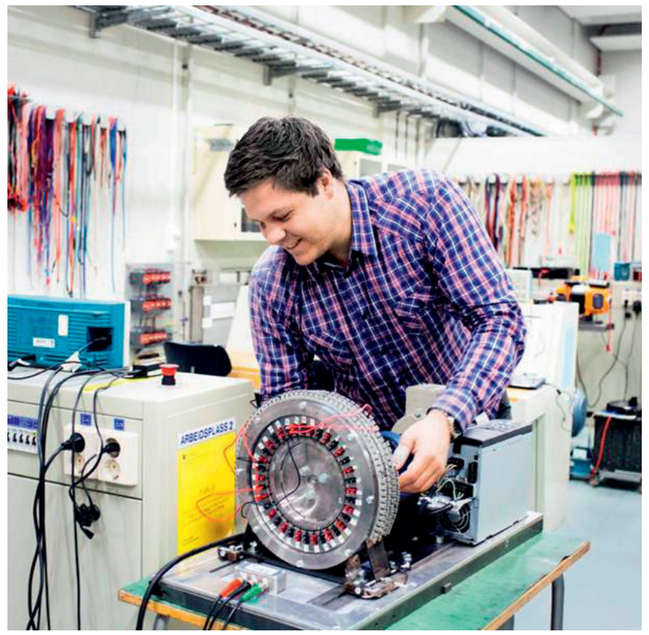
Masteroppgaver 2013
Institutt for elkrafteknikk

NTNU
Norges teknisk-naturvitenskapelige universitet
Fakultet for informasjonsteknologi, matematikk og elektroteknikk
Institutt for elkrafteknikk

Studieprogram:

- Energi og miljø
- Energibruk og energiplanlegging
- Electric Power Engineering



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A summary of Master Theses 2013

This internet published pamphlet gives a summary of all Master Theses submitted to the Department of Electric Power Engineering in 2013.

NTNU, September 2013

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Virkning av mekanisk spenning på vanntrevekst i PEX isolerte høyspentkabler

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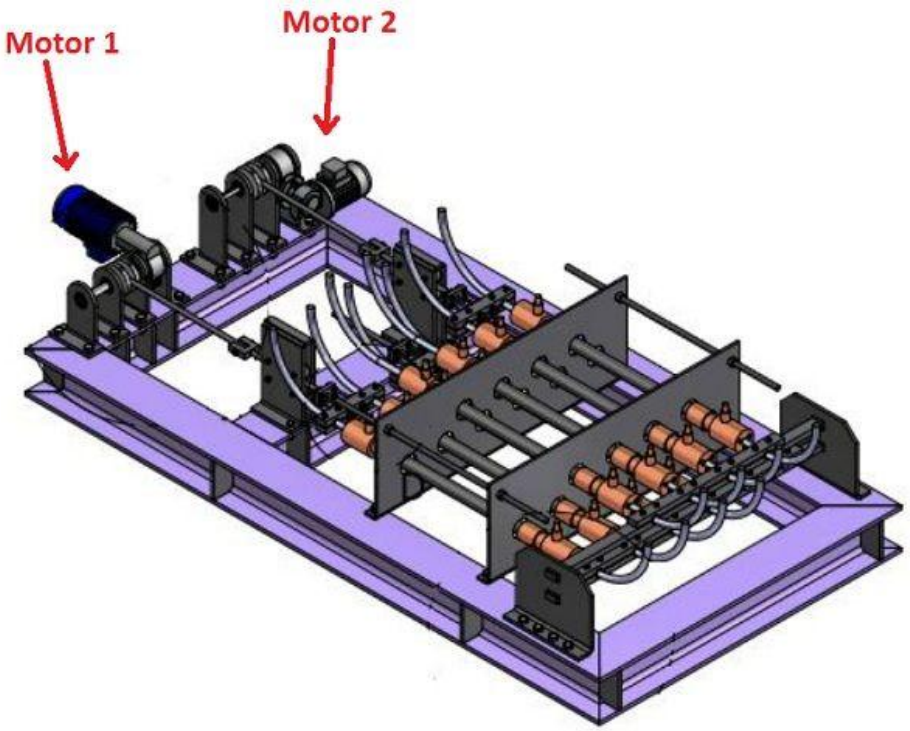
I samarbeid med: **SINTEF**

Vanntrær er en nedbrytningsmekanisme som kan oppstå i alle polymerisolerte kabler ved interaksjon mellom fuktighet og et elektrisk felt. Polymerisolerte kabler kan få redusert levetid grunnet dette nedbrytningsfenomenet. Den siste tiden har et økt miljøfokus ført til en elektrifisering av flytende olje- og gassinstallasjoner, samt økt satsing på flytende vindturbiner offshore. Kabler som benyttes til slike formål blir utsatt for både statiske og dynamiske krefter. Det har i denne oppgaven blitt undersøkt hvordan mekanisk belastning påvirker vanntreveksten, da særlig dynamisk mekanisk strekk. Det har også blitt undersøkt om de innfryste strekk- og kompresjonskrefter som dannes under produksjonsprosessen får betydning for vanntreveksten.

Det ble gjennomført 9 forsøk med samme type 12 kV trippelekstrudert PEX-kabel, hvor 3 av disse ble gjennomført høsten 2012 i forbindelse med prosjektoppgaven. Kablene ble påtrykt 50 Hz AC-spenning hvor $U= 2U_0$, men det ble også gjort ett forsøk med 25 kV spenning. Samtlige kabler benyttet i eksperimentene ble aldret ved romtemperatur med vann både i og utenfor kabelisolasjonen. I forsøkene ble kabler uten leder utsatt for statisk og dynamisk mekanisk belastning med strekkprosent, ε=1 %. Kabler ble belastet med ulik dynamisk mekanisk belastning ved å benytte to motorer med ulik rotasjonsfrekvens. Det ble også gjort forsøk uten mekanisk belastning. I det ene av disse forsøkene ble en kabel uten kobberleder varmebehandlet ved 120 grader celsius og deretter nedkjølt gradvis til romtemperatur. Det ble også gjort forsøk med lederen beholdt i kabelen.



Figur 1 Den mekaniske testriggen benyttet i forsøkene

Etter endt aldring ble kablene snittet opp og innfarget før vanntreveksten ble dokumentert ved mikroskopanalyse. Alle ventilerte vanntrær ble registrert med tilhørende lengde. For bow-tie trær ble det lagt særlig stor vekt på registreringen av det lengste treet i hvert snitt.

Resultatene dokumenterer at forekomsten av ventilerte vanntrær ved den indre halvlederen er 3-5 ganger større og at den gjennomsnittlige lengden er 27,3 - 32,8 % større i de mekanisk belastede kablene sammenlignet med ubelastet kabel. Den mekaniske belastningen er funnet å ikke påvirke forekomsten av ventilerte vanntrær ved den ytre halvlederen og tettheten av bow-tie trær i det ytre isolasjonsområdet. Innfryste kompresjonskrefter i den ytre delen av isolasjonen antas å hindre vanntreveksten, selv om kablene belastes med strekk.

Det er dokumentert at innfryste strekk- og kompresjonskrefter er den dominante effekten som gir høy vanntrevekst i det indre isolasjonsområdet og lav vanntrevekst i det ytre isolasjonsområdet.

Forsøk viser at det kan ha blitt fjernet strekkrefter på mer enn 5,6 % i aksiell retning for en varmebehandlet kabel. Den mekaniske avspenningen med varmebehandling indikerer at det må ha blitt dannet strekkrefter som er i størrelsesorden med fjernet strekk under produksjonsprosessen. Det er dokumentert at forekomsten av ventilerte vanntrær ved indre halvleder er 5 til 10 ganger større i en PEX-kabel med lederen beholdt sammenlignet med mekanisk avspente kabler. Grunnet innfryste strekkrefter er forekomsten like stor eller større sammenlignet med kabler utsatt for eksternt påført mekanisk strekk.
Resultater fra forsøk med dynamisk mekansik belastning gir grunnlag for å anta at en økt frekvens på den dynamiske belastningen ikke øker vanntreveksten.

Coping with Harmonics in Smart Grids: Variable speed drives with the Matrix Converter versus Back-to-Back voltage source converter

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Problem description

Since the 60s the use of power electronic interfaced loads has considerably increased with the proliferation of personal computers, TV sets, adjustable speed motor drives for pumps or air conditioning appliances, etc… When these loads are connected to the grid through passive diode rectifiers, harmonics are injected into the grid. This trend has led to a harmonic pollution problem which is now subject to new regulation in the context of Smart Grids.

When using active front ends (voltage source converters) in variable speed drive systems instead of diode rectifiers it is possible to reduce the harmonic content of the grid by active filtering. By replacing some of the passive diode rectifiers with voltage source convers, the regulations on harmonic content can be met.

Similarly, the matrix converter can also be used in adjustable speed drive systems and can also provide active filtering. The matrix converter is a direct AC-AC converter that does no feature a DC link capacitor and is therefore interesting for aerospace and offshore applications where a small volume or temperature independency are important.

In the Master thesis the two drive systems with matrix converter and back-to-back voltage source converters should be compared in terms of active filtering capability. The simulation software PSIM should be used to develop models of the drive system as a first step. A simulation model of the matrix converter will be provided

And to design the LC filter for the MC converter so it avoids creating and sending the harmonics current to the grid.

Abstract

In this master thesis it has been investigated to utilize the matrix as a shunt active power filter and an adjustable speed drive and then compare the matrix converter with the Back-to-Back voltage source converter in terms of active filtering capability and reactive power compensation.
In first steps to utilize the matrix converter as a motor drive and a shunt active power filter the control systems for the Permanent magnet synchronous machine, shunt active power filter and 3-phase LC-filter are built.
In second steps the simulation result of the matrix converter as motor drive and shunt active power filter is compared with the Back-to-Back voltage source converter in terms of active filtering.
The simulation results show that the matrix converter can operate as motor drive very well, but it cannot operate as a shunt active power filter at the same time. In other words it does not have the capability to compensate the harmonic current of the nonlinear load and to make the source current sinusoidal and harmonic free.

Whereas the simulation results for Back-to-Back voltage source converter shows that, it can operate as motor drive and a shunt active power filter at the same time. In other word Back-to-Back converter has a good capability for the harmonic current and reactive power compensation.
From the simulation results it can be concluded that the Back-to-Back voltage source converter is the best in terms of active filtering capability and reactive power compensation.

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Model

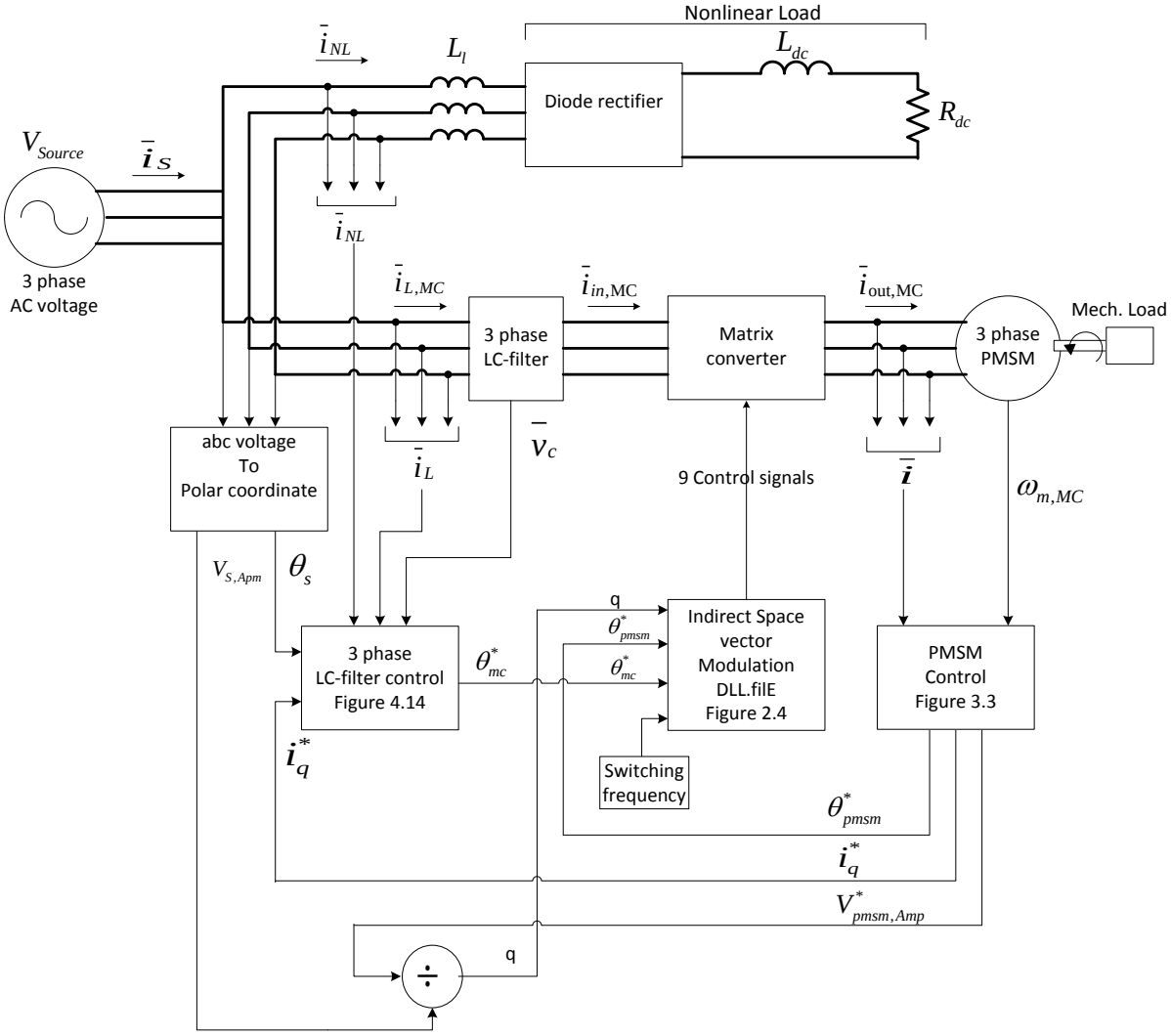

Figure 1 system overview of the Matrix converter shunted with the nonlinear load

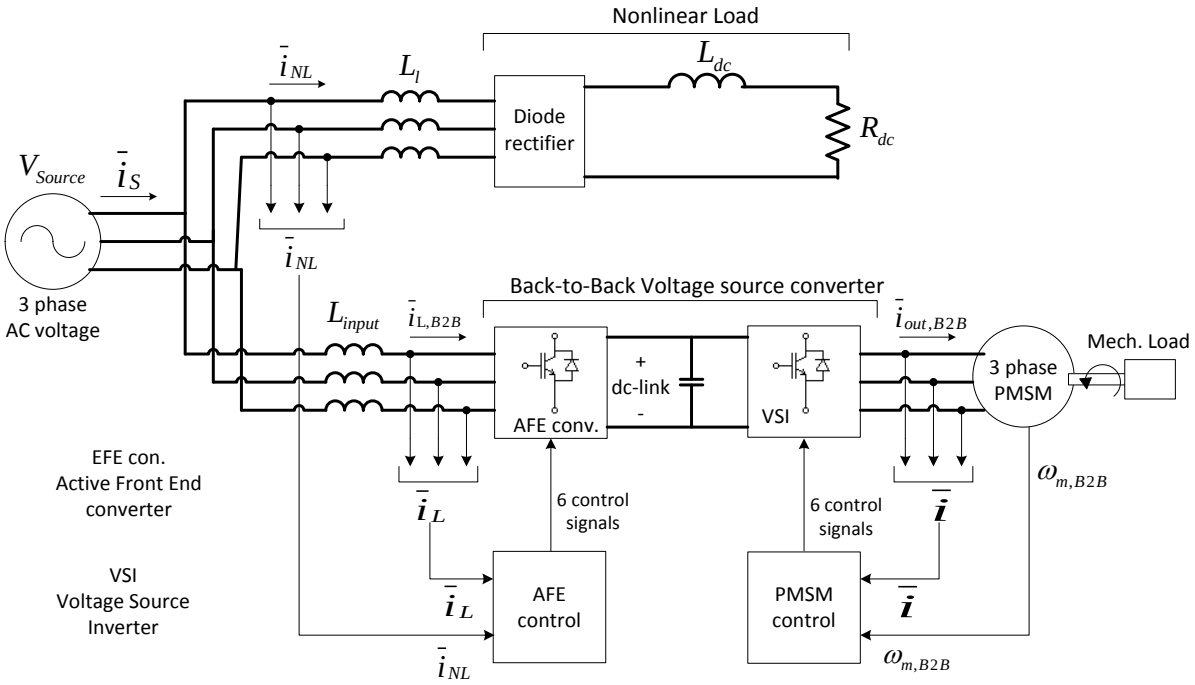

Figure 2 system overview of the Back-to-Back voltage source converter shunted with nonlinear load

Discussion

From the simulation results of the matrix converter in section 5.1 it is evident and fair to assert that the matrix converter does not have the active filtering capability at all, when it is operating as an adjustable speed drive for the PMSM or any other motor. The reasons that the matrix cannot operates/functions as an active filter while it is interfaced as an adjustable speed drive between the PMSM and the voltage source, are as follows:

I. It does not has reactive energy storage component like DC-link capacitor and inductor
II. The instantaneous input power is equal to the instantaneous output power
III. The input current of the matrix converter contain/consist of switching pulses
IV. Permanent magnet synchronous machine behave as an electrical load, which further operates as an active and reactive power sink, this cause absorption and consumption of active and reactive power from source.

And from the simulation results of the Back-to-Back voltage source converter in section 5.2, it is obvious that the Back-to-Back converter has an excellent active filtering capability and reactive power compensation. The reasons for excellent active filtering are as follows:

I. It has reactive energy storage component like DC-link capacitor which separates the voltage source inverter from the active front end filter.
II. The reactive energy stored in DC-linked capacitor can supply the reactive power to the motor for magnetization and to the nonlinear load for harmonic and reactive power compensation.
III. The instantaneous input power is not equal to the instantaneous output power

IV. Both the voltage source inverter and the Active front end filter each have its own control system and they are independent of each other.

Having the reactive energy storage component is one of the conditions for the active filtering and in addition it also gives better reactive power compensation.

Conclusion

In this master thesis it was investigated to find out, if the matrix converter has the capability to compensate the harmonic current, while it is operating as a variable speed drive. And to compare it with the Back-to-Back voltage source converter in term of active filtering.
To use the matrix converter as a motor drive and a shunt active power filter the control systems for the PMSM, shunt active power filter and 3-phase LC-filter were built.
The simulation results shows that the matrix converter with the presented control strategy cannot perform two functions at the same time, those are:

a) To behave as a variable speed drive
b) To act as a shunt active power filter

The reasons that the matrix converter cannot operate as a shunt active power filter are; in matrix converter the instantaneous input power is equal to the instantaneous output power, and it does not has energy storage component like DC-link capacitor or inductor.
In other word it can be described as, in case of the matrix converter the instantaneous input active and reactive power is consumed and absorbed instantaneously by the motor
Therefore it can be concluded that the Back-to-Back voltage source converter is the best in the term of active filtering and to cope with the harmonic in smart grids. On the other hand the matrix converter cannot cope with the harmonics in smart grids.

Tilstandskontroll av mellomspenning kabelsystem til vindpark

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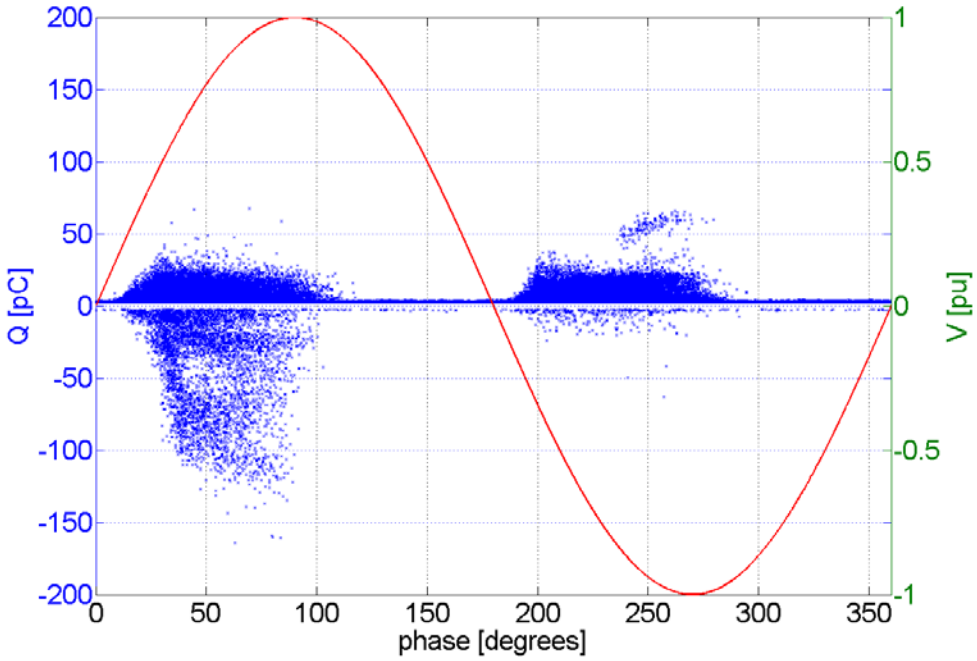
Medveileder: **Sverre Hvidsten**

En stor andel av distribusjonsnettene verden over har allerede passert sin tekniske levetid, og med inntoget av distribuert generering (DG) med vindkraft, er det registrert flere feil enn ved tradisjonelt forbruk. Her er skjøter på PEX-kabler sett på som hovedfeilkilden, hvor varmgang i skjøtehylsen er antatt årsak. Denne oppgaven har sett på hvordan de høye strømmene og raske strømendringene fra DG påvirker skjøtene i distribusjonsnett.

Arbeidet i dette prosjektet er basert på en skjøt med redusert elektrisk kontakt. Det er utviklet et laboratorieoppsett hvor skjøten aldres ved hjelp av strøminduksjon, for deretter å tilstandsvurderes ved hjelp av partiell utladningstest (PD-test) utført ved flere frekvenser og dielektrisk respons. Aldringsprosessen er satt til å foregå ved 130 °C og 180 °C med så hurtige temperaturendringer som mulig uten å overgå maksimaltemperatur for selve kabelen.

Ved 130 °C oppstod det ingen tydelig aldring etter 400 timer fordelt på 200 sykler. Ved 180 °C ble det observert PD etter 120 timer fordelt på 60 sykler.



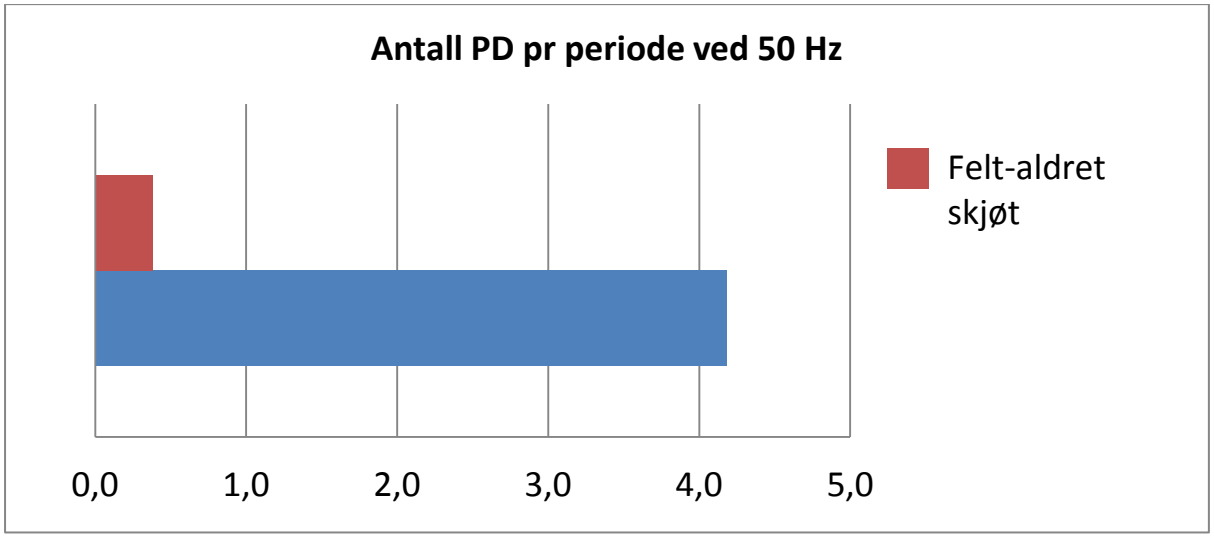
Figur 1 PRPD ved 12 kV og 50Hz for testobjekt 5, aldret i 60 sykler, og 120 timer ved kjernetemperatur 180 °C.

Resultatene fra de laboratoriealdrede skjøtene sammenlignes med målinger utført på et utvalg feltaldrede skjøter for å undersøke om resultater funnet i labben kan brukes til å vurdere tilstanden på kabler aldret i felt

.

Det ble observert at skjøter som er aldret med høy temperatur i labben ofte utvikler flere mindre hulrom. Disse hulrommene førte til et høyt antall forholdsvis lave utladninger per periode.

