity in Norway, more wind power development in both Norway and Great Britain and an increased exchange capacity from Norway to continental Europe and Great Britain. These analyses are realized using EMPS/Samkjøringsmodellen, using an existing model and an extended model. Results are evaluated regarding production pattern (distribution energy sources), emissions (Mt-CO_2), energy flows (import/export) and economics (area prices).

Model

The model of the European energy system includes:

- 34 countries with 44 areas
- Total of 98 transmission lines
- 787 thermal power plants of 17 different types
- 43 areas with hydro power, split into reservoirs and run-of-river
- 39 areas with solar generation
- 43 areas with wind generation, whereof 27 also has offshore wind in addition

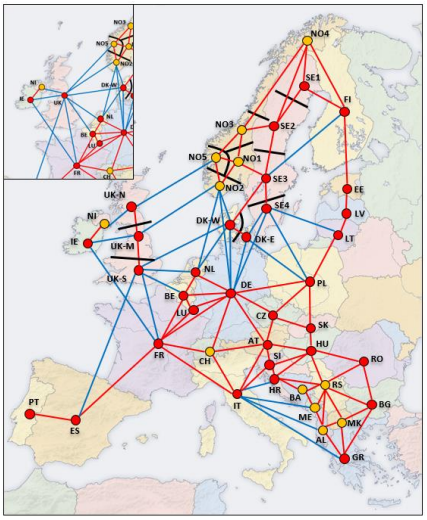


Figure 1: Schematic description of analysed EMPS model (top left section: excerpt of old model)

Calculation

In total 16 different simulations for developed scenarios for focus years 2020, 2030 and 2040 are performed. Realised using two different policies for fuel-prices and CO_2-taxes. In year 2020 the distinction between the two ploicies is low for emissions, 3,4 Mt-CO_2. This distinction increases over the year, due to increasing differences between the policies. In year 2040 the reduction with the strictest policy is 255,5 Mt-CO_2 compared to the less strict policy. The thesis has also investigated the distinctions within a policy. The scenario with highest reduction of emissions compared to the base scenario is a scenario with an investment algorithm deciding development for offshore cables from Norway and wind power development in Norway and Great Britain (in year 2040). The reduction is 125,6 Mt-CO_2 compared to the base scenario. The reduction with inclusion of more hydropower in Norway and development of offshore cables in is smaller, 11,7 Mt-CO_2. Both scenarios depend on a developed transmission network for export/import of power Especially will the scenario with high development of wind power need strong connections. A developed transmission network in Europe will also give more equal area prices, since the system have less bottlenecks.

Conclusion

Results from the different focus-year shows that inclusion of more renewable energy sources and higher exchange capacity makes a positive impact for emissions in ton CO2. This favours a well-developed transmission network that can meet the production/consumption and surplus/deficit of power every hour regarding the lateral distribution of flexible and variable energy sources in Europe.

A Shorterm assessment of flexibility analyzing different levels of VRES deployment in a Unit Commitment model

Student: **Rodrigo Villanueva Revenga**
Supervisor: **Hossein Farahmand**

Abstract
Flexibility has become an important property of the electric power systems and currently plays a crucial role in delivering efficient balancing to supply-demand operations. The rise of an environmental concern from governments to mitigate CO2 emissions and ensure a sustainable future for next generations has increased over the last decades the interest of investing in Renewable Energy Sources (RES). The integration of RES has rapidly transformed the power system since some of them, especially solar and wind power, cannot control its power output. These Variable Renewable Energy Sources (VRES) bring uncertainty and inflexibility to the power system. Additional flexible sources and new players must be also integrated, causing an additional cost due to this inflexibility.

Consequently, the concept of flexibility is changing and must incorporate new elements. Classical flexibility definitions can no longer include the different scenarios provoked by the deployment of VRES that the current power market faces within this topic. The present thesis proposes additional ideas to the flexibility concept paying special attention to the curtailment effect on the power markets, demand flexibility, synergy between hydro power generators and VRES, nuclear power role etc. The thesis investigates the concept of flexibility under very short time steps, from minute-to-minute to an hour. These very short time resolution analyses shed new light on the concept of flexibility from a different perspective.

To make this possible, the present research implements a Unit Commitment (UC) model in General Algebraic Modeling System (GAMS) software using CPLEX solver, considering multiple generator constraints, such as ramp rate, maximum power output etc. The UC model has been adjusted after some simulation tests, accurately emulating the actual power markets behaviour.

Moreover, the deployment of VRES and the digitalization of the power sector are forcing the actual power markets to shorten its time resolution. Operators, as California Independent System Operator (CAISO) are leading this transition by “using” 5 minutes time resolution instead of the classical hourly based (NordPool).
Using the developed UC model, the present research shows and analyses the effect of shorten the time resolution for UC problems. Thus, 1 minute, 5 minutes, 15 minutes and 60 minutes timesteps have been considered. This innovative analysis faces many challenges specially from the data collection and computation time. To make it possible, a demand data conversion method, data analysis of Great Britain (GB), Netherlands (NL) and Germany (GE) power demand, a flexibility analysis of UC models and an analysis of optimization complexity, are presented.

Most of these theoretical insights are summarized in the paper “A Minute-to-Minute Unit Commitment Model to Analyze Generators Performance”, that will be presented in the 16th International Conference on The European Energy Market 2019 (EEM19). The paper has contributed to understand: 1) opportunities and challenges in converting traditional hourly UC

models to finer time-resolutions, 2) how to convert hourly data to shorter time periods, 3) the notion and awareness on how generators might actual behave in real-time operations and 4) the importance of considering shorter time resolution.

To conclude, the thesis analyses a case study where the concept of flexibility (based on very short time steps) is analysed and redefined in order to cover a wider spectrum of the concept. Besides, the high synergy between Hydro power and VRES is demonstrated as well as the incompatibility of nuclear power with high share of VRES. For the given portfolio and demand, the curtailment effect sets a limit of VRES share, motivating the development of flexible demands for a green and VRES future.

Investigation of the Transient Recovery Voltage across Circuit Breakers in Networks with Distributed Energy Resources

Student: **Siri Kjærstad Wetjen**
Supervisor: **Kaveh Niayesh**
Contact: **kaveh.niayesh@ntnu.no**

Problem description

Introduction of renewable power generation methods such as wind and photovoltaic into medium voltage level power distribution systems leads to fundamental changes of the conventional network configurations. Switching devices designed to cope with the stresses, such as transient recovery voltage and short circuit current, in conventional networks are faced to new types of stresses.

In previous investigations, the switching transients in networks with distributed generation have been studied. It has been shown that in some cases much more severe switching transients in such systems may be produced.

In this master thesis, the idea is to investigate the influence of distributed generation units on the stresses applied to circuit breakers. The focus will be on the characteristics of the applied transient recovery voltages.

The task

The objective of this report has been to:

- Make two base case networks in the simulation tool PSCAD: one base case photovoltaic network and one base case wind power network. PSCAD is a Power Systems Computer Aided Design which uses an electromagnetic transient simulation engine called EMTDC.
- Use these base case networks to simulate the transient recovery voltages for different case scenarios of a short line fault. The different case scenarios were used to investigate the effect of changing networks parameters such as: line length, cable length, power flow, and the time between the short circuit instant and the opening operation of the circuit breaker.
- Investigate the simulation results of the different case scenarios to check if the addition of photovoltaic (PV) and wind power to the distribution grid can lead to a situation where the capability of the breaker is exceeded.

Model/ measurements

In this thesis there have been made two different base case networks that were used to perform the simulations. Transient models of a photovoltaic plant and a wind power plant provided from *PSCAD knowledge base* were used. In both of the base case networks a model of the network system 1-2 buses away from the switching device under investigation was included. This includes all relevant stray capacitances. In addition, it was ensured that the maximum possible short circuit current was used in the current interruption study.