Skjøtene fra felt ser ikke ut til å ha blitt utsatt for høy varme. Her bestod antagelig feilen av en skarp kant mellom skjøtehylse og PEX-isolasjon fulgt av utilstrekkelig krympet skjøtisolasjon. I disse skjøtene oppstod større hulrom som medførte et lavt antall forholdsvis høye utladninger.



Figur 2 Antall PD per periode målt ved 50 Hz

Det kan dermed være mulig å skille mellom aldring som følge av høy temperatur og utilstrekkelig krympet isolasjon over skjøten ved hjelp av antall utladninger per periode.

Dielektrisk respons kan brukes til å si noe om hvor langt i aldringsprosessen skjøtene har kommet om det måles flere ganger under driftsperioden.

Voltage stability during braking in DC Diesel electric Propulsion System – BlueDrive PlusC

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Contact: **Roy Holen**
Collaboration with: **Siemens**

Problem description

A new system of diesel electric propulsion has been developed by Siemens, it is called BlueDrive PlusC. This system utilizes a common DC bus; hence motors and generators of the system may operate with individual speed. This is an advantage as it will improve the fuel economy of the diesel motors.
This project will focus on the DC diesel electric propulsion system of an offshore supply vessel, and look into advantages and problems related to implementing an energy storage device to the DC voltage bus of the system. The report will try to illustrate how an energy storage system affects the DC bus by acting as a buffer for excess power and periods of increased power demand.
The main emphasis will be on creating a simulation model of the propulsion system in Matlab Simulink including components as the frequency converter, induction motor and propeller load. The objective will be to make a model that emulates realistic values of system voltage and current during operating modes as dynamic positioning (DP). The model will measure the response in DC bus voltage and motor current caused by acceleration and regenerative braking during variations in propeller speed, thus illustrating how the energy storage system affects the DC bus voltage stability.

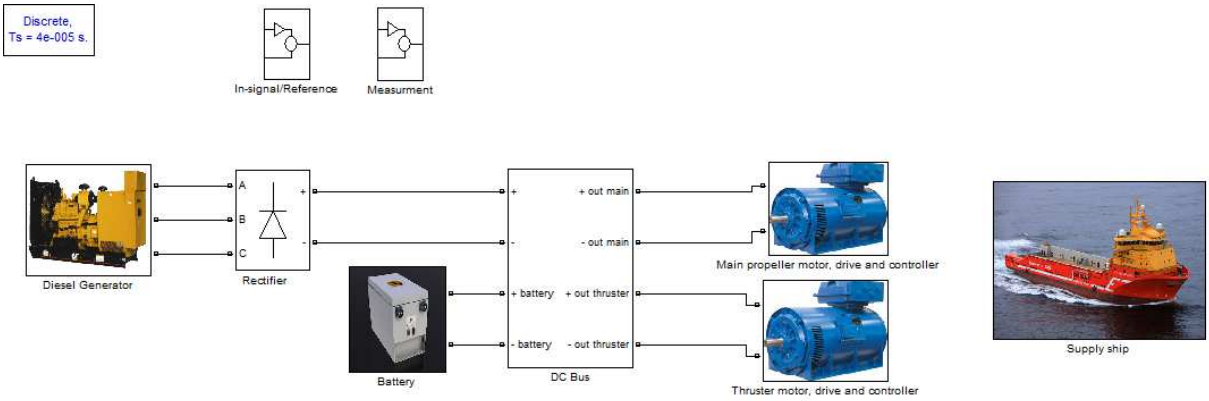
The task

In station keeping in rough seas a high positioning accuracy is required. The propellers will need to vary speed and rotation directions instantaneously to keep the ship from moving at wave impact. The propeller motors will accelerate and decelerate accordingly.
When decelerating a propeller motor using a frequency converter the motor runs in generator operation for a certain amount of time. This process is known as regenerative braking, as a reverse power will be produced. This power has to be dissipated in some way, in order not to receive overvoltage in the DC bus. A braking chopper may be a good way of absorbing braking energy, but has its limits in stabilizing the DC voltage. A solution with energy storage devices such as batteries and supercapacitors will quickly stabilize the DC voltage during power transients and acts as a buffer providing fast power sharing between the consumers on the DC bus. The system may be charged by the generators in low power operations, and receive charge from the load in regenerative braking.

The report gives a description of the components and functions of a DC diesel electric propulsion system in an offshore supply ship. The propulsion part includes the frequency converter, propulsion motor and the propellers.

A dynamic model of the propulsion system was created in the Matlab Simulink software. Using the Simulink model, the report presents measurements from simulations of different operational cases like dynamic positioning and transit.

Model/ measurements



Conclusion

With a battery attached to the DC bus, the simulations in Simulink show that the propeller motor control system manages to keep the voltage at acceptable levels, both at a speed reference step and in continuous load variations. The regenerated power during braking is successfully charged by the battery.

Even though the battery bank works well in the simulations, the limited life-time of a battery may be an issue in a real life propulsion system as the battery has a weakness to high charge/discharge currents. A solution may be to add a supercapacitor bank connected in parallel with the battery bank. The supercapacitor covers the highest current peaks at load variations. Consequently the battery may charge/discharge at its most efficient at a lower steady current. In this way the supercapacitor may aid the batteries to an improved life-time.

Battery Configurations in Siemens DC Diesel Electric Propulsion System for Ships
BlueDrive PlusC

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Contact: **Roy Holen**
Collaboration with: **Siemens Trondheim**

Abstract

Recent year's development and decrease in price for power electronics have resulted in development of diesel electric propulsion for ships, using DC voltage on the main switchboard. These systems have proven to have several advantages for ships like platform supply vessels, compared to more traditional propulsion systems, like diesel mechanical and AC electric systems. They have shown to be more fuel efficient and require less maintenance and at the same time, be more redundant and built with fewer components. Siemens new diesel electric propulsion system, BlueDrive PlusC, have the possibility to use an energy storage solution based on batteries. This will further decrease fuel consumption and increase the redundancy of the system, compared to a diesel electric system with AC on the main bus. Since this is a new way of designing diesel electrical propulsion systems, this raises some questions, like how the batteries should be configured optimally.

This report describes the main buildup of the BlueDrive PlusC, characteristics of lithium batteries, and why there is an advantage to use this kind of solution in a platform supply vessel. The objective of this report has been to further develop an existing Simulink model, to perform battery simulations on a BlueDrive PlusC configuration, based on operational data from the Østensjø built platform supply vessel, Edda Frende. The operational data provided by Siemens, contains power levels for generators and propulsion units during dynamic positioning in calm and rough weather conditions, during transit operation and waiting offshore. By simulation these scenarios, the goal has been to find a suggested battery capacity, capable of handling the currents that can occur during these conditions.

The existing Simulink model was built during a master thesis at the spring of 2012, and had its main focus area around voltage control of a BlueDrive PlusC configuration, without batteries. This model has been further developed by adding a control module, battery modules, fuel calculation module and new power consumption modules. The different battery sizes were then tested as power buffer, spinning reserve and with batteries as the only power supply for the vessel.

Based on the available data, the report suggested a battery capacity that was able to handle the current rates during the different scenarios. This battery capacity made the batteries able to act as a power buffer, in the scenarios with large power fluctuations on the DC bus. The suggested capacity was also able to supply the vessel with power for up to 25 minutes, during waiting offshore.

Effekt av jordslutningsspole i distribusjonsnett

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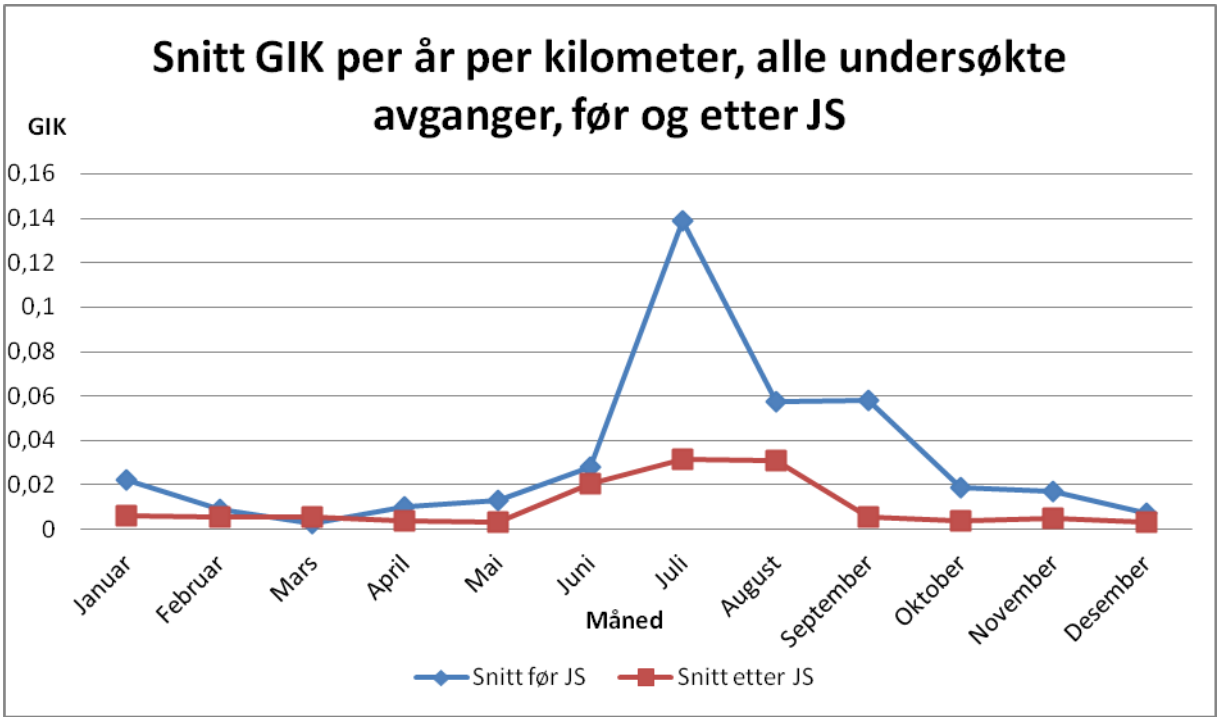
Supervisor: **Gerd Hovin Kjølle**
Contact: **Kjell Anders Tutvedt**
Collaboration with: **Hafslund Driftssentral AS**

Sammendrag

Det er i denne oppgaven blitt undersøkt den praktiske effekten av å installere jordslutningsspole (JS) i høyspennings luftnett. Dette er gjort ved å analysere antallet gjeninnkoplinger (GIK) som er har forekommet på utvalgte stasjoner hvor spolejording har blitt tatt i bruk. Det er fokusert på å finne forskjeller i både det totale antallet GIK per år, samt hvordan GIK per kilometer per år endres. Oppsummeringen av endringene før og etter installasjon av JS er vist i Figur 1.



Figur 1. Snitt GIK per kilometer per år for alle undersøkte avganger.

Det er knyttet betydelig usikkerhet til noen av dataene som har blitt analysert for Hafslunds transformatorstasjoner. Det er grunn til å tro at det endelige resultatet blir påvirket av feil i datamaterialet, men i hvilken grad er uvisst.

Det er utviklet en metode for å estimere den årlige KILE-kostnaden i årene før og etter at JS ble installert. Med bakgrunn i dette har det blitt utført kost-nytte -analyser for å undersøke om investering i JS har vært lønnsomt for de undersøkte stasjonene. Videre har også tilbakebetalingstiden blitt estimert. Hvor sensitiv lønnsomheten er overfor endringer i KILE-satsene er også undersøkt.

FASIT data for hele landet er blitt analysert. En metode har blitt utviklet i et forsøk på å estimere linje- og kabellengdene i de forskjellige nettnivåene, dette med hensikt å kunne beregne feil per lengdeenhet for hele det norske luftnettet. Denne metoden har vist seg ikke å være tilstrekkelig med de tilgjengelige dataene. Dette har ført til at det ble gjort analyser med den hensikt å finne trender for

hvilke feilårsaker som skiller isolerte og jordede nett fra hverandre. Dette har blitt gjort på årsbasis, ukesbasis og dagsbasis. Det er laget analyser over hvilke feilårsaker som er vanlige i forskjellige perioder og satt dette i sammenheng med hva som observeres av avbrudd for isolerte og jordede nett.

For å oppnå en dypere forståelse omkring hva som skjer når jordslutningsspole blir installert er det gjort undersøkelser for å finne hvilke type feilårsaker jordslutningsspolen har størst og minst effekt på. Det er også utført en analyse som ser på hvordan antallet transienter i nettet forandres.

Off-grid energy system for Wawashang, East Nicaragua: analysis of the energy potential and design of a micro hydropower installation

Student: **Marco Boninella**
Supervisor: **Marta Molinas**
Collaboration with: **IUG (Ingeniører Uten Grenser), FADCANIC (Fundación para la Autonomía y el Desarrollo de la Costa Atlántica)**

Problem description
The Wawashang Complex on the Caribbean Coast of Nicaragua is a typical example of remote rural area that can benefit from off-grid renewable energy solutions.
Over 84% of the people on this Coast have no access to electricity; the remaining 16% rely on an inconsistent national grid or isolated diesel generators.
In Wawashang, the non-profit foundation FADCANIC (*Fundación para la Autonomía y el Desarrollo de la Costa Atlántica*) supports the development of the communities of the Caribbean Coast through an innovative agro-forestry program, a school, a carpentry workshop as well as a natural reserve. No power grid reaches the Complex, but many buildings are electrified by dislocated systems of photovoltaic modules and batteries with gasoline generators as backup.

Scope
FADCANIC is trying to exploit better the natural resources in Wawashang, in order to provide power for more initiatives and make energy supply less expensive, more reliable and sustainable.
The higher power demand, the need of higher efficiency and lower costs have led FADCANIC to study new sustainable and reliable energy solutions for the Complex. These solutions need to be adjusted to the cultural, social, economic, environmental and technical aspects of the Autonomous Regions of Nicaragua to make the project sustainable.
In this connection, FADCANIC has established a contact with Engineers Without Borders Norway, IUG (*"Ingeniører Uten Grensen"*), in order to reach the goal of sustainable energy supply for Wawashang. The group of IUG at NTNU (*Norwegian University of Science and Technology*) is contributing to it through "Meaningful Masters", with thesis projects like the one presented in this summary. IUG sponsored the field trip to Wawashang in February 2013.

Main purpose of this Master Thesis is to propose a micro hydropower installation in State Creek, the river flowing through the Complex.
Moreover, this plan presents an analysis of the Wawashang buildings power consumption, measured on the field.
Harvesting the natural resources at the location is also important part of this project.

Measurements
The trip to Wawashang in February 2013 was made to collect the necessary data.
The hydropower potential in State Creek was measured by inexpensive tools, i.e. a wooden folding ruler and a current meter borrowed from NTNU. The Creek offers a site with a low head of 3 to 5*m* over a distance of 200*m* and a good water flow of 100-200*l/s* at the beginning of the dry season.

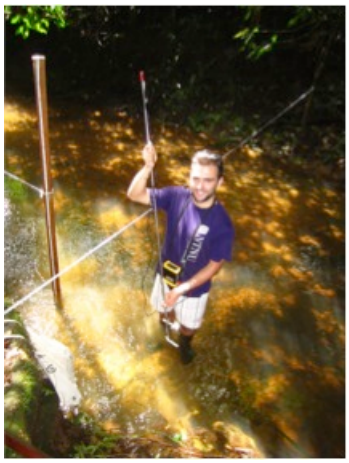


Fig: Water flow and head measurements in State Creek (Feb 2013)

The total present power demand has been measured by means of current meters and the future power demand forecast. The present and future peak powers required are about 17kW and 47kW during the week, while they are 2.5kW and 13kW during the weekend, respectively.
The analysis of the energy resources has revealed that, besides solar energy and low head micro hydropower generation in State Creek, biomasses could be an interesting option for power generation in the future. Particularly, coconut husks and shells, sugar cane, excrements and waste wood may be considered as an important resource for the production of energy within the Wawashang Complex.

Micro hydropower design
Three different beneficiaries have been considered for the design. The first one being the farmer's house, which requires little power for a small number of appliances for as long as possible throughout the year. The second possible beneficiary of the micro hydropower plant is a coconut processing facility, which demands more power. The last beneficiary is the Complex itself: the micro hydropower installation could, indeed, support the PV system during the rainy season with the greatest possible amount of power.
The design has been limited to choice of the turbine and the waterway, being the components with the highest influence on the cost and feasibility of the project. The choice of the turbine has been the starting point of the design, since the low head limits the possible solutions available on the market. Turbines in a head range between 0.2kW and 3kW have been considered and one (or more) solution has been selected for each power beneficiary.
A waterway has then been designed for LH1kW by Energy Systems&Design, being the most satisfactory solution, as it could power the coconut grinder during the day and electrify the farmer's house at night. MHG-200LH and MHG-500LH by Powerpal, which can provide sufficient energy to the farmer, should also be considered good options, because of the low initial costs.

Comments
Cooperation and human relationships have been fundamental to this project. A good interaction between IUG and FADCANIC made the trip to Wawashang pleasant and successful for the purpose of the project. Friendship with people in Wawashang made the work easier and more motivating for both parties. Particularly, sharing the purpose of the project with the locals aroused their interest and they helped with enthusiasm.
Altogether, this project has been a wonderful experience for professional, personal and cultural enrichment.

Development of high efficiency Axial Flux Motor for Shell Eco-marathon

Student: **John Ola Buøy**
Veileder: **Robert Nilssen**

Sammendrag

In 2011 Lubna Nasrin designed an optimized in-wheel axial flux motor for the competition Shell Eco-Marathon. A motor was built for the 2012 competition by Fredrik V. Endresen. Testing of this motor showed however that the performance was nothing like the one anticipated by Nasrin. The conclusion was that the production methods were not good enough and this was the main reason for the poor result.

A new motor was built for use in the 2013 competition. Several design improvements over the old motor which was built in 2010 has been made. Litz wire is used in the stator and Halbach array permanent arrangement in the rotors. Rims, axle and other mechanical parts have also been made brand new this year to try to make the best possible design.

The assembly didn't go without problems, but in the end the motor was fit to the car and tested. It was used in the competition where the team ended up with a third place in the battery electric class.

Several tests were performed on the motor to identify how well it performed compared to the FEM results. Question marks have however been raised when it comes to the results of the test due to problems aligning the motor in the test bench. The results indicate rather high rotational losses, but also an induced voltage 35% lower than anticipated. This should not be critical though as the theoretical efficiency, rotational losses discarded, still is 99% with this value.

The high eddy current and friction losses measured do however ruin the real efficiency of the machine.

Using Harmonic Impedance to Investigate the Stability in a High Voltage Direct Current System
A Sensitivity Analysis with Focus on the Control System

Student: **Sigmund Bødal**
Supervisor: **Marta Molinas**
Contact: **Øyvind Rui**
Collaboration with: **Statnett**

Summary
In this report, a method for determining the stability in a High Voltage Direct Current (HVDC) system by using harmonic impedance is explained and applied. This method turns out to be a powerful tool for performing sensitivity analysis of the control system, but applications for other parts of the power system should not be excluded.

A model of a HVDC link has been developed in MATLAB/Simulink, which constitutes the basis for simulations. As the HVDC model is based on Modular Multilevel Converters (MMC), the latest generation of converter technology, the control system is quite complex and sophisticated.
The chosen approach has been to determine the stability by investigating satisfaction of the Nyquist stability criterion. The HVDC system was then partitioned into a source and load subsystem, each represented as a harmonic impedance. Frequency response analysis was applied to obtain the harmonic impedance of the two subsystems.

The frequency response analysis involves two slightly different methods; current injection for the source subsystem and voltage injection for the load subsystem. The current injection method proved to be very sensitive for changes in simulation parameters and regulator settings at frequencies up to 100 Hz, and the accuracy in this frequency range is uncertain. On the other hand, the voltage injection method was found to be almost immune to any parameter value changes, as the harmonic impedance ended up as the same for all simulations.

The impedance magnitude for both subsystems was found to be the same at frequencies above 100 Hz. As both subsystems are identical, except from the control systems in the converters, this means that the two methods for frequency response analysis are accurate at high frequencies. It also means that the converters' influence on the harmonic impedance, and therefore also the stability, are less significant above this frequency.

From the sensitivity analysis, it has been discovered that the initial state of the system is actually vulnerable, as the curve in the Nyquist plot approaches the instability point at high frequencies. This means that instability is likely to occur if perturbations at the correct frequencies are present. The sensitivity analysis for the rectifier shows that the initial tuning of the control system is actually the most stable of the ones that are simulated. By changing the regulator parameter values in any direction, the Nyquist plots indicates increased probability for instability to occur. For the inverter, which proved to be almost immune to changes in the regulator parameter values, no changes concerning instability were observed during the sensitivity analysis.

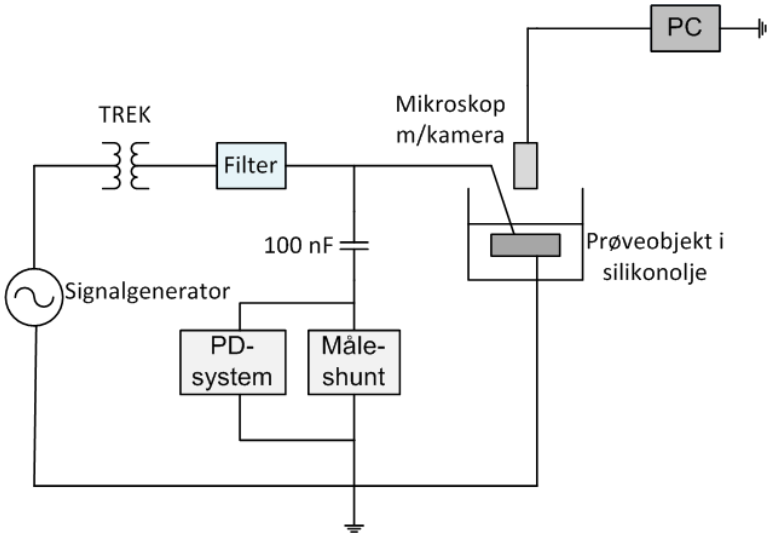
As many values close to the instability point in the Nyquist plot represents frequencies that exceeds the frequency range where the converters are significant, the power system itself must be redesigned to guarantee stable operating conditions.

Elektrisk trevekst i kryssbundet polyetylen (PEX) kabelisolasjon ved ulike spenninger og frekvenser

Student: **Kristian Fauskanger**
Veileder: **Erling Ildstad**
I samarbeid med: **SINTEF**

Tilstandskontroll og feiltester av høyspentkomponenter har de senere årene vist seg som nyttige hjelpemidler for å unngå uønskede utkoblinger. Blant moderne kabelisolasjon har særlig lavfrekvent testing av dielektriske tap ned mot 0,02 Hz blitt mer aktuelt grunnet lavere utstyrskostnader sammenlignet med 50 Hz spenningsprøving. En av de vanligste årsakene for feil i polymeriserte kabler er utladningsaktivitet og akkumulering av elektriske trær. Imidlertidig er det fortsatt uklart hvordan målinger ved så lav frekvens kan korreleres med 50 Hz siden flere av feilmekanismene ikke har signifikante dielektriske tap ved så lav frekvens.

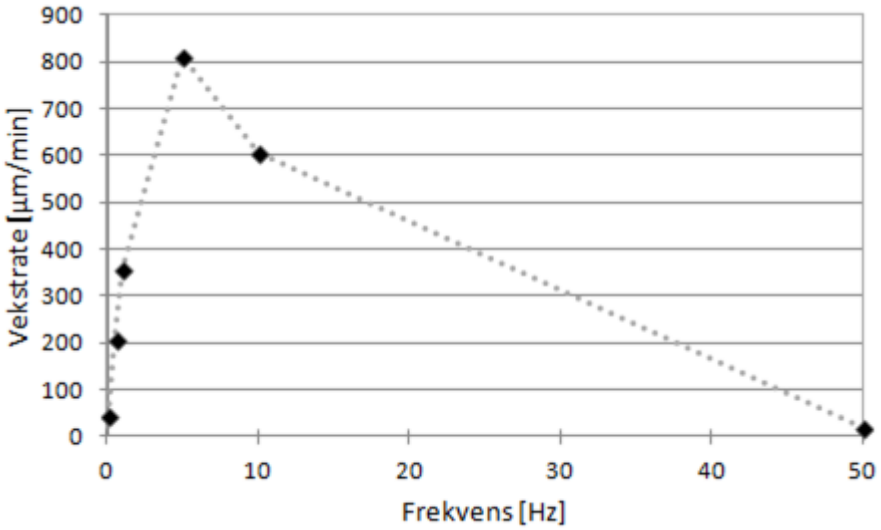
Hensikten med denne rapporten har derfor vært å undersøke hvordan elektrisk trevekst og partielle utladninger i kryssbundet polyetylen (PEX) forandrer seg som funksjon av spenning og frekvens. Testobjektene bestod av stålnåler som var støpt inn i 2 mm tykke prøver av PEX hvor avstanden mellom nålspiss og jordelektrode var 1,1 mm. Hvordan treveksten utviklet seg og så ut ved havari ble undersøkt ved hjelp av optisk- og elektronmikroskopiske teknikker. Prøvene ble testet i frekvensområdet 0,1-50 Hz ved 14 kV_{rms} og for 10-20 kV_{rms} ved 50 Hz.



Figur 1 - Målekrets

Resultatene har blitt sammenlignet med en teoretisk modell om spennings- og frekvensavhengig trevekst. Forsøkene indikerte at når spenningen ble holdt konstant økte vekstraten proporsjonalt med frekvensen mellom 0,1 og 5,0 Hz. Ytterligere økning av frekvensen medførte en strukturforandring fra grenvekst til buskvekst som igjen påvirket vekstraten til å synke ved økt frekvens.

Når frekvensen ble holdt konstant 50 Hz og spenningen justert mellom 10 og 20 kV_{rms}, viste resultatene at vekstraten kun økte lineært med spenningen innledningvis. Samtidig viste det seg at amplitudeverdien til utladningene økte med tiden ved grenvekst mens det for tett buskvekst ble registrert et stabilt forløp. Analysen fra elektronmikroskopet viste at tettheten av trekanaler er større ved buskvekst enn grenvekst. For en typisk prøve med grenvekst ble det registrert en avstand på 10 µm mellom kanalene, mens kanalene for buskvekst i mange tilfeller kan vokse sammen på kryss og tvers.



Figur 2 – Vekstrate

Kapasitetsutnyttelse og Stabilitet ved Nettilknytning av Vindkraftverk

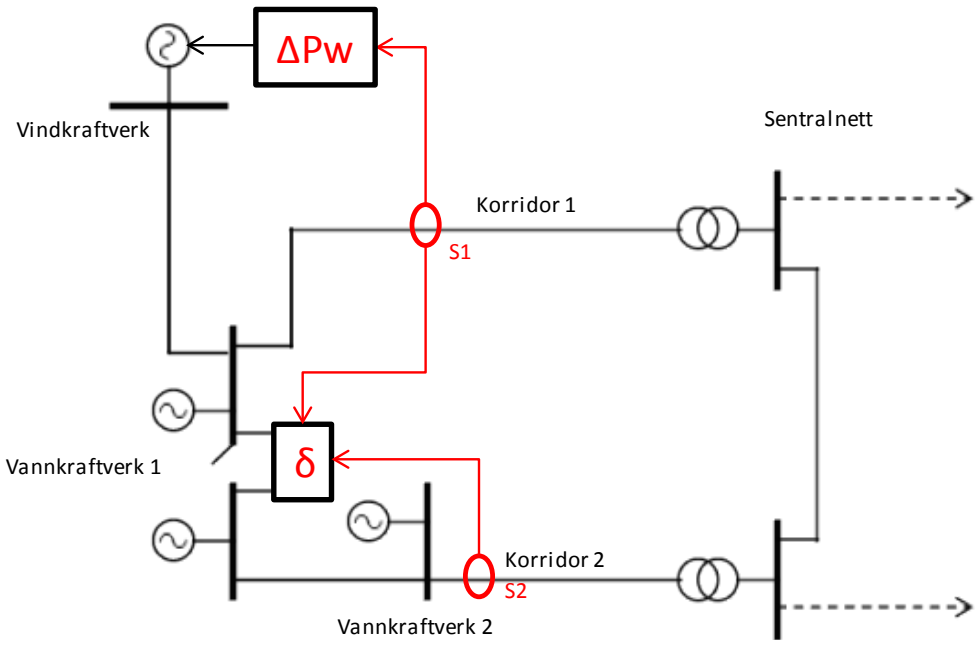
Student: Håkon Gabrielsen
Veileder: Kjetil Uhlen
I samarbeid med: Sweco Norge AS

Utfordringer i forbindelse med nettilknytning er i mange prosjekter en hindring for god utnyttelse av de verdifulle vindkraftressursene som finnes i Norge. Tradisjonelle tilnærminger for kapasitetsvurdering ved nettilknytning av nye produksjonsenheter i Norge tar ikke hensyn til mulighetene ved å bruke smartgrid-løsninger for å utnytte tilgjengelig kapasitet best mulig. Det er her vist at det kan være økonomisk gevinst i å legge opp til større vindkraftutbygging enn det dagens praksis for kapasitetsvurdering tillater. Når belastningen i nettet er gitt av en kombinasjon av forbruk og produksjon fra ulike kilder, vil effektflyten variere over et stort spenn, og ytterpunktene representerer svært usannsynlige scenarier. Å bruke ytterpunktene som dimensjonerende tilfeller blir derfor misvisende, og gir dårlig utnyttelse av den ressursen som kapasiteten i kraftnettet er.

Ved å etablere kommunikasjonssystemer for å gjøre utvalgte målinger i nettet tilgjengelig for en regulator i et kraftverk, kan overbelastning forhindres med dynamisk regulering. Selv om nedregulering vil bety produksjonstap for et vindkraftverk, kan det være økonomisk gunstig. Dette er vurdert med basis i et case-studie av et vindkraftprosjekt i Østfold. Ved bruk av produksjonsbegrensning kan utbyggingen økes fra 60 MW til 81 MW, og gi større inntekt i forhold til investeringskostnaden. Grunnen til dette er at investeringskostnaden pr MW utbygging går ned med 1,8 %, og det mer enn kompenserer for de omtrent 0,9 % som den relative inntekten reduseres med på grunn av produksjonsbegrensning og økt marginaltap.

Ved å bruke for eksempel tyristorstyrt fasevinkelregulator med ytelse på 10 MVA til å fordele effektflyten optimalt mellom parallelle overføringskorridorer i case-prosjektet, kan tapene i kraftnettet reduseres, og behovet for produksjonsbegrensning nesten elimineres. Nåverdien av inntekten fra dette tiltaket er beregnet til 14,8 millioner NOK, og det vil være lønnsomt dersom kostnaden i forbindelse tiltaket ikke overstiger dette.

For å kunne dra nytte av potensialet i ny teknologi og tankegang, er det essensielt å kunne vurdere virkningene gjennom modellering og simulering. Det har vist seg å være en utfordring å få gjennomført de nødvendige analysene med den funksjonaliteten som er i eksisterende programvare. Det er derfor utviklet tilpassede analyseverktøy for å kunne vurdere de relevante problemstillingene og samtidig inkludere mulighetene med ukonvensjonelle tekniske løsninger.



Ved å gå vekk fra tankegangen om at *worst case scenario* er dimensjonerende, kan en ikke lenger se på en enkelt driftssituasjon, men må ta hensyn til alle mulige tilfeller. For å gjøre det, er det brukt statistiske tilnærminger for å beskrive variasjonen i vann- og vindkraftproduksjon, og disse er kombinert med tidsserier for forbruk, eksport, kraftpriser og marginaltapssatser. For å ta dette med inn i beregningene er det utviklet en utvidelse til lastflytprogrammet Matpower i Matlab®, som gir støtte for tidsserier og egendefinerte regulatorfunksjoner. For å kunne gjøre modelleringen i grafisk grensesnitt i PSS®E er det også utviklet et konverteringsprogram for å overføre nettmodeller fra PSS®E til Matpower. Dynamiske problemstillinger er vurdert ved hjelp av lineær analyse og dynamiske simuleringer. Det er etablert en dynamisk modell av kraftnettet i PSS®E, men utvikling av regulatorer for PSS®E er en omfattende jobb, og det er derfor valgt å etablere nye regulatormodeller utenfor programmet. For å gjøre lineær analyse er det derfor utviklet verktøy for å hente den lineariserte nettmodellen fra PSS®E inn i Matlab®, og utvide denne med tilbakekoblinger gjennom egendefinerte regulatorer. Egenverdiberegningen i Matlab® er også utvidet til å kunne vise hvordan egenverdiene påvirkes av andre systemendringer, og utskrift av *mode-shapes*. Dynamisk simulering for systemet med de eksterne regulatorene er gjort ved å programmere regulatorene i Python-skript med grensesnitt mot den dynamiske simuleringen i PSS®E, slik at simuleringen kan kjøres parallelt og utveksle variabler for hvert tidsskritt i den numeriske integrasjonen.

Regulatorene som brukes i systemet er designet for å kunne regulere belastningen i flaskehalser uten avvik, samtidig som stabilitetshensyn ivaretas. Det oppnås ved å sette forsterkningene så lave at reguleringsprosessene går sakte nok til å unngå frekvensområdene for svakt dempede egenverdier i systemet. Ved bruk av både produksjonsbegrensning og fasevinkelregulering vil regulatorene påvirke hverandre, og det er derfor beregnet hvordan parameterinnstillingene kan samordnes for å unngå oscillasjoner eller oversving. Både lineær analyse og dynamiske simuleringer bekrefter at regulatordesignet som er brukt fungerer i henhold til designkriteriene.

Protection of capacitor banks

Nuisance tripping of overcurrent relays; causes and possible remedies

Student: **Christopher Gebs**
Supervisor: **Hans Kristian Høidalen**
Contact: **Ragnar Mangelrød**
Collaboration with: **Statnett**

The origin of this master thesis is problems encountered at Statnett involving nuisance tripping of capacitor banks. Statnett's own measurements are said to indicate that harmonics are confusing the overcurrent relays. Disconnecting a large capacitor bank from the transmission system can have large consequences for the stability of the system. Consequently any nuisance tripping such as Statnett has experienced should not be allowed to happen again. Measures must be taken to increase the security of the protection system.

The aim of this thesis is to investigate the overloading of capacitor banks and operation of numerical relays in harmonic rich environments. Further investigate why Statnett have experienced nuisance tripping of overcurrent relays, and introduce possible mitigation measures. The definition of nuisance tripping has been broadened to also include correct tripping because of unwanted resonance.

A literature study was conducted on numerical relays, capacitor banks and harmonics to identify possible causes of nuisance tripping.
There were no data available describing an actual nuisance tripping. Therefore a simple model was derived from the data sheets of a typical capacitor bank installation. The Pi-equivalent line model was added to illustrate that any real system will have multiple resonance frequencies. This model was implemented in ATPDraw as shown in Figure 1. First the frequency response of the system with and without filters, and with different short circuit power was calculated by ATPDraw. Based on the frequency response a short-circuit power of 4500MVA was used in the time domain simulations. Characteristic harmonics was injected at the load and the capacitor banks load current was measured and compared to IEC limits. It was shown that during resonance conditions overloading was very likely unless some sort of filtering or dampening was applied.

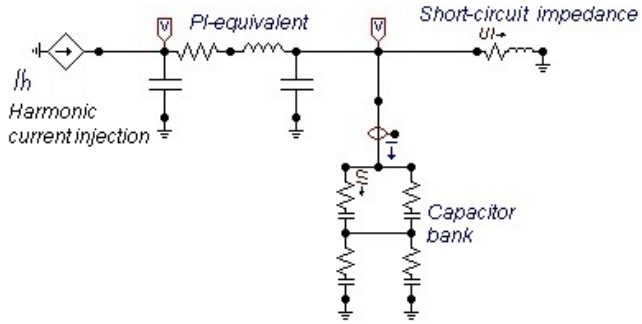


Figure 1: Simplified model for calculation of capacitor bank currents

With regards to avoiding nuisance tripping the most important action is to make sure the overcurrent relay is capable of detecting all harmonics that are present. This will remove the possibility of aliasing and the relay not detecting significant harmonic loading. The thresholds should be controlled to check that they are in accordance with the standard of which the capacitor bank is based. Applying filters for mitigation of resonance conditions where harmonics are significantly amplified will reduce the number of disconnections. Both due to actual overloading and nuisance tripping. It will keep the harmonic loading lower in general to give the relays better working conditions. In systems with varying short-circuit power and many parallel resonances the c-type filtered capacitor bank should be the preferred filter.

Langsiktige scenarier for europeisk energiforsyning

Student: **Raghav Gogia**
Veileder: **Gerard Doorman**

I LinkS ("Linking Global and Regional Energy Strategies") prosjektet genereres det scenarier for verdens energiforsyning ved hjelp av den globale energi og klimamodellen GCAM. Scenariene starter i 2010 og går fram til 2100. Resultatene fra denne modellen er på regionbasis, med Vest og Øst Europa som regioner. For å kunne analysere hva disse scenariene innebærer i praksis, er det nødvendig å disaggregere resultatene på landsbasis. Dette gir også en mulighet til å studere regional infrastruktur og spesifikt kraftnettet. I et pågående dr.grads arbeid er det utviklet en utbyggingsmodell som genererer scenarier for enkeltland og utvekslingskapasiteter. Disse er basert på en relativt grov modell, og scenariene skal derfor videre analyseres i Samkjøringsmodellen.

Oppgaven består derfor av følgende punkter:

1. Lage en fremgangsmåte for å overføre resultatene fra utbyggingsmodellen til Samkjøringsmodellen

2. Teste Samkjøringsmodellen på basisår og et framtidsstadium og verifisere Resultatene

3. Definere viktige resultater og lage prosedyrer for enkel framstilling av disse. Dette inkluderer bl.a. produksjon per brenseltype og land, priser og utveksling mellom landene.

4. Gjennomføre simuleringer for flere scenarier for perioden 2010-2050 (eventuelt 2100). Presenter resultatene på en hensiktsmessig måte. Vurder om resultatene er i samsvar med utbyggingsmodellen og forklar avvik.

5. Hvis tid: differensiere de marginale produksjonskostnadene med en viss spredning og analysere hvordan dette påvirker resultatene.

Framtidig kraftutveksling mellom Norge og det europeiske kontinentet

Student: **Odd Kristian Hagen**
Veileder: **Professor Gerard Doorman**
Medveileder: **Stefan Jaehnert**

Sammendrag

Sertifikatsystemet er innført for å øke produksjon av ny fornybar kraft i Norge og Sverige med 26,4 TWh i 2020. Samtidig vil også 1600 MW Olkiluoto 3 kjernekraftverket i Finland komme i drift, og til sammen vil dette føre til en betydelig økning i kraftproduksjonen i Norden.

Formålet med oppgaven er å se på konsekvensene av denne produksjonsøkningen for det nordiske kraftsystemet, å analysere hvordan dette påvirker kraftutvekslingen med kontinentet og å studere hvordan økt utvekslingskapasitet vil virke inn på systemet .

Det nordiske kraftsystemet analyseres ved å simulere kraftsystemet i 2020 uten og med den nye fornybare kraftutbyggingen. Videre analyseres konsekvensene av å bygge kraftforbindelser til Danmark, Nederland, Tyskland og Storbritannia. Simulerings-scenarioene er som vist i tabellen:

Scenario:	Utbygget ny fornybar.	Danmarks-forbindelse.	Nederlands-Forbindelse.	Tysklands-Forbindelse.	Englands-Forbindelse.
A	0	950 MW	700 MW	0	0
B	26,4 TWh	950 MW	700 MW	0	0
C	26,4 TWh	1600 MW	700 MW	0	0
D	26,4 TWh	1600 MW	700 MW	1400 MW	0
E	26,4 TWh	1600 MW	700 MW	0	1400 MW
F	26,4 TWh	1600 MW	1400 MW	1400 MW	1400 MW

26,4 TWh ny fornybar kraftproduksjon i Norge og Sverige fordelt etter dagens rammevilkår vil øke importen fra Sverige og redusere de Norske kraftverdiene. Denne kraftverdireduksjonen vil ikke fullt utlignes selv med 1400 MW kraftutvekslingsforbindelser til både Tyskland, Nederland og England. Skulle alle disse forbindelsene bygges ut står Skagerak IV ubrukt i tilnærmet halve året. Isolert sett øker den norske eksporten betydelig mer pr MW kabel til Tyskland enn til England.

Den årlige variasjonen i den norske og svenske produksjonen øker som følge av den nye fornybare kraftproduksjonen. Den norske produksjonens årsvariasjon øker også med nye utenlandskabler, men utenlandskablene reduserer sesongvariasjonen.

Vannkraftmagasinene i Norge driftes lavere som følge av den nye fornybare produksjonen, mens utenlandsforbindelsene øker den årlige variasjonen i de norske magasinene.

Med de nye kraftforbindelsene kan Norge eksportere grønn kraft, men økt kraftutveksling mellom Norge og det europeiske kontinentet øker også Sveriges gasskraft- og kjernekraftproduksjon.

Smart Grid: Shunt Compensation in Non-sinusoidal Regimes

Student: **Thomas S. Haugan**
Supervisor: **Professor Marta Molinas**

Problem description

The electric power theory is of fundamental importance in most aspects of electric power engineering, enabling to analyze and control the grid based on an unambiguous physical interpretation of the power and current flow. The futuristic *SmartGrid* concept will include scenarios of potentially very challenging network conditions, due to large impact of non-linear loads, combined with unsymmetric and non-sinusoidal voltage regimes. New and more advanced power theories are needed, in order to maintain correct phys- ical understanding of the power grid, independently of voltage conditions. Moreover sophisticated power theories can help identify and eliminate detrimental effects induced by loads; i.e. unsymmetry, reactive power consumption and harmonic pollution. This project has reviewed the recent and promising conservative power theory (CPT).

Conclusions

Major part of the project was dedicated to experimental research, evaluating the CPT purely from a power theory perspective. Central part of these experiments was a real- time rapid prototyping system (RPS) and three-phase voltage source converter. Control system for the programmable voltage source, data acquisition and CPT-algorithm were implemented by the RPS. Based on extensive tests it was found that the CPT offers enhanced and physical correct interpretation of current and power flow, in all tested voltage conditions. Obtained results from the virtual instrumentation are principally consistent with and support previous research presented in the literature.

Second part evaluated the CPT in context of shunt active power filter (SAPF). Ex- perimental implementation of SAPF failed, mainly as the RPS did not provide sufficient sampling rate. Selected cases of reactive and harmonic compensation were demonstrated, utilizing computer modeling tools (MATLAB/Simulink). The results conclude that the CPT performs excellent selective compensation, only when grid voltages are balanced sinusoidal. In scenarios of unsymmetric or distorted voltages, the compensation strate- gies provided by the CPT are apparently less versatile and effective, compared to the popular *pq-theory*. Overall this study demonstrated that optimal network operation can only be achieved, through the joint action of series and parallel compensators. Future work will amongst others include further in-depth study of the rapid prototyping system, and experimental implementation of SAPF.

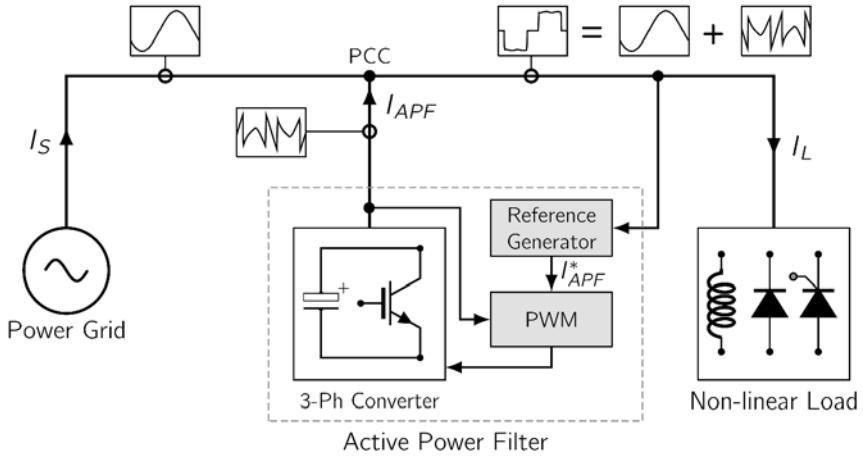


Figure 1: *Simplified presentation of active shunt compensastion.*

Romladningsdistribusjon i XLPE HVDC kabelisolasjon for flytende vindturbiner

Student: **Line Helland**
Veileder: **Frank Mauseth**
Medveileder: **Øystein Hestad**

Offshore vindkraft er en av fremtidens mest lovende fornybare energikilder. For å tilkoble vindturbinene til land er HVDC en nødvendig og lovende løsning, grunnet avstand og nødvendig kapasitet. Kryssbundet polyetylen (PEX) er allerede et materiale benyttet i HVAC-isolasjon, og er tilsiktet å ta over markedsandelen til masseimpregnerte kabler.

En av hovedproblemene under drift, er at høy DC-spenning muliggjør romladning å akkumulere innad. Dette forårsaker endring i den elektriske feltfordelingen, og påvirker derfor gjennomslagsmekanismer. Derfor er det interessant og viktig å undersøke og studere romladning og den elektriske feltfordelingen.

Denne masteroppgaven presenterer en detaljert analyse og diskusjon av resultater, oppnådd ved *Pulsed Electro-Acoustic* (PEA) målesystem, og utført på flate testobjekt og miniatyrkabel utsatt for DC-spenning. De flate testobjektene besto av kryssbundet polyetylen LE4253 med gullelektroder, og miniatyrkabelen besto av AC polyetylenmateriale LS4201S, med halvledermaterialet LE0595 som katode og anode.

Måleserier for flate testobjekt ble utført med spenningsnivåer på 10, 15, 20 og 25 kV. Med målte tykkelser på 0,51 mm, korresponderer spenningsnivåene til elektrisk feltstyrker på 19,6, 29,4, 39,2 og 49 kV/mm. Måleseriene for miniatyrkabel ble gjort med spenningsnivåer på 30, 52,2 og 70 kV. Med en tykkelse på 1,75 mm, var korresponderende gjennomsnittlig elektrisk feltstyrke på 20, 30 og 40 kV/mm.

Basert på undersøkelsene ble følgende utvikling observert; for flate testobjekt viste alle romladningsprofilene like trender på grenseflaten mellom katode og isolasjon, der en endring i akkumulasjonen fra homoladning til heteroladning ble observert raskere med høyere påtrykt elektrisk feltstyrke. I grensesjiktet mellom anode og isolasjon ble homoladning utviklet i samtlige måleserier, bortsett fra i måleserien med høyest påtrykket feltstyrke, der en lignende trend til polaritetsbytte i romladningsregionen utviklet med tiden. Den elektriske feltdistribusjonen viste maksimal feltforsterkning korresponderende til regioner med heteroladning. Maksimal feltforsterkning var 38 % av den påtrykte elektriske feltstyrken 19,4 kV/mm.

Måleseriene for samtlige miniatyrkabler viste akkumulering av homoladning i grensesjiktet mellom katode og isolasjon. Utviklingen av romladningsakkumulasjonen i grensesjiktet ved anode var av mindre netto verdier, og viste indikasjon mot et bytte i romladningspolaritet og forskyvning av regionen. Elektrisk feltøkning oppsto økende mot katode. I bulk, for både flate testobjekt og miniatyrkabler, utviklet romladningsregioner med motsatt polaritet forskjøvet mot eller nært romladningsfeltene i grensesjiktene. En større feltforsterkning ble observert i miniatyrkabler til sammenligning med feltforsterkningen med en større netto romladningsakkumulasjon i flate testobjekt.

Trender i romladningsutviklingen for de forskjellige testobjekttypene ble sammenlignet og diskutert. På denne måten ble effekten av ulike nivå av påtrykt elektrisk felt på romladningsutvikling sammenlignet og diskutert. Basert på presenterte resultater ble følgende konklusjoner trukket: Romladning vil akkumulere i både flate testobjekt og miniatyrkabel. Med tiden vil romladning akkumulere nært elektrodene, og heteroladning vil resultere i en elektrisk feltforsterkning nær elektrodene. Basert på måleseriene for flate testobjekt, vil netto maksimal romladningsakkumulasjon ikke være avhengig av påtrykt elektrisk feltstyrke.

Kriterie for design av HVDC skøytar

Student: **Martha Helvig**
Hovedveileder: **Erling Ildstad**

I denne masteroppgåva er det sett på kriterier for design av ein DC -skøyt. Ved DC-spenning er det konduktiviteten som påverkar leiingsevna til isolasjonen. I ein skøyt vil isolasjonen gradvis verte fjerna ned mot leiaren, også kalla ein nedkoning av kabelsiolasjonen. Langs denne nedkoninga kan det ved skøyting fort kome forureiningar og andre ytre påverknader som skader isolasjonen og påverkar konduktiviteten. Ei forandring i konduktiviteten vil auke det elektriske feltet i det aktuelle området, og vil vidare kunne øydelegge den elektriske holdfastheita, noko som kan føre til overslag og nedbryting av skøyten. Hovudformålet med denne oppgåva er å forbetre utforminga og designet til DC-skøytar slik at det ikkje vil vert påverka av ein eventuell forureining langs den nedkona delen av isolasjonen. Tanken er å utforme skøyten med eit materiale som er meir leiande enn forureininga, og med eit design av skøyten kor dette materialet er lagt over den nedkona delen av isolasjonen. Dette vil gjere at lekkstraumen frå leiaren går gjennom dette leiande materialet i staden for gjennom isolasjonen og forureininga. Ei forureining langs den nedkona delen av isolasjonen vil da ha mindre å seie for den elektriske feltfordelinga langs skøyten.

I oppgåva er FEM-programmet COMSOL nytta for å vise korleis denne ideen i teorien vil verke inn på det elektriske feltet. Simuleringa viser at dersom det forekjem forureiningar eller andre ytre påverknadar som vil auke det elektriske feltet i skøyten, vil denne feltauka kunne reduserast betrakteleg ved å leggje eit leiande materiale utanpå den nedkona delen av isolasjonen i skøyten. Det å leggje eit leiande materiale utanpå nedkoninga til isolasjonen vil derimot også gje ein kraftig felt forandring i starten og slutten av nedkoninga. Det er ikkje fokusert så mykje på korleis denne feltforandringa kan reduserast i denne rapporten, då dette dannar grunnlaget for vidare arbeid.

I andre delen av oppgåva er det gjort målingar av leiingsevna til ein feltstyrande duk. Dette for å verifisere om den feltstyrande duken er eit materiale som er mogleg å nytte som det leiande materiale utanpå den nedkoninga til isolasjonen. Det er og gjort teoretiske berekningar på kor stor konduktiviteten til det leiande materialet utanpå isolasjonen maksimalt kan vere.