The relevant capability curves were plotted in the same graph as the TRV for each of the three phases. This was done to compare the actual TRV to the relevant capability curves, and thereby check if the TRV exceeded the capability curves at any point.

Results

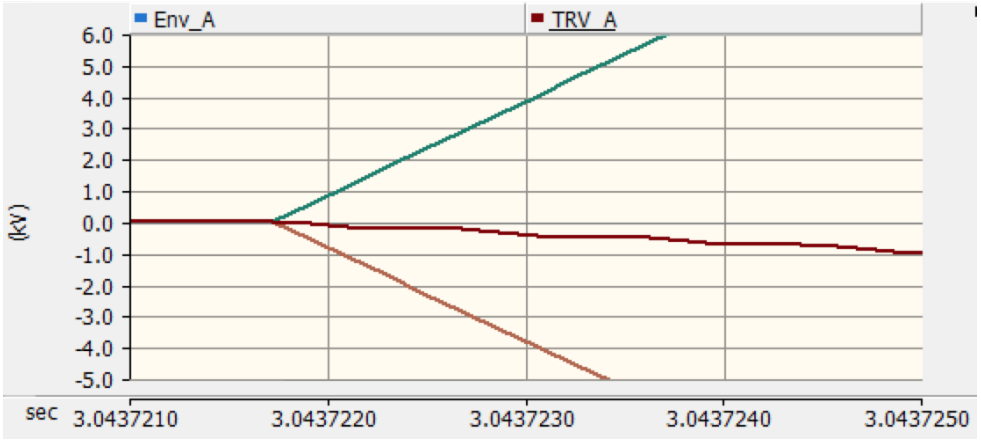


Figure 1: RRRV (red) and capability curves (green and orange) in the base case photovoltaic network.

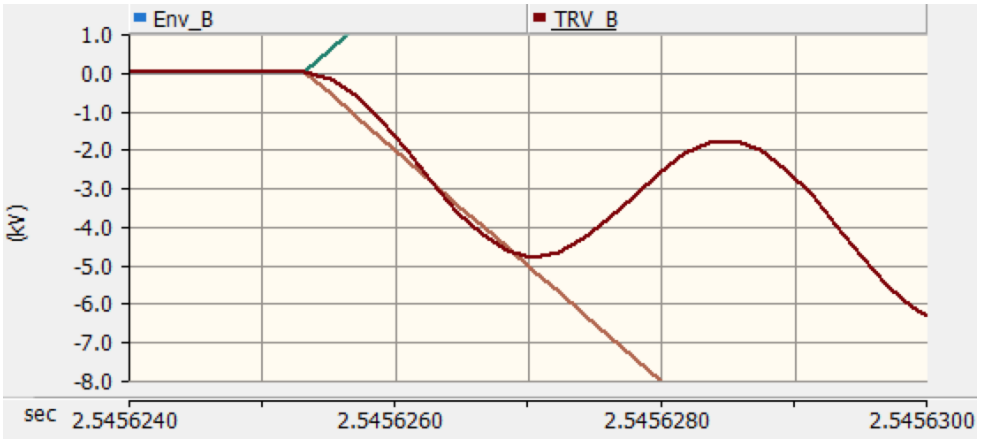


Figure 2: RRRV (red) and capability curves (green and orange) in the base case wind power network.

It can be observed that the RRRV is exceeding the capability of the breaker only in the wind power network.

Conclusion

In the photovoltaic network it was observed that both the TRV peak and the rate of rise of recovery voltage (RRRV) were kept inside the capability of the breaker for all the chosen parameter variations. Among all the case scenarios, the highest RRRV observed in the PV network was observed in the scenario with a line of 0.6 km. This RRRV was measured to 0.658 kV/µs, and it is within the capability of the breaker which is 3.01 kV/µs.