Electrical Storage Possibilities in the Future Power System

Student: **Kristin Kolås Henriksen**
Supervisor: **Gerard Doorman**
Contact: **Hossein Farahmand**
Collaboration with: **SINTEF**

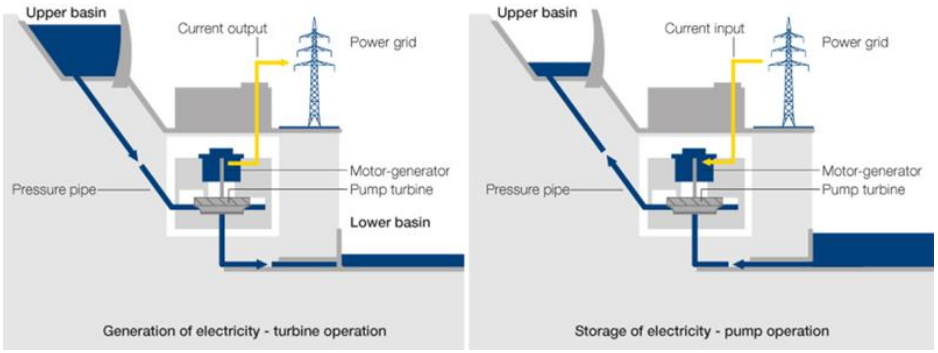
Problem description

The climate changes has been addressed with great concern in EU the last years, and they are willing to change their energy production to generators that emit less greenhouse gases. This willingness is presented in the "Energy Roadmap 2050" written in 2009, with obliged targets for all member states. This has led to a significant increase in the use of renewable energy sources, especially in Germany \cite{EUCom}. The increase is expected to continue for the whole EU, and will affect the transmission planning and system operation significantly. Solar and wind energy are two renewable energy sources which have had an increase in Europe. However, solar and wind energy are hardly controllable and predictable, and the need for flexible energy sources is growing proportionally with the expansion of renewable energy. Electric storage might be part of the solution, but electricity can not be stored as it is and need to be converted to another energy form instantaneously. Different ways of storing energy exist today, but in order to benefit from the storages, the optimal storage technology for each location and how to use it must be defined.

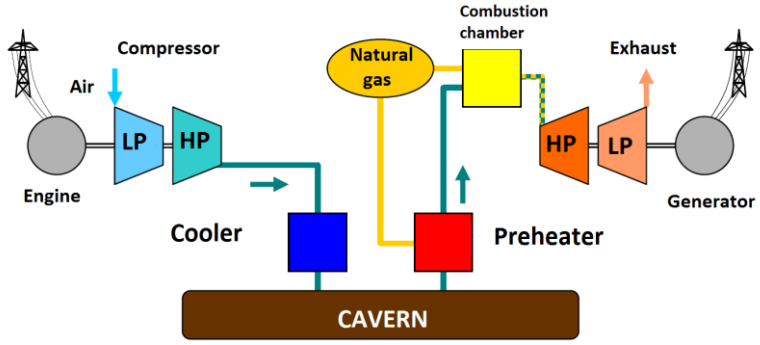
The task

The scope of the thesis is to implement wind and solar energy in the Power System Simulation Tool, PSST, developed by SINTEF Energy, and look at the impact these energy sources have on the European power system. Additionally electric storage possibilities are modeled in PSST, based on present and future projects in Europe. The objective is to give suggestions on how the storage possibilities should be modeled and used to increase optimization of the power grid.

Modeling



The pump is modeled as a generator with negative production output. The production from the pump is added to a reservoir with a hydro generator, times 80% due to the losses. The pumps starts when the system's marginal cost is 80% less than the reservoir's water value.



Compressed air is modeled the same way, but with an efficiency of 46%. The turbine starts when the system marginal cost is more than 48 €/MWh and the compressor starts when the marginal cost is less than 22.18 €/MWh.

Conclusion

Wind and solar power decreases the electricity price and the use of hard and lignite coal. Wind power gives more variation in prices and generation, and in 2020 there is a higher need of peak generators, like gas to cover the intermittent production. The hydro pump modeling was not adequate for this study, and did not give reasonable results. The results did not show any benefit of the hydro pump storages, which is not the case in reality. Compressed air energy storage was revealed to have few occurrence with profit, due to the low efficiency and the use of gas as a fuel. In addition, the modeling of compressed air energy storage is simplified and the results are an approximation.

Influence of HVDC with Overlaid Transients on the Life Time of Wet XLPE Cable Insulation

Student: **Halvor Hoen Hersleth**
Supervisor: **Frank Mauseth**
Collaboration with: **SINTEF**

Abstract

There are many technological challenges related to the production of electrical power from offshore wind farms. Norwegian companies are working on different aspects of offshore wind power generation and the Norwegian Research Council has in this context supported a five year project called: “High Voltage AC and DC Subsea Cables for Offshore Wind Farms and Transmission Grids”. This master thesis has been a part of that project.

Power electronics used for HVDC converters will stress the cable with a HVDC component with overlaid transients. The effect of the DC component and the overlaid transients on the performance of the polymeric cable insulation is not yet known and the main purpose of this master thesis has been to investigate how transients can influence water tree growth within wet XLPE insulation. The effect of the DC component has also been evaluated.

Laboratory experiments were conducted on Rogowski shaped test objects with an insulation thickness of 1.1 mm. 20 sodium chloride particles were added on the lower semiconductor during the manufacturing process. This was done to facilitate the initiation of water trees. The finished test objects were preconditioned with demineralized water in a heating cabinet at 30 °C for four weeks to ensure that the insulation was saturated with water.

An experimental setup capable of applying a DC voltage with a superimposed high frequency AC component was used to simulate the HVDC component and the overlaid transients that occur close to the power electronics used for AC to DC conversion. Two sets of experiments were conducted. The first set was conducted using a 15 kHz AC component, with resulting electrical field strength of ± 2.05 kV/mm. The second set of experiments was conducted combining the same high frequency AC component with a superimposed DC voltage, resulting in an electrical field strength of 12 ± 2.05 kV/mm. Nine Rogowski shaped test objects were aged in both sets of experiments. Three test objects were aged for one week, another three for two weeks, while the last three test objects were aged for three complete weeks. The test objects were kept in a heating cabinet at 30 °C during testing, and with the exception of the electrical field, treated identically during both sets of experiments.

All test objects experienced water tree initiation and growth. The length of the longest water tree and the aggregated water tree density were observed to increase as a function of ageing time for both sets of experiments. All water trees were oblong and grew in the direction of the electrical field. The longest observed water tree, after three weeks of ageing exposed to an AC component only, was 607 µm, corresponding to 55 % of the total insulation thickness. Two out of three test objects, exposed to a DC voltage with a superimposed AC component, suffered breakdown before enduring three complete weeks of ageing. This was most likely the result of a water tree bridging the 1100 µm thick insulation. Test objects exposed to a DC voltage with a superimposed high frequency AC component were also observed to experience a higher aggregated water tree density, with vented water trees observed at the lower semiconductor constituting the main difference. As a result, it could be argued that the DC

voltage, when combined with a superimposed high frequency AC component, increases water tree initiation and growth within wet XLPE insulation. The experiments also indicate that HVDC cables should be made water tight to prevent water tree degradation due to the transients originating from the switching of the power electronic converters.

Funksjonalitet for intelligente veilyssystemer

Student: **Anders Idsø**
Veileder: **Hansen, Eilif Hugo**

Sammendrag
Denne rapporten er et resultat av en masteroppgave våren 2013 ved NTNU omhandlende kartlegging av dagens driftssituasjon og en kartlegging av hva som er tilgjengelig på markedet av styresystem til veibelysning.

Installering av veibelysning er et viktig tiltak for å oppnå Norges nullvisjon for trafikksikkerhet, men dette medfører store drift- og vedlikeholdskostnader for veilysholderne. Det ble derfor gjort en undersøkelse for å finne ut hvilken tilstand dagens veilysanlegg er i. En rekke driftsselskap ble kontaktet underveis, og spurt om hvordan dagens situasjon er. Det ble forhørt om hva de mener er de største utfordringene med å drifte veibelysning, samt hvilken tanker de har om fremtidige løsninger.

Videre ble diverse leverandører av styresystem til veilys kontaktet for å finne ut om de kunne oppfylle manglene som ble funnet i dagens veistyringssystemer. Kun de som har egenproduserte styresystem ble kontaktet, ettersom man antar de sitter med mest kunnskap om systemene sine.

Resultatene fra undersøkelsen viser at tilstanden til veibelysningsanleggene er hovedsakelig i dårlig fatning, og det er nødvendig med store reinvestering for å få anleggene opp på et akseptabelt nivå. En gjenganger er at anleggene har konvensjonell styring med bruk av fotoceller og/eller astrour. Et av unntakene er Oslo kommune som har et nytt og avansert veilyssystem med toveiskommunikasjon.

På leverandørsiden finnes det i dag mange godt utviklete styresystemer, som kan styres ved hjelp av rekke forskjellige styringsparametere. Systemene har ikke noe problem med å dekke behovene som driftsselskapene føler de mangler i dag, og det er kun økonomien som setter begrensninger på hvor avansert systemet skal bli.

Det mest avanserte systemet har Comlight, der styringen skjer ved bruk av radardeteksjon. Konseptet går ut på at veilysene kun skal lyse når det er folk til stede.
Det har blitt konkludert med at den største utfordringen i dag er mangel på kompetanse hos veilysholderne. Men man kan forvente at dette vil øke i fremtiden ettersom både Vegdirektoratet, Statens vegvesen og EU har økt fokus på veibelysning.

Investigating G-parameters Modelling of Power Electronc Devices

Student: **Sigurd Hofsmo Jakobsen**
Veileder: **Marta Molinas**

Problem Description

The work will consist of developing a methodology to model power electronic converters as a multiport model, where the multiport model is described by g-parameters. The models are to be verified by simulations and implemented to a generic controlled converter of the same topology for validation purposes. A stability analysis will be performed using the g-parameters as basis, both by Nyquist's criterion and simulations

Samandrag

I takt med eit stadig aukande folketal på jorda, aukar også energibehovet.
Det er også ei brei internasjonal semje om at utviklinga må vera berekraftig.
Store kolkraftverk og andre særskild forureinande kraftverk, må derfor bytas ut med reinare kraftkjelder. Noko som må skje på likt med utbyggjinga av ny kraft, for å møta det aukande energibehovet. Sentralt i denne utviklinga er fornybar energi, både i form av tradisjonell vasskraft, geotermisk varme og distribuerte system. Sæleg vindparkar og solcellepanel har auka i omfang, desse må koplast saman med resten av elektrisitetsnettet ved hjelp av kraftelektronikk. Det foreligg også planar om å byggja høgspenninglikestraumsnett, som også vil trengja kraftelektronikkomformarar.

Det er derfor åapenbart at gode modellar av kraftelektronikkomformarar vil verta viktige. I denne avhandlinga vil ein måalingsbasert modell verta undersøkt. Styrken til denne framgangsmåaten ligg i, at ein ikkje treng å veta noko om styringssystemet eller dei indre parameterane til omformaren.

Fyrst vert ein teroi og metodedel presentert, her vert teorien og metoden grundig forklart. Saman med eit stabilitetskriterium for modellen, og eit forslag til eit nytt likningssett for å rekna ut modellen. Metoden vart fyrst testa ut på ein vekselrettar, som vart utvikla ved hjelp av Simulink. Dette gav ein nyttig plattform for å testa ut ulike aspekt ved metoden, i tillegg til at det er lettare å verifsera modellen ved hjelp av simuleringar. For at metoden skal ha ein praktisk relevans, så må det sjølvsagt også vera mogleg_a bruka han på verkelege omformarar. Ein testbenk beståande av ein likestraumsomformar vart utvikla for å testa metoden i eit praktisk tilfelle.

Samtidighet i elektriske bygningsinstallasjoner

Student: **Thomas Aleksander Johansen**
Veileder: **Eilif Hugo Hansen**

Sammendrag

Undersøkelser har vist at belastningen av bygg ikke stemmer med forventet forbruk, og det antas at store installerte effekter står ubrukt. Hvordan installasjonene kompenserer for samtidighetene i belastningen, og hvordan påvirker samtidigheten forbruket og samtidighetsfaktorene i installasjonen? Fire konkrete yrkesbygg ble sett på for å undersøke tilstandene, kontorbygget Nordregate 8, bank- / kontorbygget SpareBank1, sykehjemmet Munkvoll HSV og Rosenborg Skole.

Strømmålinger gjort på installasjonene ble utført over tid for å kartlegge forbruket inn til fordelingene og ut på kursnivå. Man måtte velge ut noen kurser å studere nøye på grunn av begrensninger i utstyret. Effektmålinger ble utført momentant på alle kursene for å finne effektfaktorene for belastningene i fordelingene.

Resultatene viste at samtidigheten på kursnivå varierte mellom belastningen kursene forsyner. Stikkontakter til uspesifisert bruk ble målt til å ha de laveste gjennomsnitts samtidigheter med 0,1655, belysningskursene 0,2631, varmekursene 0,5138 og diverse spesifikk belastning ble målt til 0,6292. Uspesifiserte stikkontaktskurser sin lave samtidighet var som forventet, og man så de samme resultatene fra målingene gjort i fordypningsprosjektet høsten 2012 [1]. Resultatene fra belysningskursene var overaskende, siden disse har en mer kontinuerlig belastning. Bedre kontroll på installerte effekter er eneste mulighet til å unngå denne typen overdimensjonering.

Samtidighetsberegningene for belastningen på inntaket viste meget forskjellige samtidigheter mellom yrkesbyggene. Rosenborg kom ut lavest og hadde maksimal samtidighet på 0,1230, Sparebank1 0,1344, Nordregate 8 0,4559 og Munkvoll 0,9413. Rosenborg og SpareBank1 er begge nye installasjoner med energieffektive belastninger. Begge fordelingene har en stor del stikkontaktskurser med lavest samtidighet av belastningsgruppene sett på. Overraskelsen var nok størst for resultatene i Munkvoll, som viste meget høy samtidighet på fordelingen. Dette var den eneste installasjonen med topografisk inndeling av kursene, og stor bruk av trefase kurser. Det kan virke som Munkvoll er underdimensjonert.

Å sette riktig samtidighetsfaktorer viste seg å være komplisert. Der er flere faktorer å ta med i betraktningene, men det viktigste man må ta for seg er å bestemme de installerte belastningene. Planleggernes motivasjon for å effektivisere sluttresultatet blir ofte overskygget av risikoene for å underdimensjonere installasjonene. Besparingsmulighetene er store, og man så i flere tilfeller at man kunne halvert antall kurser og installert effekt, uten å overbelaste vernene med samme belastning.

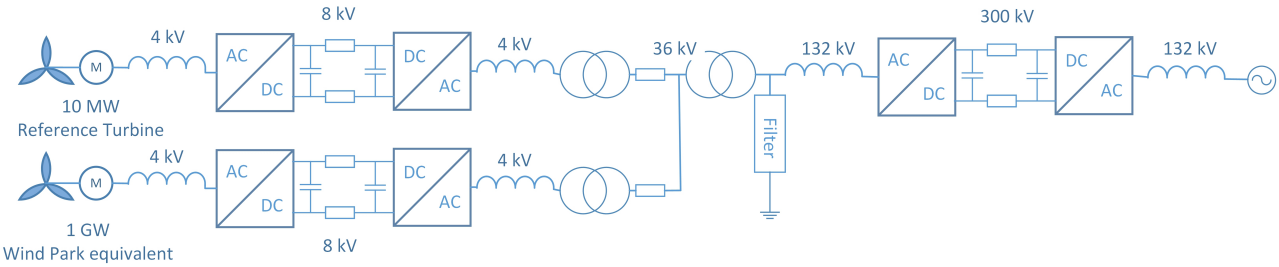
Control of VSC During Unsymmetrical AC faults in Offshore Wind Farms

Student: **Henrik Kirkeby**
Supervisor: **Kjetil Uhlen, Atle Rygg Årdal & Kamran Sharifabadi**
Collaboration with: **NTNU, SINTEF Energy AS, Statoil ASA**

Problem description:
During unsymmetrical AC faults in offshore wind farms, large unbalanced currents will flow through the converters in the wind turbines and in the HVDC link. Oscillating active and reactive power will flow through the system, and active power oscillations in the offshore AC grid will transfer to the HVDC link as oscillations in the DC voltage. It is desirable to employ a control system that can control and minimize these oscillations, and such a control system that separately controls positive and negative sequence currents have been examined and tested.

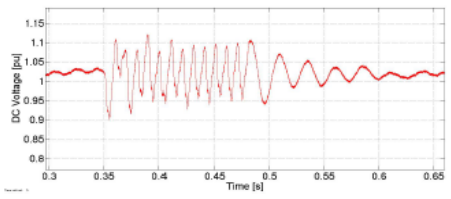
The task:
A model of an offshore wind farm has been constructed in Matlab SIMULINK, complete with a converter control system, in order to simulate different types of short circuits on various locations in the offshore AC grid. A standard vector current control system has been compared to a parallel positive and negative sequence current controller, in order to test out which of these is the most efficient in controlling DC voltage and other parameters.

The Model:

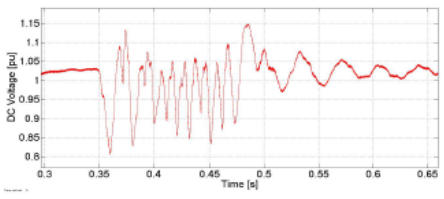


The simulation model is presented schematically above. It includes an onshore grid, a HVDC link with two converter stations, an offshore AC grid, and two wind turbine models. One of these is the NOWITECH reference turbine, while the other is an aggregated turbine of the rest of the wind farm, consisting of 10 MW NOWITECH turbines. In this manner, both the effects on the park and on a single turbine might be studied.

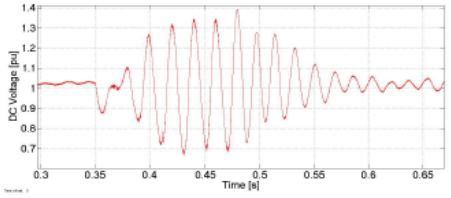
Results:
The results can be summed up the following graphs showing the HVDC Link DC voltage during a double line to ground fault:



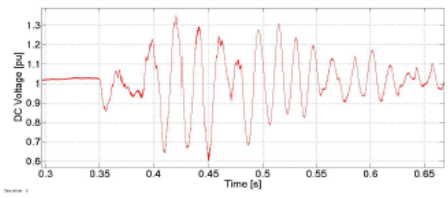
(a) Fault at Point B without NSCC



(b) Fault at Point B with NSCC



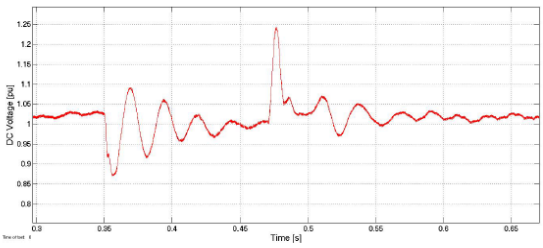
(c) Fault at Point C Without NSCC



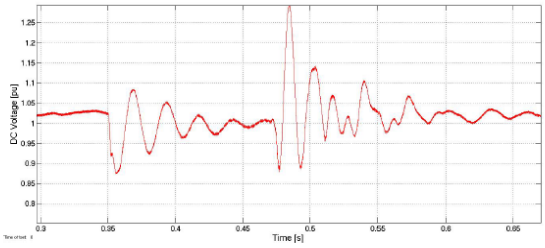
(d) Fault at Point C With NSCC

Here one can see that the Negative Sequence Current Controller (NSCC), does not improve the DC voltage oscillations during a fault at point B, whereas there is a slight improvement when the fault is applied at point C. After a transient period of about 0.05 seconds, one can see that the oscillations in DC voltage when the NSCC is enabled becomes smaller. It might be therefore, that the theory behind the controller is sound, but the controller is slow and unable to react fast enough to clearly show the improvement. In other words, creating a controller to control active power oscillations to be zero seems not to have worked as intended, as this in theory should give zero oscillations in DC voltage on the HVDC link.

Conclusion:
The negative sequence current controller does not work as intended. It shows a slight improvement over the standard controller in some situations, but it is hampered by being slower and slightly unstable. Tests confirm that the parallel positive and negative sequence controller also performs worse than the standard controller during balanced transient conditions, where they in theory should perform the same. This is shown below where DC voltage during a three phase to ground fault is presented. The result for the two controllers are similar, but when the fault is cleared at 0.470 seconds, the transient response is much worse for the sequence controller. The problem therefore seems not to be with the theory of negative sequence current control, but rather the implementation of the controller itself. Further works should be done, including to create a more detailed model with more finely tuned controllers. This might then more clearly show the improvement of using a parallel positive and negative sequence current controller.



(a) DC Voltage Without NSCC



(b) DC Voltage With NSCC

Smart Building Networks

Student: **Katarina Knezovic**
Supervisor: **Ivar Wangensteen**
Cosupervisor: **Slavko Krajcar**
Collaboration with: **FER, University of Zagreb**

Summary

Smart Building Networks

This paper gives insight into the paradigm of Smart Grid with focus on the smart building as its fundamental part. After a theoretical description of a current grid's evolution to smart form as well as basic features and functionalities of a smart building, a draft model of the building has been developed in the AnyLogic program. It simulates the behavior of a smart building and possibilities it can provide to the grid through various scenarios. In the end, a cost and benefit analysis has been conducted to show expenses and revenues in case of implementing a smart house at different locations (Norway and Croatia), and profitability of such a project.

This assignment is realised as a part of the collaborative project "Sustainable Energy and Environment in Western Balkans" that aims to develop and establish five new internationally recognized MSc study programs for the field of "Sustainable Energy and Environment", one at each of the five collaborating universities in three different WB countries. The project is funded through the Norwegian Programme in Higher Education, Research and Development in the Western Balkans, Programme 3: Energy Sector (HERD Energy) for the period 2011-2013.

Keywords: smart, grid, city, building, behavior, features, functionality, model, simulation, costs, benefits

Integrating Offshore Wind Power and Multiple Oil and Gas Platforms to the Onshore Grid using VSC-HVDC technology.

Student: **Magne Lorentzen Kolstad**
Supervisor: **Professor Tore Undeland**
Contact: **Dr. Kamran Sharifabadi**
Collaboration with: **Statoil**

Problem description
The oil and gas industry are responsible for about 25 % of the total greenhouse gas emissions from Norway. Most of these emissions are due to energy production. Today most of the offshore oil and gas platforms get there energy from gas fired turbines located on the platforms. These turbines have efficiency between 30 % - 40 % and are the major source of emissions from the Norwegian continental shelf. By replacing the energy from the gas turbines with renewable energy from offshore wind farms and hydro power from the onshore power grid the total greenhouse gas emissions from Norway can be greatly reduced.

The task
A system consisting of five oil and gas platforms and one offshore wind farm connected to the onshore power grid through a common High Voltage Direct Current (HVDC) transmission system based on Voltage Source Converters (VSC) are studied. The feasibility of the system is evaluated based on simulations. The following tasks have been done in this master thesis:

- Develop a dynamic simulation model of the system using SimPowerSystems in MATLAB®/Simulink®.
- Develop a control strategy and a VSC control system.
- Run simulations and study the dynamic behavior of the system during sudden variations in the load including: disconnection of the wind farm, load shedding, and large motor start up.
- Interpret and discuss the simulation results based on the grid code regarding offshore power systems and the simplification done in the model.

Model
An overview of the system can be seen in Fig. 1. In order to save computation time aggregated models are used. The load on the platforms consists of a passive load, a fixed speed induction motor, and a constant power load representing variable speed drives on the platform. The wind farm consists of a wind turbine and a permanent magnet synchronous machine operating at variable speed using a back-to-back VSC. The converters in the VSC-HVSC transmission system and the wind farm are modeled using average models.

The control system is realized using vector control based on a rotating dq reference frame. The main goal of the control system is to let the wind farm produce maximum amount of active power at all times and let the VSC-HVDC transmission system assure that the oil and gas platforms have stable operating conditions with as little voltage and frequency fluctuations as possible.

This is realized by the following control objectives:

- The wind turbine generator side converter controlling the speed of the turbine.
- The wind farm grid side converter controlling the DC link voltage.
- The offshore VSC-HVDC converter controlling the frequency and the voltage on the offshore busbar.
- The onshore VSC-HVDC converter assuring stable operating conditions for the offshore converter by controlling the estimated voltage offshore DC-terminals.

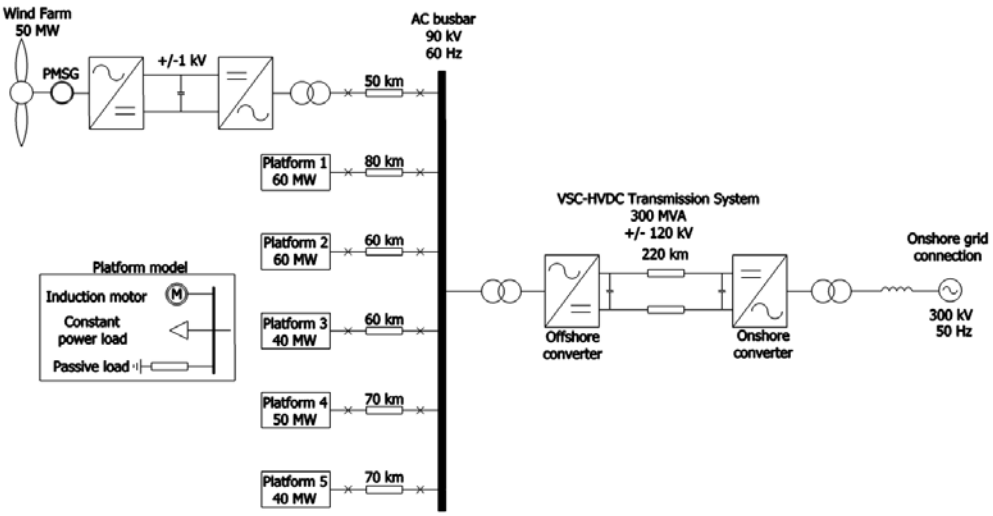


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Fig. 1 Overview of the system.

Simulations are performed on system disturbances that are thought to be critical for the operation of the system. The simulation cases represent large and partly exaggerated disturbances in order to test the limitations of the system.

Conclusion

The simulation results showed that the developed control system was able to keep the voltage and frequency variations within the offshore grid code, IEC 61892, even during large disturbances. It was concluded that the system handles variations in the load very well and that the system configuration studied in this thesis is regarded as a feasible way of integrating oil and gas platforms and offshore wind power to the onshore grid. However more detailed studies are recommended including short circuit analysis.

Indikatorer for sårbarhet og leveringspålitelighet i kraftnett

Student:	**Jostein Lille-Mæhlum**
Veileder:	**Gerd Kjølle**
Medveileder:	**Matthias Hofmann**
Samarbeid med:	**SINTEF Energi AS og Skagerak Nett AS**
Kontaktperson:	**Eivind Gramme ved Skagerak Nett AS**

Sammendrag

Det er et behov for å overvåke sårbarhet i kraftnett. Indikatorer kan benyttes til dette formålet, og det skilles mellom såkalte lagging- og leading indikatorer. Lagging sårbarhetsindikatorer beskriver sårbarheten i kraftnettet i dag, basert på historiske data, mens leading sårbarhetsindikatorer beskriver sårbarheten i framtiden. I denne oppgaven ble det derfor sett nærmere på hvilke aspekter som er viktig å overvåke i kraftnettet for et nettselskap, og hvordan det kan etableres sårbarhetsindikatorer for noen utvalgte aspekter. Det ble etablert lagging- og leading sårbarhetsindikatorer for deler av regionalnettet som eies og driftes av Skagerak Nett AS.

Sårbarhetsaspektene som i denne oppgaven ble ansett som aktuelle å etablere indikatorer for, var driftspåkjenninger i forbindelse med utfall av kraftledninger. På den måten ble også enkelte forhold som angår leveringspålitelighet inkludert i indikatorene. Utfallsanalyser ble utført med simuleringsprogrammet PSS/E fra Siemens. Følgende indikatorer ble etablert for år 2012 (lagging indikatorer) samt årene 2017 og 2022 (leading indikatorer):

- Feilfrekvens på kraftledninger (feilsannsynlighet)
- Belastningsgrad på anleggsdeler
- Kaskaderende hendelser i kraftnettet
- Reparasjonstid
- Avbrutt effekt
- Kritiske laster i kraftnettet
- Kostnader ved avbrudd (KILE-kostnader)
- Kombinerte indikatorer for alle enkeltindikatorer

I prosessen med etableringen av indikatorer ble det avdekket flere utfordringer. En av disse viste seg å være hvordan man skal komme fram til et datagrunnlag for de framtidige forholdene som inngår i beregningen av indikatorer. Det ble også funnet at det kan være vanskeligheter med hvordan kombinerte indikatorer skal etableres. Herunder inngår blant annet hvordan aggregering og vekting av indikatorer skal gjøres.

Resultatene fra indikatorene viser at kraftnettet er lite sårbart overfor enkeltutfall av kraftledninger. Dette gjelder både for lagging- og leading indikatorer. Det ble funnet at dersom maksimallasten øker mer enn prognosene tilsier, kan det oppstå flere hendelser i kraftnettet i år 2022 som medfører overlast. Et av de simulerte utfallene fikk i tillegg flere kaskaderende hendelser, og større konsekvenser. Utfallskombinasjoner av to kraftledninger ble simulert, og indikatorene for disse hendelsene viste at det kan oppstå utfall som er meget kritiske, men at sannsynligheten for at de skal inntreffe er liten. Det ble funnet at sårbarheten overfor utfallskombinasjoner av to kraftledninger er høyest i år 2022.

Arbeidet viser at indikatorer for å overvåke sårbarhet i kraftnett kan være hensiktsmessig å ta i bruk. Den helt klare fordelen med bruk av indikatorer i denne sammenheng, er med tanke på å enkelt kunne rangere hvilke utfall av kraftledninger som kraftnettet er sårbart overfor. Dette gjelder både for lagging- og leading indikatorer. Flere antagelser og forenklinger har blitt gjort for å etablere indikatorene, og det anbefales derfor grundigere analyser for de mest alvorlige hendelsene som indikatorene peker ut.

Det har også blitt vist at det fortsatt er et behov for videre arbeid med etablering av leading indikatorer, for å overvåke sårbarhet i kraftnett.

Innvirkning av HVDC-komponent med overlagrede transienter på vanntrevekst i PEX-isolasjon

Student: **Andreas Lind**
Veileder: **Frank Mauseth**

Sammendrag

Produksjon av elektrisk kraft fra offshore vindparker vil trolig bli en stor utfordring i fremtiden. Norges forskningsråd har i den forbindelse tilfelt SINTEF Energi femårsprosjektet; «High Voltage AC and DC Subsea Cables for Offshore Wind Farms and Transmission Grids». Denne masteroppgaven er en del av dette prosjektet.

Kraftelektronikken som benyttes ved HVDC omformere vil påkjenne kabelisolasjonen en DC spenning med overlagrede transienter. Effekten av denne påkjenningen er ukjent. Hovedformålet med denne oppgave er å undersøke hva effekten av denne spenningspåkjenningen har på vanntrevekst i våt PEX-isolasjon over tid, samtidig å undersøke påvirkningen til DC-spenningen.

Laboratorieforsøk er gjennomført på Rogowski-kopper med en isolasjonstykkelse på 1,25 mm. 20 saltpartikler var plassert mellom nedre halvleder og isolasjonen for framskyndelse av initiering og vekst av vanntrær. Testobjektene var fylt med demineralisert vann i en uke før spenningspåkjenningen, for forsikring om at isolasjonen var mettet med vann. Forsøket og prekondisjoneringen foregikk ved 30 °C.

Det elektriske oppsettet skulle simulere spenningspåkjenningen kabelisolasjonen opplever ved en HVDC omformer. Det ble gjennomført to forskjellige forsøk, hvor det ikke ble benyttet DC-spenning i forsøk nummer to. Det elektriske feltet påtrykt testobjektene var 15 ± 2,05 kV/mm og ± 2,05 kV/mm, med en frekvens på 15 kHz. Testobjektene ble tatt ut vilkårlig etter en, to og tre ukers aldring for undersøkelse av vanntrevekst. Antall og lengde på vanntreene ble notert, for analysering av endring i tetthet og lengste vanntre.

Testobjektene ble behandlet identisk ved begge forsøk, så eneste forskjell mellom forsøkene var det elektriske feltet. Resultatet fra forsøket med høyfrekvent AC var motstridende med teoretisk grunnlag, og det ble følgelig stor tvil til kredibiliteten til resultatet. Da resultatet var utroverdig og stor tvil tilknyttet årsaken, ble det ikke funnet ut påvirkningen DC-spenningen har. Forsøket anbefales å gjennomføres på nytt, hvor resultatene fra dette forsøket ikke kan benyttes.

Resultatet fra påkjenningen av HVDC med overlagrede transienter viste rask aldring, og det var etter tre ukers aldring kun 85 μm fra gjennomslag. Lengste ventilerte vanntre hadde etter tre ukers aldring flere vanntrær som hadde brutt mer enn 70 % av isolasjonen, slikt at forsøket kan ikke ha lengre forsøksvarigheten siden risikoen for gjennomslag blir høy. Tettheten av vanntrær økte betraktelig utover forsøksvarigheten, dette medførte at gjennomsnittslengden til vanntreene holdt seg tilnærmet stabil gjennom aldringstiden.

AC loss in a round MgB_2 superconductor

Student: **Sandra Madeleine Lindau**
Supervisor: **Frank Mauseth**
Contact: **Niklas Magnusson**
Collaboration with: **SINTEF Energy Research**

Problem description

Recently a new, inexpensive superconductor (MgB_2) has entered the market. Currently the conductor is used in DC applications, but the leading European MgB_2 producer, the Italian company Columbus Superconductors, has a program for developing also a superconductor with low AC losses of the material.

At NTNU/SINTEF a system for measurements of AC losses on short superconducting wires was finalized during spring 2012. The task is to perform systematic measurements of AC losses in superconducting wires as function of magnetic field, frequency and temperature. Particularly the relationship between the twist pitch and the losses of multi-filamentary wires should be evaluated. The twist pitch will be simulated by cutting non-twisted wires in different lengths. The results of the measurements will be used as feedback to the superconductor development, and as input to designers of AC electric power components.

The task

The task is to perform systematic measurements of AC losses as a function of magnetic field, frequency and temperature were particularly the relationship between the twist pitch and the losses of the superconductor should be evaluated.

Method

Calorimetric AC loss measurements have been performed on seven samples of a non-twisted multi-filamentary round MgB_2 wire superconductor. The sample lengths are between 3 mm to 50 mm. A sample length represents half the twist pitch of a similar wire. This means that the AC losses of these sample lengths can be assumed to represent the AC losses of long wires with twist pitch between 6 mm to 100 mm.

Results

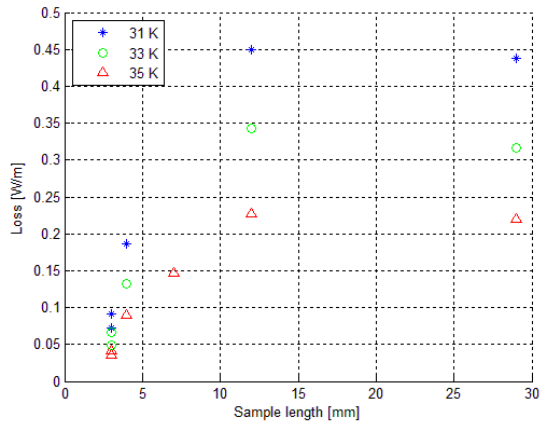


Figure 1. 150 mT, 50 Hz. Loss as a function of sample length at 31 K, 33 K and 35 K.

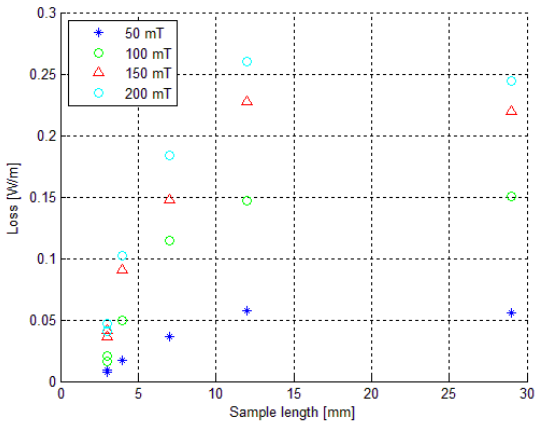


Figure 2. 35 K, 50 Hz. Loss as a function of sample length at 50 mT, 100 mT, 150 mT and 200 mT.

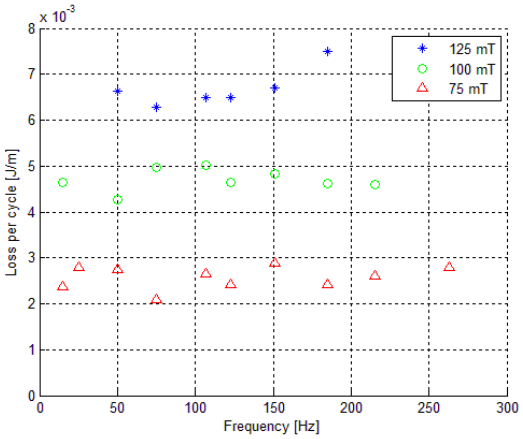


Figure 3. Sample length of 3 mm, 32.3 K. Loss per cycle as a function of frequency. Corresponding twist pitch is 6 mm.

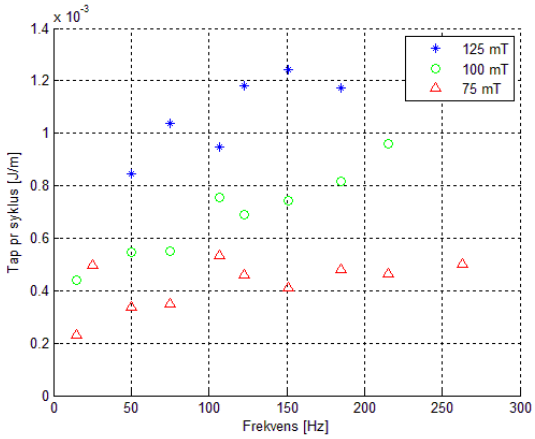


Figure 4. Sample length of 29 mm, 31.4 K. Loss per cycle as a function of frequency. Corresponding twist pitch is 58 mm.

Conclusion

The results show that:

- The losses increase with lower temperature, increasing magnetic field and increasing frequency.
- The losses are dependent on sample length and is increasing with sample length up to 12 mm.
- The losses at 50 Hz, 100 mT and 35 K decreases with a factor of 6 when decreasing the length of the test wire from 12 mm to 3 mm. From theoretical calculations it can be assumed that by reducing the twist pitch from 24 mm to 6 mm the benefit of the twisting will be close to maximum.

Teknisk-økonomisk analyse av reinvesteringer i vannkraftverk

Student: **Sigurd Fosby Livgard**
Veileder: **Eivind Solvang**

Sammendrag

Denne rapporten, Teknisk-økonomisk analyse av reinvesteringer i vannkraftverk, er sluttresultatet av en masteroppgave skrevet av Sigurd Fosby Livgard ved Norges teknisk-naturvitenskapelige universitet (NTNU) i Trondheim våren 2013. Oppgaven markerer avslutningen av en 5-årig mastergrad i Elektrisk energiteknikk, ved fakultetet for informasjonsteknologi, matematikk og elektronikk, og institutt for elkraftteknikk. Veileder for oppgaven ved NTNU har vært Eivind Solvang.

Hensikten med oppgaven har vært å gjennomføre en teknisk-økonomisk analyse av reinvesteringer i Nedre Fiskumfoss kraftverk. Bakgrunnen for analysen er et litteraturstudium av aktuelle rapporter som omhandler reinvestering, tilstandskontroll og vedlikehold, samt en befaring av anlegget. NTE har bidratt med informasjon og kunnskap om komponentene. Det er i oppgaven lagt et stort fokus på å gi en detaljert beskrivelse av hovedelementene i kraftverket, typiske skadetyper og aktuelle tiltak. Dette har dannet grunnlag for et bredt utvalg av rehabiliteringsalternativer.

Selve analysen omfatter stator, rotor og løpehjul. For hver av disse hovedkomponentene er det valgt ut noen relevante skadetyper med høy konsekvens ved svikt. Ved hjelp av en modell utarbeidet av SINTEF er levetidskurver brukt for å kalkulere sviktsannsynlighet. Modellen benytter informasjon om design, alder og teknisk tilstand.

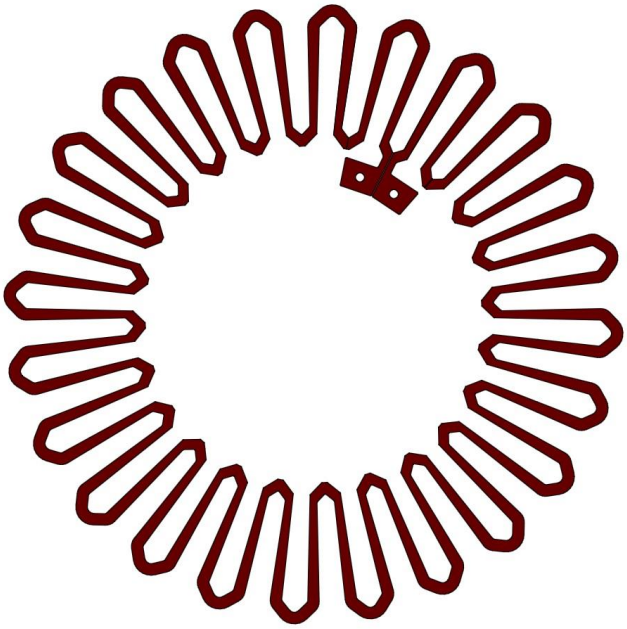
Med utgangspunkt i de valgte skadetyper og sviktsannsynlighet før og etter rehabilitering er kostnad ved svikt beregnet. For å utføre lønnsomhetsberegningen benyttes modellen ”Vedlikeholdskalkyle” som er et verktøy utviklet av SINTEF. Det er vurdert syv alternativer for rehabiliteringen, alle med en analyseperiode på 20 år. Formålet med analysen er å planlegge rehabiliteringen slik at videre drift kan sikres med kun normalt vedlikehold 20 år etter rehabiliteringens ferdigstillelse.

Modellen viser at det lønner seg å utnytte en stans best mulig ved å gjennomføre flere tiltak på en gang. Det er i de fleste tilfeller slik at produksjonstapet er den største kostnaden i forbindelse med en rehabilitering. Samtidig er dette også en balanse mellom havari- og kapitalkostnader. Dersom de ulike komponentene i kraftverket er på forskjellig stadium i forringelsesprosessen er noen tiltak nødt til å fremskyndes, mens andre utsettes for at de skal kunne utføres samtidig. Dette må ikke strekkes så langt at sannsynligheten for svikt blir overhengende. Totalkostnaden ved en svikt vil i alle tilfeller overstige kostnaden av en planlagt stans. Dette er alle problemstillinger som det er enklere å ta stilling til dersom det er utført en analyse som det er gjort i denne masteroppgaven.

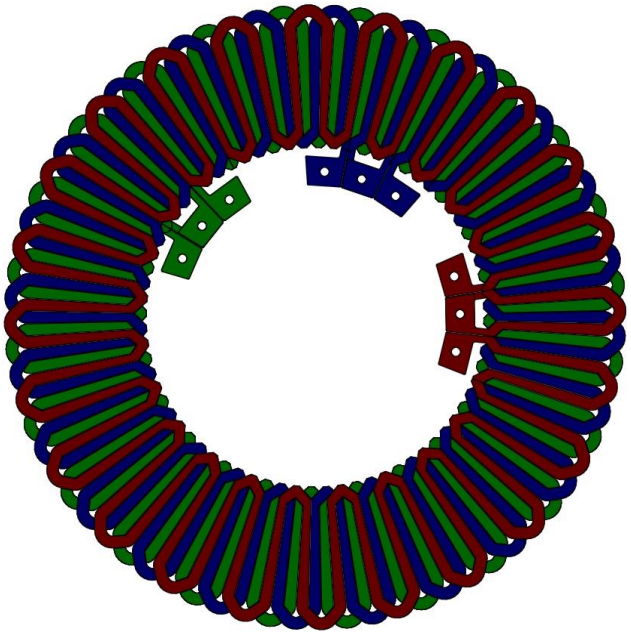
Analysis of a Novel Coil Design for Axial Flux Machines

Student: **Sigbjørn Lomheim**
Supervisor: **Prof. Robert Nilssen**
Contact: **Dr. Jon Eirik Brennvall**
Collaboration with: **Greenway Energy AS**

Today the electrical motors are embedded in almost every market segment in the industry, providing a smarter, safer and efficient alternative to cope with the work load. However, there are a number of areas where the electric motor has yet to be introduced.

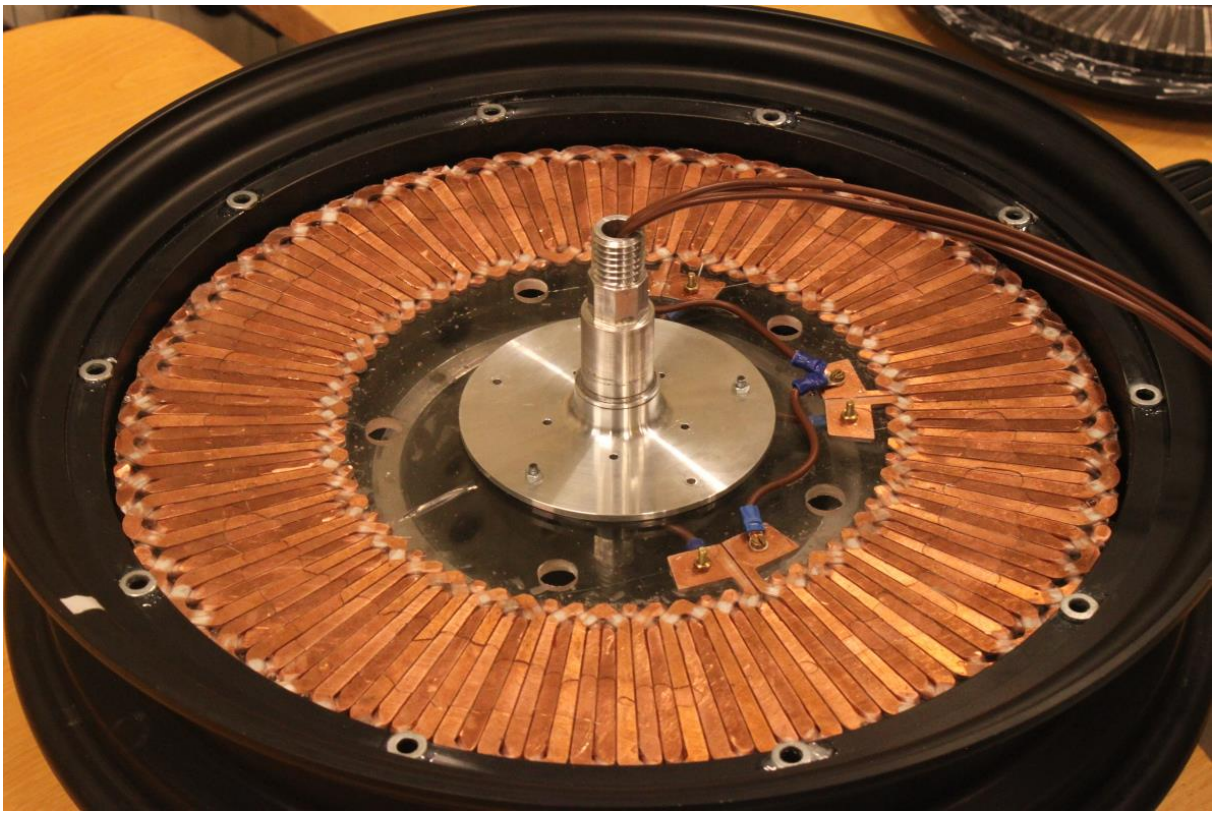


A difficult challenge to the electric motor is to compete with hydraulic motors, where the torque density requirement is beyond any machine design today. In order to build a torque dense electrical machine, the geometrical dimensions must be small while the current densities are high, which results in a low efficient machine. The low efficiency implies that the machine has high losses, and must be very efficiently cooled. In effort to build such a machine, a novel coil design has been developed by Dr. Jon Eirik Brennvall at Greenway Energy AS. This master thesis work has been to study this design, identifying how such a machine can be made, and how it performs in an industrial application.



Summary - A novel coil design for permanent magnet axial flux machines is presented. An analysis of its performance regarding winding layout, cooling capability, cogging torque, and back-EMF is conducted. Different manufacturing and assembly methods are described. A prototype stator has been built and tested. The prototype stator has a 90% fill factor, and is an iron free wave-winded topology. The prototype has been analyzed using analytical approaches, and compared to the performance in the laboratory testing. An analysis of introducing iron in the stator has been done, where the effect of iron stator is compared to the iron free prototype. An analytical model describing the performance of the iron stator has been developed and presented in this thesis. The model is used to present its performance in industrial applications, where high torque - low speed properties are needed. The results show that this design may compete with hydraulic motors in the industry, having an extremely high torque density, but due to high current densities, an efficiency of

30% to 40%. An investigation of the cooling capability of the coil design has been conducted by master student Lars Johan Clad at the Department of Energy and Process Engineering at NTNU. It has here been proved that the cooling of this coil design is sufficient to enable a current density of 20A/mm² in the stator conductors, with only 60° operating temperature.



Control of Grid Connected Active Converter

Student: **Han Wee Low**
Supervisor: **Lars Einar Norum**
Contact: **Roy Nilsen**
Collaboration with: **Wärtsilä Norway AS**

Problem description

Application of power electronics in power distributed generation industry has been a fast evolving technology. This is due to the rapid shift from conventional non-renewable energy source to renewable energy source which led to the rapid rise of distributed generation. Efficient power generation from renewable energy source is highly dependant of the efficiency of the power electronics converter. Thus control of power electronics converter has been a vastly researched subject.

The task

A conventional cascaded control structure serves as a model for grid synchronization control design. Current and voltage control design and simulation will be the main research focus. Control system strategies are divided into approach with different type of controllers, hysteresis and proportional integral controller. It is further subdivided into approach with different control signal reference frame which consist of three phase stationary *abc* reference frame, two phase stationary *αβ* and synchronous *dq* reference frame. On top of this, a new voltage control structure approach which sees independent control of voltage magnitude and voltage frequency-phase angle is implemented too.