On the other hand, in the wind power network there were observed several parameter variations that resulted in a violation of the capability of the breaker. In similarity to the PV network, the highest RRRV measured in the wind power network was observed in the case scenario with a line of 0.6 km. This RRRV was measured to 3.167 kV/µs, and it is exceeding the capability of the breaker which is 3.01 kV/µs. The RRRV exceeded the breaker capability for a cable/line with lengths between 0.6 - 3 km. In addition, the breaker was operating beyond its limit in the case scenarios with 43 ms and 103 ms between the short circuit instant and the contact separation. By comparing the RRRVs for different power flows through the breaker it was observed that only the highest power flow of 20 MW resulted in a violation of the breaker capability. Regarding the TRV peak values in the wind power network, it was observed that the peak TRV was kept inside the capability of the breaker for all the chosen case scenarios.

Modellering og kontroll av en bølge-til-kabel av punktabsorbator WEC-er

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Co-veileder: **Dan El Andres Montoya Andrade**

Problemstilling

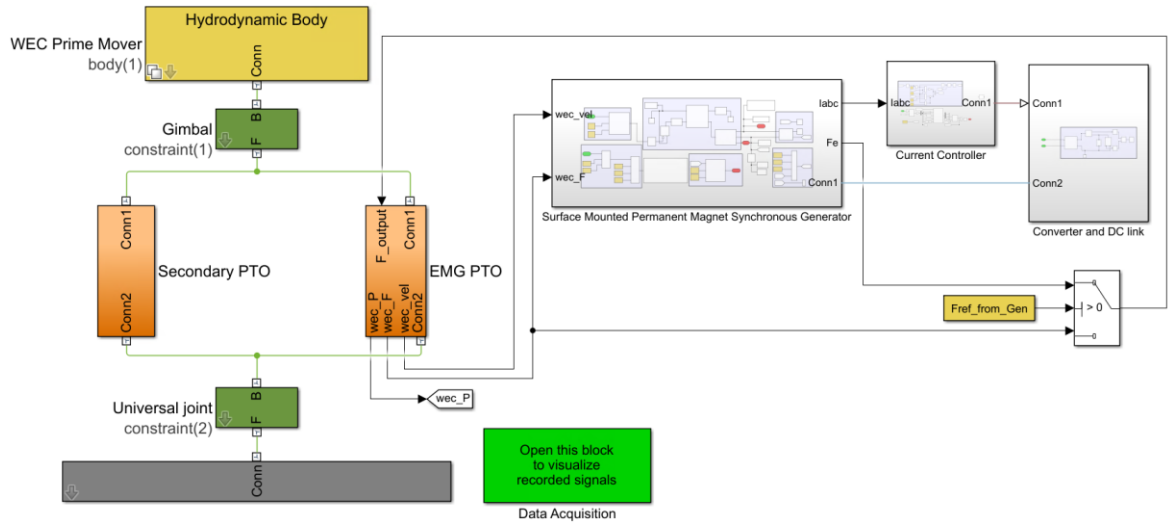
Bølger har et stort potensial, da rundt 10% av verdens strømforbruk kan leveres fra bølgeenergi. Dette gir en unik mulighet til å bringe mer fornybar energi inn i verden ved bruken av bølgeenergiomformere (WEC). WEC-er sin evne til å stå alene på steder der det ikke er noe nett, gir også WEC-er en spesiell betydning. Hovedoppgaven går ut på å maksimere effekten utvunnet fra innkommende uregelmessig bølge.

Oppgaven

Denne masteroppgaven presenterer modellering og kontroll av en bølge-til-kabel (wave-to-wire-modell) av punktabsorbator WEC-er.

Modell

Punktabsorbatoren (PA3) som brukes er fra Cruz-Atcheson Consulting Engineers-modell, utviklet i EU-prosjektet IMAGINE og inspirert av CETO3 WEC. WEC-en er koblet til en roterende permanentmagnet synkrongenerator (PMSG) direkte gjennom en resirkulerende kuleskrue. PMSG-en er koblet til en DC-kobling gjennom en omformer. Masteroppgaven er begrenset til en innkommende uregelmessig bølge av Bretschneider-spektrum med en betydelig høyde på 3.25m og en topperiode på 12 sekunder.