Model/ measurements

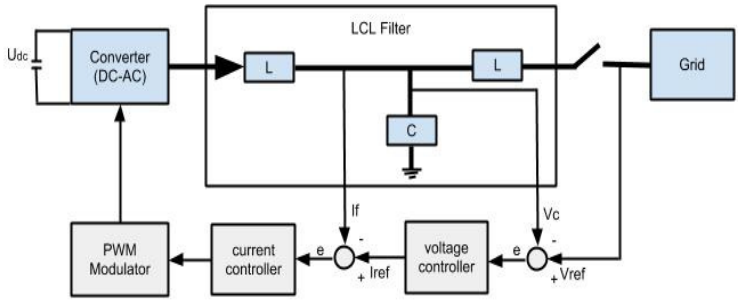


Figure 1: Control system structure of grid connected converter

Three model for current controller is built:

- PI controller with stationary *αβ* reference frame
- PI controller with synchronous *dq* reference frame
- Hysteresis controller with stationary *abc* reference frame

Three model for voltage controller is built:

- PI controller with stationary *αβ* reference frame
- PI controller with synchronous *dq* reference frame
- Voltage magnitude and frequency-phase angle controller

Simulation Results

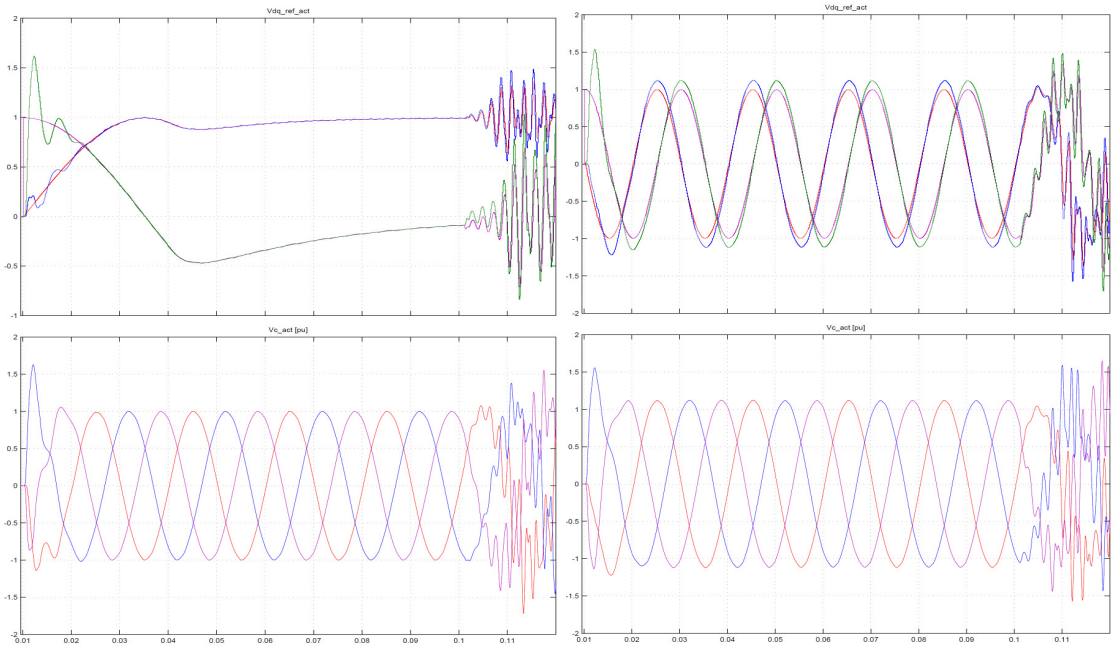


Figure 1: Voltage control system with PI controller in syncrhonous and stationary reference frame

Conclusion

Current Control

Current control with PI controller found to be working better in synchronous *dq* reference frame compare to stationary *αβ* reference frame. As in synchronous frame, PI controller is correcting DC error signal instead of an AC error signal which will lead to a steady state sinusoidal error.

While for hysteresis controller in three phase stationary *abc* reference frame, three phase filter current waveform is observed to be fast and accurate. Hysteresis controller approach is simple and load parameter is not needed in designing the controller. Hysteresis controller produces an irregular switching frequency while PI controller with PWM gives a fixed converter switching frequency.

Voltage Control

Voltage control with PI controller in synchronous *dq* reference frame and stationary *αβ* reference frame in general share the same observation as in current control. Thus it can be similarly concluded where control in synchronous frame is found to be a better option as it will not lead to steady state error. Due to the absence of normal operation control this transient response is prolonged and deemed to be worst transient expected.

Voltage magnitude and frequency-phase angle controller sees both axes controlled separately; the system has lower tolerance for step input during initialization. Although this control structure has a lower tolerance in input error and slower in syncrhonizing, the main advantage of this control lies in its independance and flexibility of control. Where the voltage and frequency reference can be given independantly without the need of generating sinusoidal voltage reference.

Synchronous Optimal Modulation for Medium Voltage Multi-phase Machines

(Implementation of three-level modulators In Field Programmable Gate Arrays)

Student: **Mamta Maharjan**
Supervisor: **Prof. Tore M. Undeland**
Co-Supervisor: **Roy Nilsen, Wärtsilä Norway AS**

Problem Description

The advancement in power electronics devices like IGBTs have increase the low voltage ac drive to the medium voltage drive system. Medium Voltage IGBTs must have low switching frequency. Operation at reduced switching frequency requires new modulation technique to reduce the switching loss. Synchronous Optimal Modulation (SOM) pre-calculates optimal switching angles within a period of the fundamental period by minimizing total harmonic contents. These switching angles are not formed by carrier wave like in conventional way. These optimized PWM strategies are extremely difficult to realize with conventional analog circuitry. Therefore, the firmware implementation of synchronous optimal modulation in digital circuitry will be created by an extremely fast computation microchip called Field-Programmable Gate Array (FPGA). In this Master thesis a modulator for a 3-level converter should be developed. The modulator should be possible to be extended to 9-phase machines.

Methodology

In Synchronous Optimal Modulation switching events are not given by a carrier signal. These switching instants are pre-calculated by some software program to minimise the weighted total harmonic distortion.

$$THD_i = \frac{1}{\omega_1 L} \cdot \sqrt{\sum_{h=2}^{\infty} \left(\frac{\hat{U}_{a,h}}{h} \right)^2}$$

$$WTHD = \frac{THD_i}{\hat{I}_{a,1}} = \frac{\omega_1 L \cdot THD_i}{\hat{U}_{a0,1}} = \frac{1}{\hat{U}_{a0,1}} \cdot \sqrt{\sum_{h=2}^{\infty} \left(\frac{\hat{U}_{a0,h}}{h} \right)^2}$$

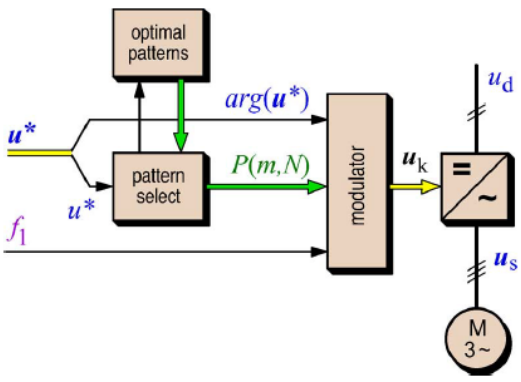


Fig: signal flow graph

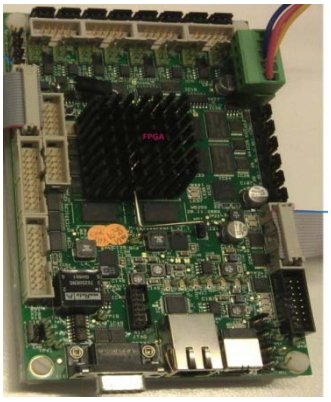


Fig: FPGA control card

The whole design is developed in Xilinx EDK (Embedded Development Kit). It consists of FPGA along with processor. Synchronous Optimal Modulation patterns are generated in Processor while the modulator is designed in FPGA.

Results

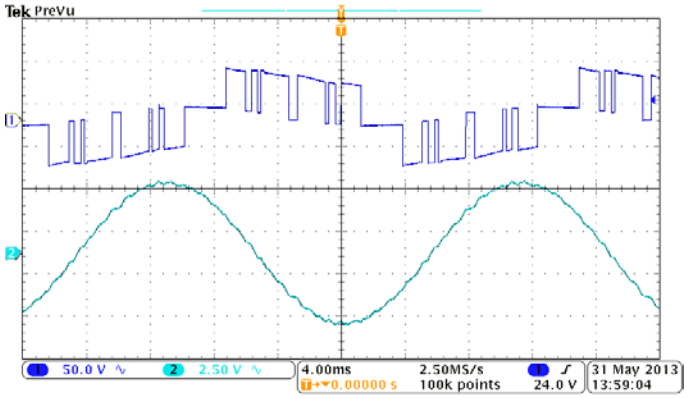


Fig: Three level Voltage signal obtained from SOM pattern
Current signal (lower) given to Induction Machine

Switching Frequency	150Hz
SPWM(%THD)	53.88
Trapezoidal(%THD)	52.70
SVPWM(%THD)	52.70
Synchronous optimal Modulation (%THD)	24.4

Table: Comparison Result of %THD for output Line voltage of inverter

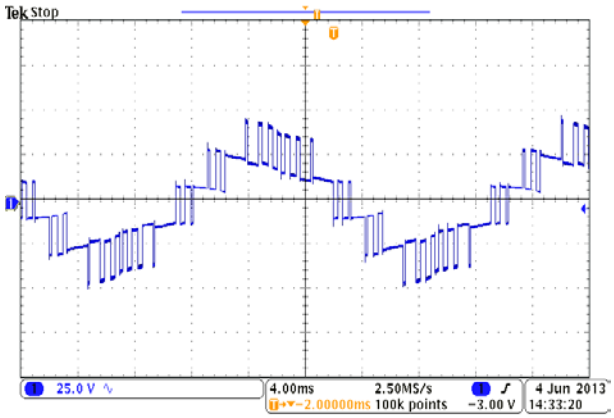


Fig: 5 level Line-Line Voltage for 3 level converter

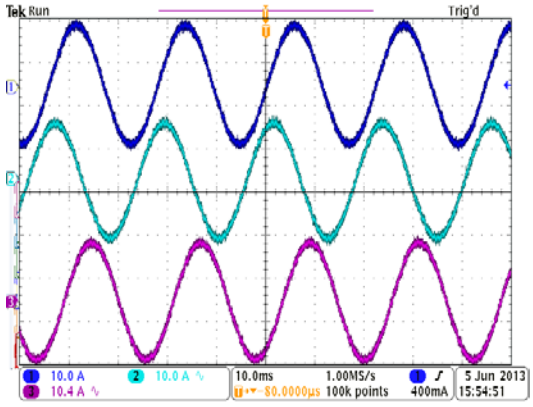


Fig: Ripple free Current for three phase

Using synchronous optimal modulation, total harmonic distortion in voltage and current is reduced to great extent for low switching frequency without even using the filters except for the inductance of induction machine. The reduction in harmonics is also enhanced by using three level converters because multilevel output voltage waveforms have less distorted output and are close to sinusoidal waveform.

Conclusion

- For operating switch in low frequency with less switching loss, synchronous optimal modulation can be utilized.
- THD is immensely reduced compared to other conventional PWM technique.
- Since this system in embedded in exceptionally fast FPGA which is operating in parallel, it can easily be used for multiphase machine.

Grid Connected PV Systems with Smart Grid functionality

Student: **Henry Massawe**
Supervisor: **Lars Norum**

Problem description

At NTNU a laboratory for renewable energy is under construction. This lab emulates several different renewable energy sources connected together. The power from the PV panels mounted outside on the building will be available for connection in the laboratory. A survey of control structures for the inverter when used as a grid connected PV inverter will be made. Based on this a suitable control will be chosen, which will include methods for grid synchronization, maximum power utilization, anti-islanding and current/voltage control. System models must be developed, which shall form a basis for controller parameter estimation. In the project the instrumentation system for collection of operation information of the PV plant into a database will be designed based on EtherCAT network. The purpose of this database is to collect and archive performance, reliability and operating cost data for this PV based distributed power systems.

This thesis focuses on the design of the single phase power stage inverter. Important parameters for the inverter stage have been proposed. The converter is designed in Multism and implemented in LabView for the control of the outputs and creates user interface. The remaining task as pointed in the future work in this thesis will be the development of the control system of the plant including instrumentation and communication controls. The control shall meet the system requirement and meet the characteristics of the proposed inverter power stage in this thesis. When required the prototype will be built after being satisfied with the performance on NI LabView after implementation. As an interesting idea, this thesis provides the room for using LabView to integrate with other renewable sources available in the basis of the suitable control systems that can be easy implemented in the software.

The task

In order to meet the objectives of this thesis, literatures for PV-grid connected inverters and various related work to this thesis was studied. The choice of the best circuitry topology was made and important parameters for the power stage inverter were calculated and proposed based on 230VAC phase voltage, 1kW ratings requirements. The dual power stage inverter was designed in Multism. The control strategy for switching the power stage inverter was proposed and the expected desired output obtained from the inverter was analyzed in LabView and compared to the standard grid current and voltage outputs.

Model/ measurements

Figure 1 shows the model of the power stage inveter designed in this thesis. The PV-array was set to produce a DC voltage of 100V. Voltage amplification and the isolation of the PV and grid side is enhnced by the full bridge conveter. The DC-link capacitor is set to handle 400V that gives an output phase voltage of 230V to the grid. The close/open of the switches in the DC-DC and AC-DC stages are operated by sinusoidal pulse width modulation (SPWM) unipolar voltage switching scheme. The harmonics from the switching effects are eliminated by the L-C-L output filter.

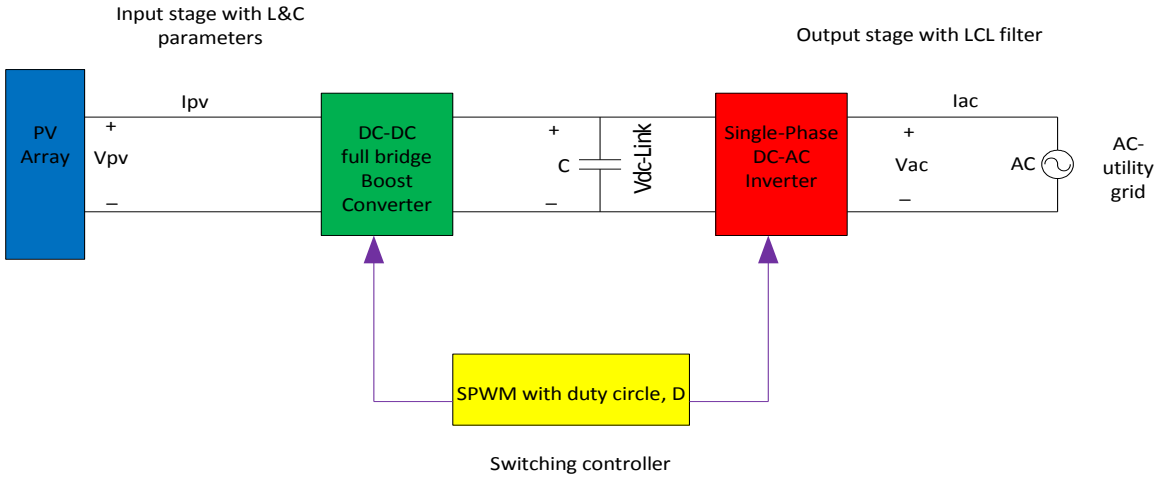


Figure 1: Power Stage Inverter model

Calculation

The power stage convetrer was assumed to convert the input voltage of 100VDC from the PV array to 230VAC rms phase voltage and to deliver a power of 1kW, 50Hz at unit power factor. Based on this assumptions the calculated parameters are depicted on Table 1. The circuitary topology with these parameters were designed in multism.

L_{pv}	C_{pv}	C_{DC}	D	$f_{switching}$	L_i	C_f	L_g	R_d
0.2mH	170 µF	100 µF	0.68	10kHz	4mH	3 µF	2.4mH	0.755Ω

Table 1: Inverter Power Stage parameters

Conclusion

The inveter power stage designed works as expected. The designed switching control and parameters proposed have analysed in LabView. The desired output voltage was obtained as expected. The phase voltage is 230V peak and the current varies up to 10A peak depends on the load impedance. The inverter's output in Figure 2 is 180°out of phase with the grid voltage, which means in this case, the electricity generation is realized by the string inverter system. The slightly phase shift in the output is due to the filter output phase.

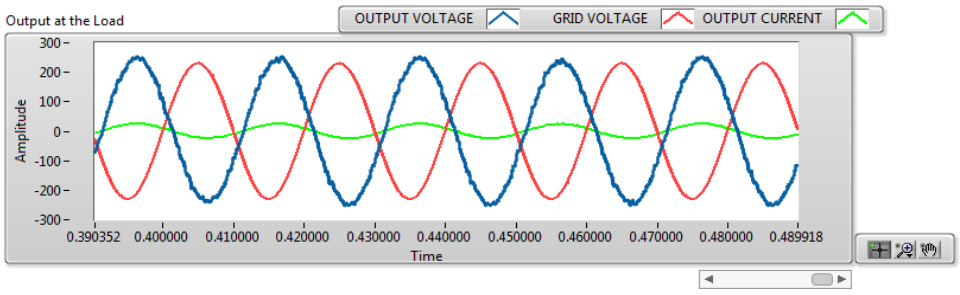


Figure 2: Inveter outupts and grid voltage

Lab Setup and Testing of Lithium-Ion Batteries with Focus on Dynamic and Aging Modeling

Student: **Eirik Molund**
Supervisor: **Prof. Lars Norum, Elkraft**
Contact: **Dr. Salvatore D'Arco, SINTEF**
Collaboration with: **SINTEF/Wärtsilä Norway**

Problem description

The introduction of new forms of dispersed energy generation and optimization of existing power plants has increased the interest in energy storage systems. Use of batteries in energy storage systems is an emerging technology and the market for this seems to be growing. The large interest in battery energy storage systems increases the need for testing of batteries for adapting battery technology to different areas of application.

The work will include creation of a laboratory setup for testing of batteries. This will be done in collaboration with researchers at SINTEF Energy and SINTEF Materials and Chemistry. Creating the lab setup will be the main part of the work. In addition to creating the setup the student will perform testing of batteries. The results from the testing can be used to fit, check or assess battery models.

The task

This work included making a lab setup for testing of different types of batteries in the energy storage lab at NTNU/SINTEF. A complete lab setup has been made and two different $LiFePO_4$ chemistry cells of size 10Ah and 130Ah have been tested in the lab confirming the usability of the setup for battery testing. The lab setup mainly consists of two DC-DC converters, a PC with LabVIEW software to control the converters and external measurements via a NI cDAQ-unit. A LabVIEW program was developed to allow automatic cycling of batteries after a reference file which allows different types of battery tests.

The batteries acquired for validating the setup were tested. The testing has included discharge tests of both cells and a comparison with dynamic battery models shows good results. Additional discharge tests can be done to make a more complete model of the battery. An aging test of the two 10Ah cells have also been initiated where the two cells were cycled in two different profiles consisting of one cycle of $\Delta DOD=0.7$ and three cycles at $\Delta DOD=0.2$.

Model/ measurements

Below is a picture of the converters used in the lab setup and a plot of the result from a discharge test of a 130Ah cell.

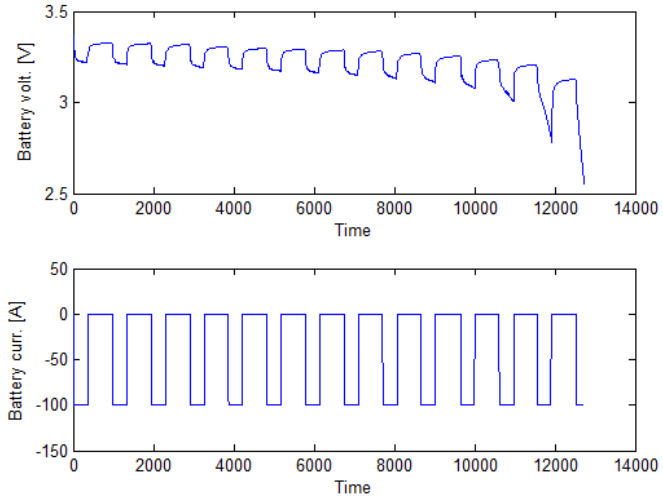


Figure 0.1 – DC-DC converters used in lab setup.
Figure 0.2 – Result from discharge test of 130Ah cell.

Conclusion

The discharge tests of the 130Ah and 10Ah cells have been used to analyze the dynamic properties of the cells. Good accordance is found between the 130Ah cell and a scaled up version of an 850mAh cell model in a comparable paper.

The two 10Ah cells have been tested with 180 and 288 cycles at two cycling profiles which consists of one ΔDOD=0.7 discharge and three ΔDOD=0.2 discharges. No degradation of the cells has been found in these cycles which coincide with Li-ion batteries being highly resistant to cycle aging. Further cycling should be performed to capture the capacity decrease of the battery.

Finite Control Set Model Predictive Control in Power Converters

Student: **Razieh Nejati Fard**
Supervisor: **Prof. Lars Norum**
Co-supervisor: **Hamed Nademi** (PhD. Candidate)

This study presents a detailed description of a cost function-based predictive control strategy called Finite Control Set Model Predictive Control (FCS-MPC) and its applications to the control of power electronics converters. The basic concepts, operating principles and general properties of this control technique have been explained. The analysis is performed on two different power converter topologies: traditional three-phase Voltage Source Inverter (VSI) and Modular Multilevel Converter (MMC). In order to verify its capabilities MATLAB (SIMULINK) simulations have been performed for both cases.

FCS-MPC is a powerful control technique that has several advantages such as high accuracy, flexibility and stability, easy implementation, simple and understandable concepts, but the most important and exclusive feature of this control strategy is the inclusion of nonlinearities and system constraints in the cost function. As a result, all the control requirements can be considered by one controller at the same time.

The design procedure of FCS-MPC is based on first, a discrete-time model of the system that is used to predict the behavior of the controlled variables for all the possible switching states of the converter and second, a cost function that should be defined according to the control requirements of the system. The switching state minimizes the cost function will be selected to be applied to the converter at the next sampling time. Fig.1 shows the control block diagram of FCS-MPC. It is applicable to all converter topologies by defining appropriate cost function. FCS-MPC has been applied to VSI and MMC topologies as two examples. The proposed FCS-MPC controller for VSI topology was successful in forcing the load currents to track their sinusoidal references with small ripple. In addition, all the discretization methods: forward, backward and midpoint Euler methods have been tested. All of them provide acceptable results, while the midpoint Euler provides higher accuracy (less current ripple) and the output currents and terminal voltages have lower harmonics than the other two methods. Hence, it

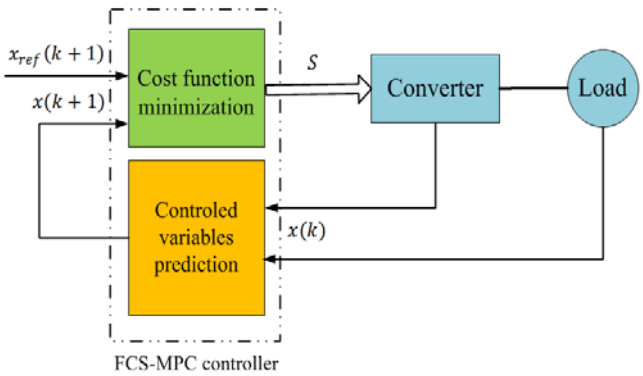


Fig.1 The control block diagram of FCS-MPC

can be the best choice for discretizing the system model. However, the switching frequency is higher in the case of using midpoint Euler which is a disadvantage and leads to higher switching loss.

In addition, it has been designed for MMC topology (Fig.2) that is very complicated than VSI. The load currents have been chosen to be the main controlled variables due to the calculated system model. Moreover, there are two control requirements regarding the MMC operating principles that should be considered: keeping the capacitors voltages balanced around the nominal value and minimizing the circulating currents. According to the simulation results of a three-phase five level MMC connected to utility grid, the FCS-MPC is capable of forcing the load currents to follow their references almost regardless of their shape.

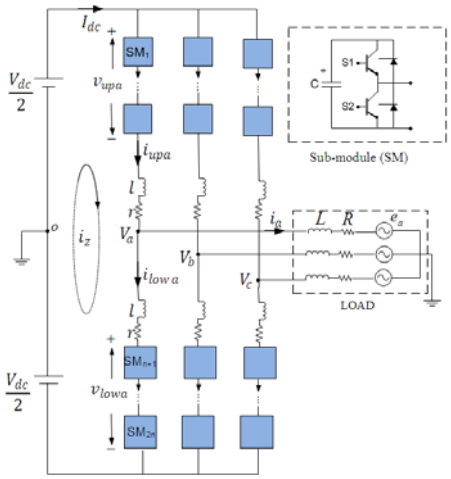


Fig.2 (n+1)-level MMC topology

In addition, the capacitors voltages can be kept in order and the circulating currents can be minimized only if suitable weighting factors are chosen (Fig.3-6).

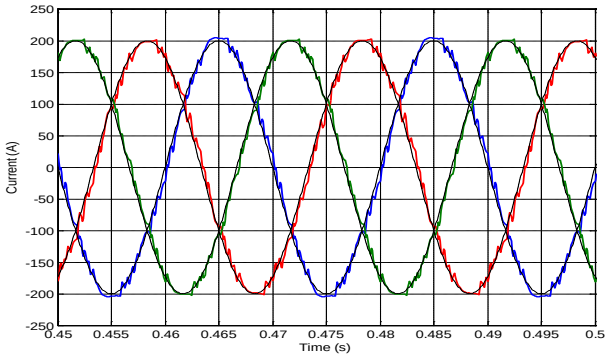


Fig.3 The load Currents in steady state

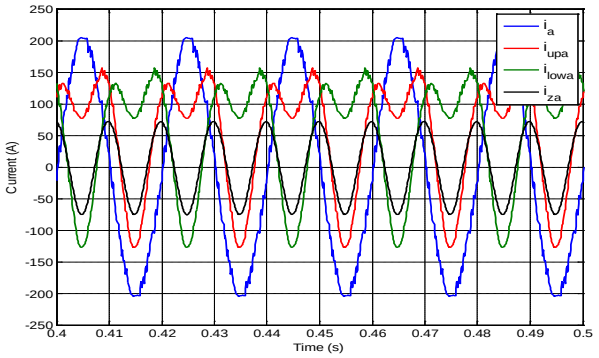


Fig.4 The load, circulating and arm currents of phase-a

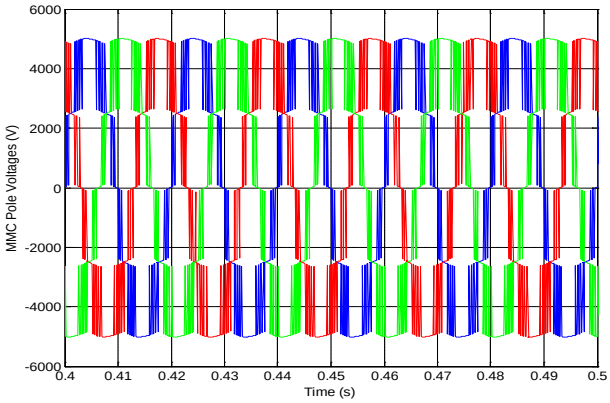


Fig.5 MMC pole Voltages

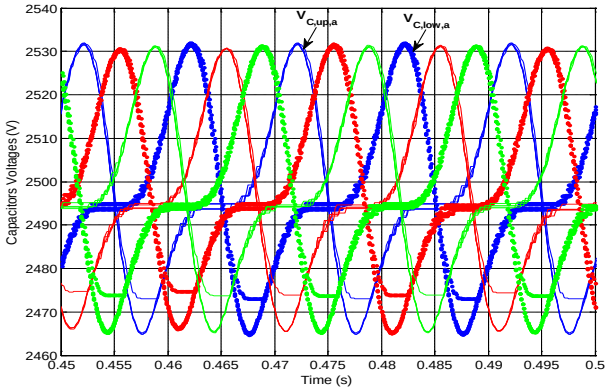


Fig.6 The capacitors voltages

The performance of the controller is acceptable not only in steady state but also during disturbances. It reacts to system disturbances very fast and keeps the currents and voltages in an acceptable range. The new steady state will be reached accurately and successfully in less than 0.5 sec.

Again in this case, all the Euler discretization methods have been tested to find the best. The controller has good and acceptable performance only with midpoint Euler method in contrast with VSI example

The robustness of the proposed FCS-MPC has been checked by considering ±20% uncertainty to the load parameters measurement. No considerable change has been detected in the system performance; consequently, the proposed FCS-MPC can be counted as a very robust control strategy.

It is reasonable that the increase of sampling frequency will increase the accuracy of prediction and it can improve the performance of the controller. However, switching frequency is dependent on sampling frequency and the increase of sampling frequency will lead to switching frequency increase which is a disadvantage. Therefore, optimization is the best solution to reach the most appropriate sampling frequency.

Reducing sub-harmonic spatial fields in concentrated winding machines using Genetic Algorithms

Student: **Thomas Nordaunet**
Supervisor: **Prof. Robert Nilssen**
Contact: **Astrid Røkke**
Collaboration with: **Smart Motor AS**

Problem description

Certain slot/pole combinations in fractional slot winding machines with concentrated coils exhibit high amount of sub-harmonic spatial fields. These harmonics may cause additional losses and ripple torque. Literature suggest solutions to reduce the amount of sub-harmonics by increasing the number of layers, varying the numbers of turns per coil or introducing flux barriers in the yokes of the machine.

The task

This article presents solutions to minimize sub-harmonics in a 24 slot 22 pole fractional slot winding machine with concentrated coils. A Genetic Algorithm is used to optimize the design of multiple layer windings with different turns per coil and implementation of flux barriers in the yokes of the machine. The proposed solutions are verified with Finite Element Analysis and compared with respect to sub-harmonic content, losses and ripple torque.

Model

Fourier transform of the analytical Magnetomotive Force produced by the winding is used to characterize the sub-harmonic content. A Genetic Algorithm optimizes the winding layout using multiple partial fitness functions. Both double layer and single layer winding constraints are implemented to construct different layouts.
Flux Barriers are implemented using Finite Element Analysis and Magnetic Equivalent Circuits to optimize the design and arrangement.

Calculation

Calculations revealed a 85 % decrease in the 1.th sub-harmonic using the double layer windings proposed by the Genetic Algorithm, and a 46 % reduction in solid losses compared to the single layer winding.
A four layer winding completely removed the sub-harmonic content in the machine, consequently decreasing the solid losses by 63 % compared to the single layer winding.

Conclusion

By optimizing the winding layout it is possible to completely remove the sub-harmonics. However, this complicates the winding layout, thus application specifications will govern the solution chosen.
Flux barriers presents a simple and promising solution reducing sub-harmonics.

Smartere feillokalisering i distribusjonsnettet ved bruk av ikke-konvensjonelle måleprinsipper

Student: **André Omdal**
Hovedveileder: **Hans Kristian Høidalen**

Rapporten omhandler hvordan jordfeil i distribusjonsnettet skal kunne lokaliseres på en bedre måte enn metodene som brukes i dag. Dagens metoder fører ofte til betydelige kostnader for nettselskapene knyttet til ikke-levert energi ved avbrudd for sluttbrukere. Nye og smartere metoder vil redusere både varigheten og hyppigheten til avbruddene på grunn av en hurtigere feillokalisering, men også siden lokaliseringsprosessen ikke vil utføres etter dagens «prøve-og-feile» metode.

Første del av rapporten tar for seg grunnleggende teori knyttet til leveringskvalitet og forskriftskrav, nettyper og jordfeilstrømmer, i tillegg til vern og måletransformatorer. Dette for å vise hvordan nettet oppfører seg ved en jordfeil og hvordan denne detekteres ved måling av strøm og spenning, men også for vise hva som kreves av måletransformatorer i henhold til krav og normer.

Det er gjennom en litteraturstudie knyttet til innovative løsninger for måling av strøm og spenning ute i nettet funnet at det mest aktuelle produktet per dags dato er isolatorer med integrerte strøm- og spenningsmålinger. Tre slike produkter er dermed presentert i oppgaven. Systemet knyttet til jordfeillokaliseringen ved bruk av slike isolatorer er også beskrevet i grove trekk. Systemet foreslås automatisert og basert delvis på kjent teknologi ved bruk av såkalte microSCADA systemer. Systemet vil dermed ligne på eksempelvis NorTroll sitt system, men hvor isolatorer vil benyttes istedenfor eksisterende feilindikatorløsninger. Isolatorer med mer nøyaktige metoder for måling av strøm vil muliggjøre bruken av slike systemer også i det norske distribusjonsnettet, hvor en deteksjon av jordfeil tidligere har vært problematisk ved bruk av feilindikatorer grunnet nett med lave kapasitive feilstrømmer.

Det er også utført simuleringer i ATP-EMTP på en reell del av et distribusjonsnett i Norge for å vise hvordan nettet oppfører seg ved en jordfeil. Simuleringene er også utført for å indikere hva isolatorer plassert ute i nettet må kunne måle for å benyttes i et slikt system som nevnt over, og som vil gi en smartere og bedre lokalisering av feil i henhold til dagens «prøve-og-feile» metode.

Til slutt er måleprinsippene som brukes i isolatorer med integrerte strøm- og spenningsmålinger testet på laboratoriet, henholdsvis en Rogowski-spole for strømmåling og en kapasitiv spenningsdeler for spenningsmåling. Testene er utført for å finne stasjonære avvik og transiente egenskaper.

Resultatene i denne oppgaven viser at de ikke-konvensjonelle måleprinsippene som er testet har tilfredsstillende stasjonære avvik i henhold til IEC-standardene, og de evnet også å måle transientene som forekom i testene. Det kan dermed oppnås et system som kan håndtere både stasjonære verdier og transienter, og som dermed vil kunne lokalisere og gi nettselskapene et bedre beslutningsgrunnlag ved de fleste feil som oppstår i nettet. Videre arbeid innen samme tema er imidlertid nødvendig for å kunne implementere sensorer i det norske distribusjonsnettet, og komplette produkter må anskaffes og testes på laboratoriet for en verifisering av nøyaktigheten.

Fuel Savings Obtained by Replacing Traditional AC-distribution Systems onboard Vessels with DC-distribution Systems

Student: **Aleksander Opdahl**
Supervisor: **Tore Undeland**
Cosupervisor: **Ottar Skjervheim**

Summary

Today most of the diesel-electric systems on board ships are based on an AC-distribution of the generated power. The electric power is fed directly from the synchronous generators into an AC-grid, where it is distributed to the different loads on board. This system requires a constant rotational speed to provide the grid with the rated frequency.

By introducing a DC-grid, the system no longer has to depend on constant speed. This opens the possibility to vary the speed during operations and thereby optimize the fuel-efficiency of the prime mover to the load-situation.

This thesis has investigated the fuel savings by replacing traditional AC-distribution systems on board ships with DC-distribution systems.

The DC-distribution systems that have been considered is a DC-grid supplied by three-phase, fullbridge diode rectifiers, and a DC-grid supplied by active front-end (AFE) IGBT based rectifiers. The thesis has concluded that vessels which experience frequent low load situations will benefit from introducing an AFE based DC-distribution system on board.

The thesis has also drawn the conclusion that vessels which mostly experience high load situations, the extra cost of investing in AFE-rectifiers cannot be justified, as the fuel savings will be virtually zero at high loads. For these vessels it will be expedient to replace the AC-distribution with the less expensive diode based DC-distribution system.

Prospective and Efficient Techniques for Model Reduction in Reliability Calculations

Student: **Robert Fossmark Pedersen**
Hovedveileder: **Olav Bjarte Fosso**
Biveileder: **Arne Brufladt Svendsen og Trond Tollefsen**

Sammendrag

A reliable electric power supply is essential for modern society. Recently, severe blackouts worldwide have attracted attention to reliability studies in power system planning and operation. The relevance of the traditional N-1 criterion has been discussed, and much focus has been directed towards developing satisfactory probability based reliability tools.

Goodtech Project & Services has developed a methodology for calculation of online power delivery reliability for use in power system operation and planning. The method, based on Markov models, analyzes the entire network for a large number of fault combinations, a useful approach for relatively small networks. However, the computation time increases polynomial with increasing system size. Because the impact of an outage has a limited geographical extent, it is desirable to reduce the system to be simulated, so that it only includes the affected area.

The objective of this project is to develop methods for identifying the components that can be considered influenced by a fault. The focus of the pre-study was to evaluate which post-processing method best suited for developing a reduced network system. In the pre-study, power flow results from the standard DC load flow were used. The main focus of this thesis has been on developing and implementing fast methods for obtaining the necessary power flow data needed in order to use the post-processing methods.

Three approaches have been investigated and tested, namely AC load flow based on the fast decoupled load flow with compensation techniques for obtaining the post-contingency power flows, DC load flow with compensation techniques and the efficient bounding method.

The key principle of the compensation methods is that the effect of outages can be calculated by introducing simple compensation terms, thus avoiding the need to rebuild and factorize the system matrices for every contingency case. The bounding method is based on the principle of sensitivity factors and the fact that given knowledge about changes inside a boundary certain conclusions can be made regarding the changes outside it, thus eliminating the need for studying the entire system. The method based on the fast decoupled load flow is the only method that gives the possibility to provide an exact solution, and is also the only method that includes reactive power and voltage magnitudes. It is therefore recommended used in cases where a high degree of accuracy is important, or if reactive power and voltages are of interest.

Tests show that the DC load flow is fastest. The accuracy is assumed sufficient for most intended purposes, and should therefore the preferred choice in most cases.
Bounding methods are especially useful in highly meshed grids, and if only the largest changes are of interest.

Reversible hydro power plants

Student: **Marko Primozic**
Supervisor: **Ivar Wangensteen**
Cosupervisor: **Nenad Debricin**

Summary

Bearing in mind the future development of the electric power system regarding the penetration of large amounts of intermittent and non-dispatchable renewable sources, energy storage is a key issue. Even though reversible hydro power plant technology has been around for almost 100 years, it is still the best way to store energy in terms of the quantity which can be stored and the energy ratio between produced and used energy. The newest improvement in pump storage systems are facilities with variable speed technology. After the first reversible hydro power plant with variable speed technology was built in Germany, all benefits from such facilities have been approved. Regulation during pumping mode, the possibility for achieving maximum efficiency for different rated speed during generating mode and pumping mode, optimum efficiency over a large power range and under all head conditions, faster decreasing and increasing output power during generating mode are only some of them.

In the other part of this paper an economic model for building a reversible hydro power plant is made. Profitability and solvency are evaluated by profit and loss account, economic and financial cash flow. Based on that, the average electrical energy production cost, payback period, net present value, internal rate of return and profitability index are computed. At the end it can be seen which parameters the most influence project rationality and, based on a forecast for the future power market with increased penetration of wind sources, what average electrical energy production cost can be expected.

This assignment is realized as a part of the collaborative project "Sustainable Energy and Environment in Western Balkans" that aims to develop and establish five new internationally recognized MSc study programs for the field of "Sustainable Energy and Environment", one at each of the five collaborating universities in three different WB countries. The project is funded through the Norwegian Programme in Higher Education, Research and Development in the Western Balkans, Programme 3: Energy Sector (HERD Energy) for the period 2011-2013.

Key words:
- Reversible hydro power plant (pump storage power plant)
- Variable speed technology
- Power electronic equipment
- Converters
- Payback period
- Net present value
- Internal rate of return

Optimal Production Balance with Wind Power

Student: **Gjert Hovland Rosenlund**
Veileder: **Gerard Doorman**

Maintaining a continuous balance between generation and load is crucial for the safeguarding of the power system. To efficiently deal with uncertainties and unexpected events the TSOs procure balancing services through the so-called balancing markets.

The variability and low predictability of the wind speed makes handling of balances a difficult task for wind power producers. Literature regarding the development of the balancing market and Elbas is presented. This research has found that the volatility in the balancing market are expected to increase as a result of cross-border integration of such markets. The low liquidity in the Norwegian Elbas market are expected to rise, as the need of an intraday market becomes more imminent. With increased investments in renewable energy and cross-border capacity the balancing markets are expected to change. With higher volatility in the markets the balancing of production will come at a higher cost. In this report the current wind power balancing done by TrønderEnergi is presented and some possible improvements to better handle the balance, are drafted.

The wind power production error and the price in the balancing market are modeled. A Monte Carlo analysis is carried out for three different alternatives:

1. Settling the imbalances in the balancing market.

2. Settling the imbalances in Elbas.

3. Settling the imbalances by using the re-bidding procedure.

The parameters are modeled stochastically, so the simulations are carried out a large number of times to get conclusive results.

It is the findings of this thesis that the implemented two-price system in the production balance leads to a large deficit when balancing the wind power production. The procedure currently used at TrønderEnergi saves the company a significant amount per annum, but as Elbas matures, this market should be exploited for reducing the costs of balancing and possibly profit seeking operations.

Analysis of large scale integration of electric vehicles in Nord-Trøndelag

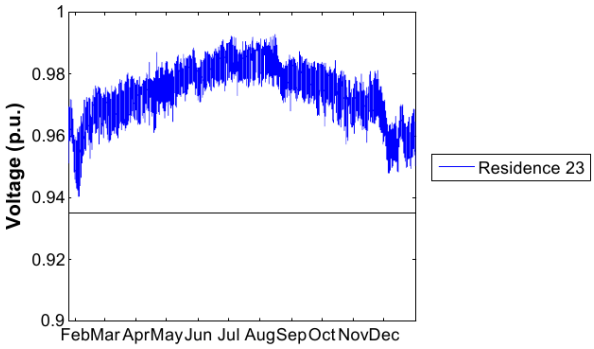
Student: **Øystein Sagosen**
Supervisor: **Marta Molinas**
Collaboration with: **NTE**

Problem description

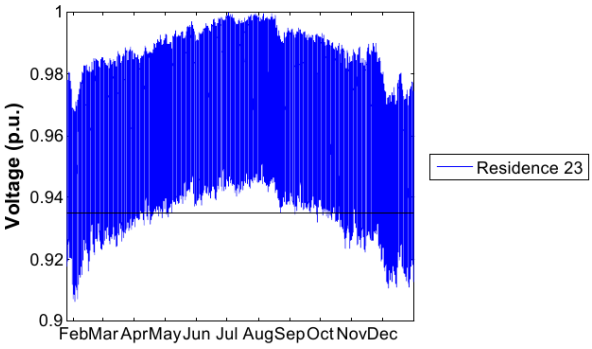
With increasing environmental awareness recent years, the number of electric vehicles in Norway has increased significantly, and is expected to increase further in the future. The transition to electric vehicles has many benefits, but it also poses challenges to the power grid. The aim of this thesis is to illuminate some of the potential problems arising when integrating a large amount of electric vehicles into a residential area. The simulated power system is created from data provided by NTE, from an existing residential area in Steinkjer. The load constituted by the charging of electric vehicles, may result in system voltage variations. The effect of introducing smart charging in the system is evaluated. The system also includes a hypothetical wind turbine, to investigate whether or not it may help mitigating the stress on the system caused by charging of electric vehicles. The simulations are focused mostly on a 24-hour "worst case" scenario, but more long term simulation is performed as well.

Model

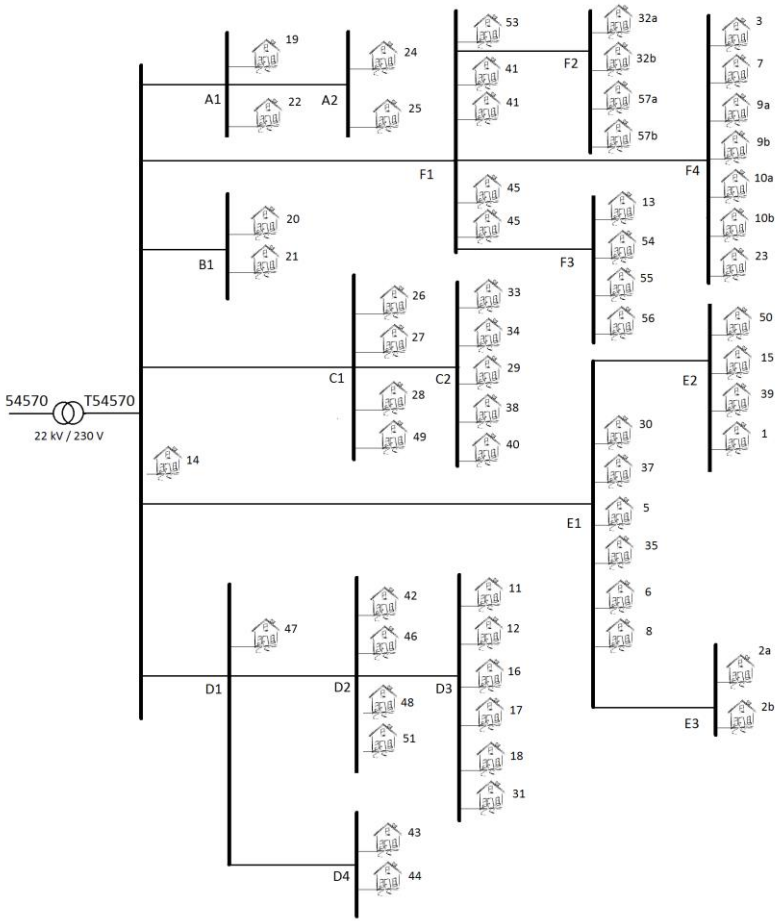
A model of an existing residential area in Steinkjer was modeled in Simpow. It is comprised mainly of residential houses, but also schools, kindergartens and other larger consumers. The total number of electrical power consumers is 856, and approximately 800 of these are residential homes. The small scale hydro power plant Byafossen is located in this area, and contributes to the power system. The power plant has a generation capacity of 2.4 MW and an annual generation of approximately 15 GWh. One part of the system has been modeled at a detailed level and is the focus of the analyses. The low voltage residential area consists of 62 residences and a hypothetically integrated wind turbine.



Voltage at residence 23 over the year with 20 % EV adoption and smart charging.



Voltage at residence 23 over the year with 20 % EV adoption and dumb charging.



Conclusion

Different scenarios were explored, investigating how sensitive the grid is to additional load under different assumptions, and how the wind generation can contribute to a more self-supporting power system. Symmetrical and asymmetrical distribution of electric vehicle charging loads in relation to physical locations have been compared and the results suggest that one cannot give an exact number of vehicles that the system can handle. The system capacity when operating with dumb charging strategies is varying, depending on where the vehicles are situated physically. With many electric vehicles located close together, the given voltage level constraints of the model were violated with a seven percent electric vehicle penetration share. However, assuming that vehicles are more spread out physically, the system restrictions were not violated for an electric vehicle share of 20 percent. In other words, the placements of the additional loads are equally decisive for the system voltage variations as the number of loads. By applying smart charging strategies, the voltage fluctuations in the system during a day are mitigated. For the 20 percent EV penetration scenarios, given the assumptions presented in this thesis, the added load does not seem to put more stress on the system than it can handle. However, for the 50 percent EV penetration scenarios, the charging load might present the system with too much stress, even with smart charging strategies.

Modular Multilevel Converter (MMC) For Motor Drive Applications

Student: **Seyed Adnan Sajjadi**
Supervisor: **Lars Norum**
Cosupervisor:

Summary

The first chapter has demonstrated on the state of art of multilevel converter technology. Fundamental multilevel converter structures and modulation paradigms has been discussed. The focus has addressed classical, modern and more practical industrial application of multilevel converters such as Neutral Point Clamped Converter (NPC), Cascaded H-bridge (CHB) Converter and Flying Capacitor (FC). The overview on Pulse Width Modulation algorithm is presented.

The second chapter overview on operation principle of Modular Multilevel Converter (MMC) and impact of its elements is done. Comparison of MMC with CHB converter in point view of advantages and disadvantages is presented. At the end of this chapter literature review has been focused on the previous work of MMC for drive applications.

In chapter three, discusses on phase shifted pulse width modulation and capacitor voltage balancing technique for five-level modular inverter will be done. The modulation and balancing strategy presented are confirmed by simulation and results are discussed.

The fourth chapter focused on MMC for drive applications. Using MMC for drive applications, each module will require capacitor value at low frequency operation which is described in this chapter with details of theoretical analysis has been shown to operate the converter for low frequency operation of drives without requiring any change in hardware. The aim of this chapter is to propose an optimization way for overcoming the problem of Modular Multilevel Converter (MMC) at low speed for Induction motors. Meanwhile comparison between two proposed methods at low frequency has been presented.

In the fifth chapter conclusion based on the whole work and special on the last two chapters is done.

Multiple barrierar i inhomogene luftgap ved lynoverspenningar

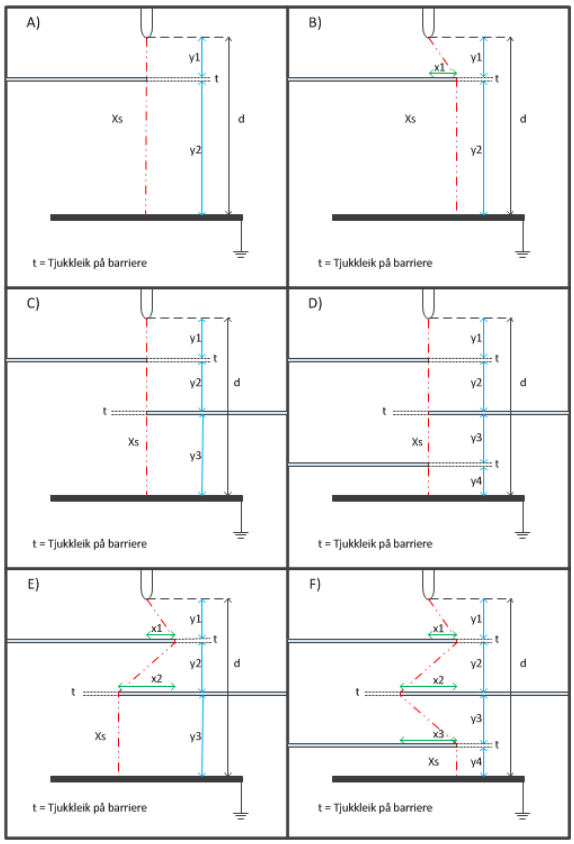
Student: **Jan-Henrik Solbakken**
Rettleiar: **Frank Mauseth**
Medrettleiar: **Atle Pedersen, SINTEF**
I samarbeid med: **ABB Corporate Research, Daetwill, Sveits.**

Innleiing

Dagens klimautfordring har gitt auka fokus på å minske forbruket av klimagassar som SF_6-gass. Gassisolerte høgspentanlegg har vore eit fokusområde for produsentar av høgspentutstyr i lengre tid fordi SF_6 har betre haldfastheit enn luft. Det er derfor ei utfordring for elektroingeniørar å lage like kompakt utstyr utan SF_6-gass. Ein mogeleg måte å oppnå auka overslagsspenning er introdusera isolasjonsbarrierar i gapet slik at lengda på ein eventuell streamer vert lengre, og dermed blir overslagsspenninga høgare. Det er også venta at ladingsakkumulasjon på barrierane fører til endring av det elektriske feltet i gapet.