Beregninger

To typer kontrollstrategier, henholdsvis passiv lasting og optimal kontroll (passive loading og optimum control), blir brukt for å maksimere effekten utvunnet fra innkommende uregelmessig bølge. Hver kontrollstrategi er simulert med og uten Begrensningene på effekt, sluttgrenser og maksimal effekt som PMSG-en kan generere, 296.20 kW, er tatt hensyn til. Passive loading og optimum control påføres med og uten begrensning av mekanisk inngangseffekt til PMSG-en ved 250 kW. Den høyeste maksimale gjennomsnittlige effekten av hver type av simulering er målt og sammenlignet med hverandre.

Konklusjon

Den høyeste maksimale gjennomsnittlige effekten på 35,82 kW genereres ved ubegrenset optimal kontroll med et forhold mellom topp og gjennomsnittlig på 8,64. Den maksimale gjennomsnittsverdien er 3,5%, 4% og 1,5% høyere enn den maksimale gjennomsnittlige effekten som er oppnådd ved henholdsvis ubegrenset passive loading, begrenset passive loading og begrenset optimum control. Forskjellen er senket på grunn av grensen for maksimal effekt generert av PMSG-en. Da PA3 har to frihetsgrader, effekten er også generert i andre retning. Derfor, den maksimale genererte kraften er høyere enn PMSG-en sin begrensende effektverdi.

Modeling of a Maritime DC-distribution System Supplied from a Diode Rectifier Connected Synchronous Generator

Student: **Arve Starheim Ytrehus**
Supervisor: **Roy Nilsen**

Problem description

The DC-distribution system has gained increased attention in the marine industry. Especially in application where Hybrid Power systems gives potential environmentally friendly solutions and reduced operation cost. The most common solutions today are Engine-Generator sets as main power source, operated either with diesel or Liquefied Natural Gas (LNG). The Gen-Sets are connected to the DC-link either with diode/thyristor-rectifier or 3-phase inverter. The main objective of the project is to model the generator/diode system.

Previous theses have investigated the instability problems concerning the synchronous generator and diode rectifier set-up. However, these theses have focus heavily on simulations of the system. The objective in this project is a theoretical analysis of the system.

The task

Strict emission regulations have been introduced to the maritime sector by the International Maritime Organization. New and existing technology are evaluated with an increased focus on developing environmentally friendly solutions. The DC-distribution system is an old technology which has been revitalized by the progression in the power electronic solutions. The DC-distribution system offers fuel saving potentials not accessible in its AC-counterpart. The objective of this thesis is to develop system models applicable for control system design purposes and stability analysis.

- Emphasis should be on obtaining a solid theoretical foundation and develop detailed models of the system.
- These models shall be used for field current control design and stability analysis of the system.
- If sufficient time, a voltage controller as a part of power control should be included.

Model

The system consists of synchronous generator, diode rectifier and a DC-link capacitor. Diode rectifiers are preferred in many cases due to low prince and simple control structures. However, diode rectifier has no option for voltage control. The DC-link voltage control is therefore realized through generator field current regulation.

A model containing the different system elements was constructed. The model was linearized, Laplace transformed and represented as a signal flow diagram. A transfer function describing the relation between the field voltage and field current was deduced by node and branch reducing the signal flow diagram. This function was utilized in the field controller tuning.

Conclusion

The theory presented in this report establishes a solid foundation for further modeling, controller design and system stability analysis. The initial method presented for tuning field current controller could be evolved further to develop a standardized tuning principle for these systems. However, it is evident that some aspect concerning modeling, stability and tuning regarding the field circuit needs to be examined further. The challenges expressed concerning the inner field circuit regulator should be priorities before further voltage control design is conducted.