I ein slik designprosess er det vanleg å nytte elementanalyse (FEM-analyse) for å berekne den elektrostatiske feltstyrken på dei forskjellige komponentane i utstyret. Men det er ikkje nok og berre vete den elektrostatiske feltfordelinga for å fastslå overslagsspenninga, det er også naudsynt å modellera utladningsprosessen noko som inkluderer initiering og utbreiing av streamere. Derfor er det starta forskingsforsøk som tar sikte på å utarbeide numeriske prosedyrar for å kunne berekne streamerane si åtferd.

Hovudtema for dette prosjektet vil vere å studere initiering og utbreiing av streamere langs isolasjonsbarrierane. Arbeidet vil bestå av laboratoriearbeid samt elektromagnetiske simuleringar av overslag i eit inhomogent luftgap med multiple barrierar. Samanlikningar av resultata vil verte brukt som designkriteriar for å kunne anslå overslagsspenninga i inhomogene luftgap med multiple barrierar.



Samandrag

Føremålet med dei utførte forsøka i denne masteroppgåva er å kunna føresjå og forklara endringar i gjennomslagsspenninga når multiple barrierar er nytta som isolasjon i eit stang-plate-gap. Forsøka vart utført med positiv lynimpulsspenning der opp og ned-metoden vart nytta for å finna haldfastheita U_{02} (2% sannsyn for gjennomslag). Ei sylinderforma aluminiumsstang med sfærisk tupp med ein diameter på 7 mm vart nytta som høgspentelektrode og ei aluminiumsplate vart nytta som jordelektrode. Barrierane som blei nytta som hindringar i gapet var laga av polykarbonat. Dei var 5 mm tjukk og hadde ein storleik på 600 x 600 mm. Dei vart plassert i ulike høgder og med ulik overlapping i eit 80 mm stort stang-plate-gap for å finna den beste kombinasjonen.

Resultatdelen er todelt og skilt mellom barriereoppsett som skapar sikksakk-design og barriereoppsett som ikkje skapar sikksakk-design.

I oppsett som ikkje skapar eit sikksakk-design synte resultata at ein kunne oppnå ei auke ved bruk av barrierar, sterkt avhengig av barrierane sin posisjon i gapet og korleis dei var oppstilte.
Plassering av barrierar heilt inntil høgspentelektroden har viste seg å gje lågare haldfastheit, og i enkelte tilfelle vart haldfastheita forverra samanlikna med eit barrierelaust gap.
Ei forklaring på dette kan vera det sterke tangentiale feltet som oppstår på barriereoverflata i desse tilfella. Det tangentiale feltet ladar barriera raskt opp og gjer det lettare for streamere å propagera langs barriereoverflata, noko som fører til raskare overslag.

Når berre ei barriere er nytta i gapet er den optimale posisjonen til barriera på rundt 20 mm, eller 25 % ut i gapet.
Ved bruk av fleire barrierar (utan sikksakk-design) syner resultata at avstanden kan aukast utan at haldfastheita minkar. Høgaste auke i haldfastheit i oppsett utan sikksakk-design viste seg å vera på 48 % samanlikna med eit barrierelaust gap.

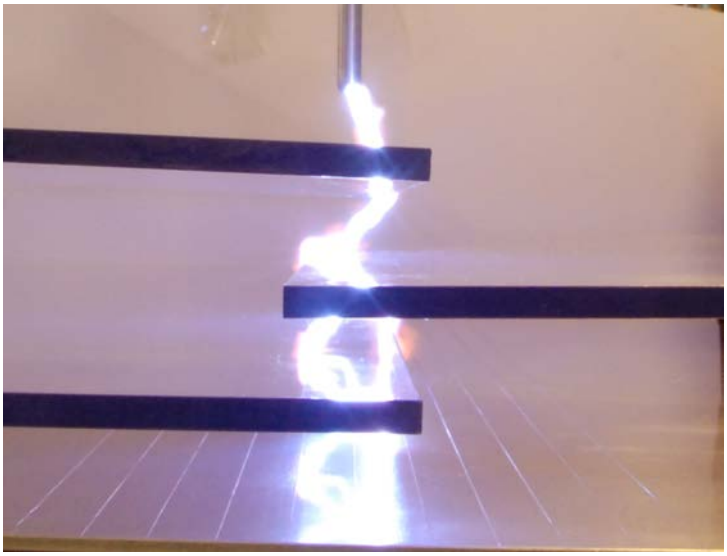
Når eit sikksakk-design av isolasjonsbarrierer vart introdusert i gapet oppnådde ein den høgaste haldfastheita observert i denne oppgåva med ein auke på 63,9 %. Det oppsiktsvekkjande med dette var at denne auken vart oppnådd med ei moderat auke i teoretisk streamerlengde.

Dette talar for at eit sikksakk design kan vera godt egna til å skapa eit kompakt høgspentdesign.

Alle forsøka med sikksakk-design gav auke i haldfastheit samanlikna med eit barrierelaust gap, men resultata var tvitydig med tanke på kva slags plassering av barrierar som gav den beste effekten.

Ved bruk av to barrierar i sikksakk-design var trenden at den beste plasseringa var lengst vekke frå høgspentelektroden.
Eit framlegg for auke i haldfastheit er at effekten til det tangentiale feltet på barrieroverflatene vert svekka av geometrien til eit sikksakk-design. Ein annan grunn kan vera at ladingsakkumulasjon på barrierar skapar eit meir homogent elektrisk felt under barriera, noko som også kan auka haldfastheita.

Når tre barrierar vart nytta, viste derimot forsøka at den beste plasseringa av barrierane var heilt inntil høgspentelektroden. Dette er i strid med dei andre forsøka som syner lågare eller redusert haldfastheit ved plassering i desse posisjonane. Grunnen til dette kan vera at den auka teoretiske streamerlengda utkonkkurerer effektane som fører til tidleg gjennomslag.

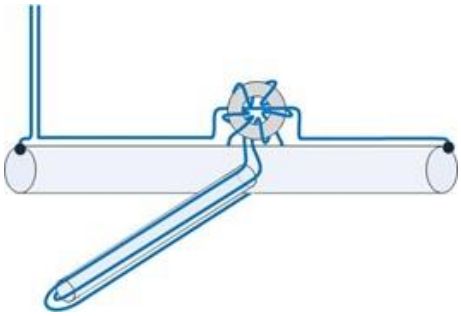

Bilete syner gjennomslag med tre barrierar ved 130 kV

Student: Kristian Thinn Solheim Supervisor: Professor Arne Nysveen (NTNU)
Co-supervisor: Atle Pedersen (SINTEF Energy Research)

ELECTRIC HEATING OF SUBSEA PIPELINES

DESIGN AND TESTING OF AN APPLICABLE TRANSFORMER

PROBLEM DESCRIPTION:



SINTEF and NTNU have together with Statoil developed a system for electric heating of subsea pipelines, DEH (Direct Electric Heating). Several systems are in operation in the North Sea. Their energy supply is customized since the load is a one phase with load with low power factor.

In the project thesis carried out in autumn 2012, a feasibility study of different t-off configurations was examined. In order to realize a system with t-offs, a transformer connected to the existing energy supply («piggy-back») is needed. The thesis aims at specify, design and test a suitable transformer.

More specifically the work shall focus on:

- Perform a literature survey and establish a theoretical foundation for transformer design with low turn numbers
- Evaluate different solutions and describe a suitable transformer
- Manufacture and test a prototype

METHOD:

Open- and short-circuit tests have been performed in order to calculate the electrical properties of the prototype transformer.

LABORATORY RESULTS:

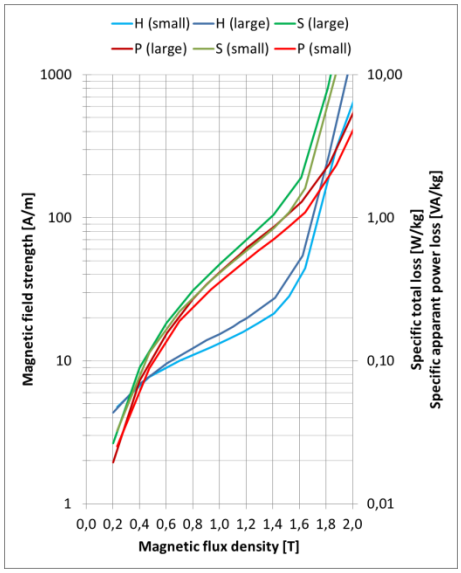
	Subsea[1] transformer		Onshore[2] transformer	
	Small	Large	Small	Large
S_n [VA]	918	7 200	748	5 880
I_n [A]	270	900	220	735
V_n[V]	3.4	8.0	3.4	8.0
P_0 [W]	15.7	93.2	15.7	93.2
P_{sc} [W]	41.6	93.8	27.7	61.7
e_z [%]	4.55	1.43	3.70	1.43
$m_{iron\ core}$ [kg]	15.81	71.76	15.81	71.2
Efficiency [%]	93.1	97.1	93.6	97.1

[1] Ambient temperature of 5°C, surrounded by water.
[2] Ambient temperature of 30°C, surrounded by air.

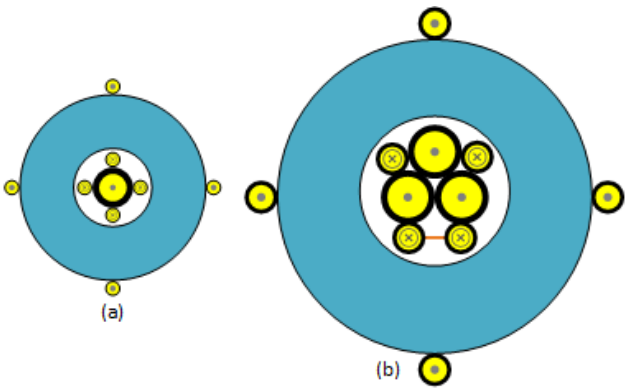
CONCLUSIONS

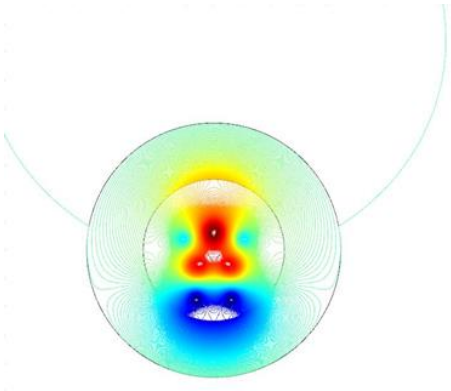
Based on transformer design theory and the special application requirements, a ring core transformer consisting of multiple stabled toroidal cores build up from magnetic tape is found to be suitable. This construction design provides the maximum utilization of magnetic flux with the minimum of magnetic force. Two main reasons distinguish themselves regarding the application requirements. The first is absence of termination points. This enables the use of a piggy-back cable as primary winding, increasing the overall system reliability compared to a system consisting of joints. The other main design benefit is the possibility to connect appropriate winding ratio in an unproblematic manner.

The rated currents of the two prototypes were found using the NEK-standard 400-5-52:2010, while the rated voltage estimates were calculated from equations based on fundamental magnetic theory. By use of regular transformer testing techniques, the actual voltage ratings were found equal to the a priori estimate. Other electrical properties of the prototypes were also extracted from these tests. No unusual electrical characteristics were found, compared with iron core theory and regular power transformers.



Using previous calculations and findings, rough calculations of a full-scale transformer is executed. 192 V is required to heat a 500 meter long and eight inch thick jumper system using DEH, while an IH-system requires 282 V. Using two metre long transformers, the iron core volume becomes 0.70 m_3 and 1.53 m_3, for the DEH and IH-system, respectively. This corresponds to a weight of approximately 5.2 and 11.2 metric tons.





Scaling a Optimized PV-Cluster as a part of a Micro-grid in Wawashang, Nicaragua

Student: **Linn Solheim**
Supervisor: **Marta Molinas**

Problem description

The rural FADCANIC complex in Wawashang close to the east cost of Nicaragua, is one of the few rural areas in the east that to a certain degree have been electrified. The Wawashang complex is a boarding school with a large plantation and a carpentry shop, educating and giving children and young adults work experience. The complex has limited access to electricity, as the electrical system consisting of decentralized Photovoltaic (PV) panels and diesel generators, is partly defect, inefficient and needs to be re-scaled as the complex will expand and there will be insufficient supply in the future. In this thesis, an investigation around the possibility of installing a large photovoltaic array as a part of a micro-grid for sufficient supply in the future, has been carried out. It has by the help of the two energy modelling software simulation tools PVsyst and HOMER, been studied whether a photovoltaic system with or without a backup diesel generator combined with the PV-cluster is a feasible, optimal, sustainable and reliable configuration of the system. The term optimality embeds economical, technical, environmental, social and cultural aspects. The main focus will be technical and economical optimality but accessibility of equipment has been also an important restriction. The closest grid connection is in a village called Kakabila, which is approximately 65 km distant from the Wawashang complex and connection to the grid as an alternative to a micro grid ha been investigated.

A large part of the work on this thesis has been data collection and a 4-week fieldtrip to Wawashang was executed for the highest possible accuracy regarding the scaling of the system. During the fieldtrip the load profiles in the complex were measured along with other key parameters for simulation. Fellow student Marco Boninella who is involved in another aspect of the same project, was investigating the hydro-power potential of the rivers in the area.

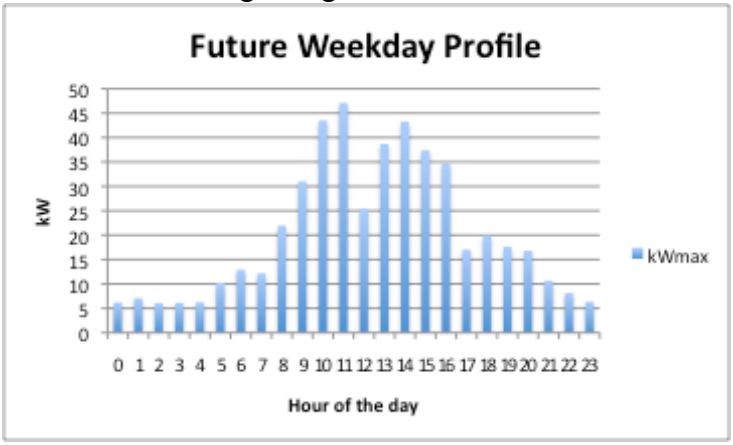
The task

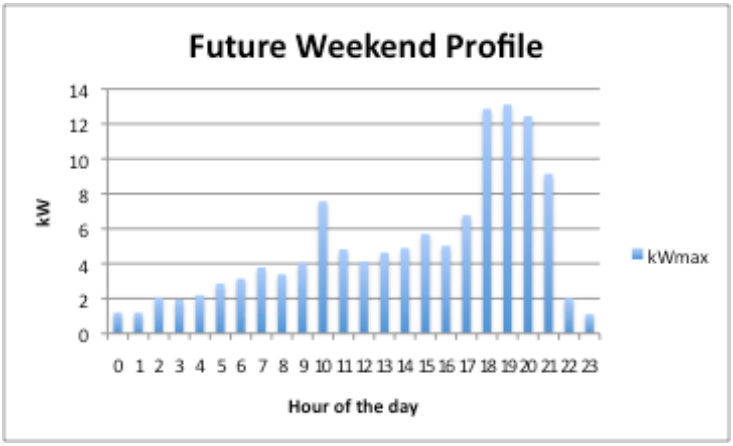
The so-called FADCANIC project is a collaboration between NTNU, Engineers Without Borders Norway, and the Nicaraguan organization FADCANIC. Two students are involved with the project, where identifying possibilities for establishing an independent, reliable and sustainable energy supply to the Wawashang Agroforestal Complex in Nicaragua, is the main scope. The main focus in this project will be to emphasize cultural, socio-economical, environmental and technical aspects of the surroundings to make the project sustainable.

Model/ measurements

The retrieval of empirical data collected during the fieldtrip to Wawashang was mainly the detection of a total load profile for the whole complex by measurements performed by a smart meter connected to the main electricity feeders. Measurements regarding the electricity consumption was performed on all electrical supply systems, being stand-alone PV-systems and diesel/gasoline generators, that had feasible measure points. After summing up all the found load profiles for all buildings and applying a multiplication factor of 2 for the carpentry

and 5 for the other buildings in the complex, the following graph for electricity demand was found regarding the demand in 2023.





The above shown graphs of electricity demand were the key data for implementation into the software tools for system design along with irradiation data, tilt angle of the modules and price information. The simulation tools HOMER and PVsyst, with focus on respectively economical and technical optimization, were the software used for identifying the optimal design of a PV-cluster as a energy source in a micro grid in Wawashang. For both software tools it was investigated whether a system solely consisting of a large PV-array or a PV-array connected to a backup diesel generator of either 10kW or 24 kW, was the optimal configuration for the conditions in Wawashang.

Calculation

PVsyst and HOMER among others provided the following summary of results.

	HOMER		PVsyst	
Parameters	PV	PV + diesel gen	PV	PV + diesel gen
Peak power [kWp]	121	121	124	123
Number of Modules	563	563	576	574
Number of Batteries	560	576	480	480
Yearly production PV [kWh/year]	182 209	182 209	158 800	150 060
Yearly production 10kW Gen. [kWh/year]		3 318		12 400
Spillage [kWh/year]	25 210	25 050	15 100	11 500
Unmet Load [kWh/year]	5 308	1 888	8 000	0
Yearly consumption [kWh/year]	139 599	143 020	136 600	144 600
LOL [%]	3.8	1.3	5.5	0

Conclusion

It was found that by performing simulations with the two software tools approximately the same system design was found and by applying PVsysts information of technical optimality and HOMERs results on economical optimality, an optimal design could be identified. By combining the results it was found that even if the reliability of a system with backup would be higher, the optimal system with no backup is stated to be the best fit for the Wawashang complex. This because the design is a result of load profiles for 2023 being applied to the simulations and the hope is to within a couple of years, study the biomass potential of the area further for considering integration with the micro grid. The fact that no backup-generator

would have to be used, would lead to yearly-avoided emissions of 3777 kg CO2. The optimal system consists of a **124 kWp PV-cluster** consisting of 576 Kyocera PV-modules of 215 Watts and a battery-pack containing 480 Trojan 6V batteries with 420 Ah capacity as well as a 50 kW inverter. The systems has a yearly supply to the user of 136 600 kWh resulting in a yearly shortage of 8000 kWh amounting to 5.5%. The net present cost of the system is according to HOMER **770 101 US$,** which is a significant amount of money, however the alternative cost related to connecting to the national grid has been found to be 1 949 928 US$, something that underlines the optimality of the suggested system.

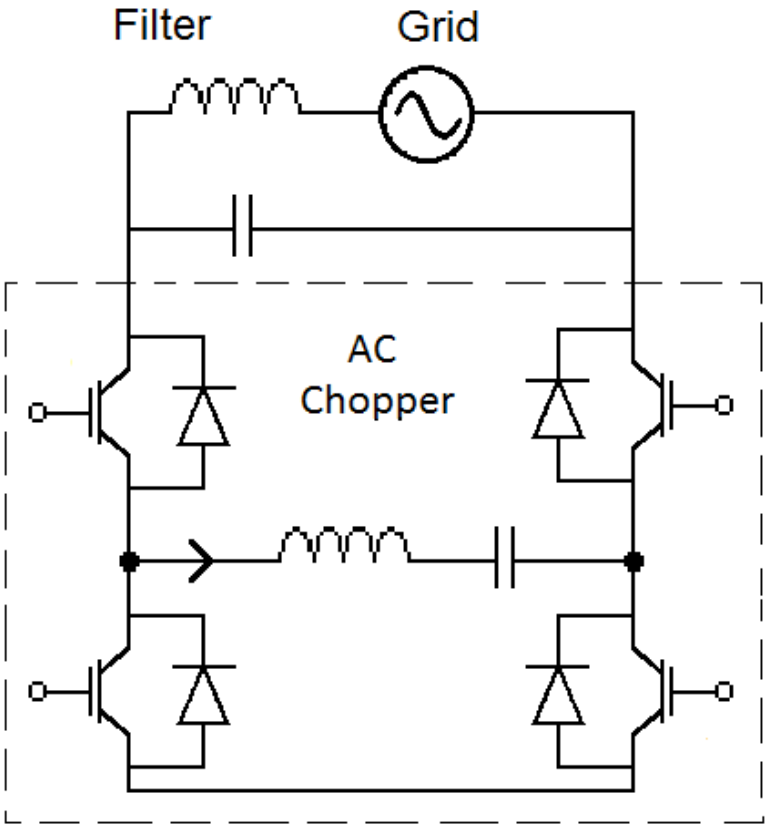
Reactive Power Compensation and Active Filtering Capabilities of the AC Chopper

Student : Ole Christian Spro
Supervisor: Prof. Marta Molinas
Collaboration with: EPFL, Switzerland
Supervisor at EPFL: Prof. Alfred Rufer

Reacitve power compensation is used to ensure system stability and rated voltage levels, and to eliminate harmonics. Railway grids and microgrids are typical grids in need of reactive compensation. In addition new non-linear loads add harmonics to the large power grids and thus raises the demand for reactive power.

On the market today there exists several technologies for reactive power compensation. Traditional solutions include fixed capacitor banks and Static VAR Compensators (SVC). A more modern solution is available today known as the Static Synchronous Compensator (STATCOM). The STATCOM can also be operated as an active filter, in which specific frequency harmonics can be eliminated or the device can operate over it's full bandwidth.

The AC Chopper is a series of AC/AC converters using semi-conducting switches as the STATCOM does. The University of Toulouse has been conduction research on a step-down AC Chopper based SVR for SNCF, the French National Railway Corporation. Their work show that the AC Chopper promises better efficiency than the STATCOM and that it also has potential for eliminating selected harmonics.



The target of this project is to investigate the AC Chopper for a single 50Hz phase to see whether the application area for this device can be expanded, i.e. identify possibilites to operate it as an active filter, making the AC Chopper an even more attractive solution. Simulations were done in Matlab Simulink.

Extensice open loop simulation reveals that harmonic control can be obtained. Two different methods of producing single harmonics were simulated, where one of them showed real potential for implementation. For such an implementation, a Discrete Fourier Transform based control system must be used.

The control system made by the University of Toulouse for the closed current loop was based on alpha beta frame and PI regulators. The disadvantage of their solution was the generation of a non-negligable amount of harmonics. An improved closed loop control of the fundamental current using RMS values was simulated, showing a improved performance.

A small prototype will be made to verify the results obtained in simulation. The prototype will be connected to the 50 Hz utility grid with an input voltage of 50V RMS and a rated reactive power output of approximatly 100VAR. The implementation is not ready at the time of writing, and the results from experiments are expected at the end of July. The results and the conclusion will be present in the final thesis rapport.

Variable Speed Pumped Storage Hydropower for Balancing Variable Power Production in Continental Europe

Student: **Andrea Linn Sætre**
Supervisor: **Marta Molinas**
Co-Supervisor: **Eivind Solvang**

Introduction

Europe is faced with a complex and challenging restructuring of its energy system. Increased penetration of variable renewable energy resources is a challenge for the stability of the transmission system. There is an obvious need for back up capacity, as well as energy storage. Pumped storage hydro power is one of the most economical storage alternatives, and Norway has the necessary reservoir capacity. However, in order to offer balancing services to Continental Europe, increased transmission capacity is required.

Test System

This master thesis has proposed and analyzed a system for balancing power in Europe. The test system consists of a pumped storage hydro power plant located in Southern Norway, directly connected by a High Voltage Direct Current (HVDC) transmission line to a varying load in Germany. The pumped storage plant is modeled by a synchronous machine and can run at variable speed in both generator and pump mode. The HVDC transmission is based on the Voltage Source Converter (VSC) technology and consists of a converter station at each end. The load profile in Germany is based on real measured wind data, and scaled to fit the power ratings of the test system.

Control Strategy

A control strategy has been developed for the VSC-HVDC and is based on the vector control principle. The grid-side converter is chosen to control the active and reactive power flows, while the generator side converter controls the DC voltage. This control strategy does not require communication between the converter substations, which is a great advantage in an HVDC system that ranges over long distances. A current control strategy in the d-q rotating reference frame is used to decouple the non-linear and strongly coupled current equations to achieve independent control of the active and reactive power. The active power control is solved by dividing the reference active power by the d-axis voltage to give the d-axis current reference. Similarly, the q-axis current reference is achieved from the reactive power control.

Results & Conclusion

The test system, with its control system, is implemented in the simulation software PSCAD/EMTDC, and fast response and stabile system operation is observed. The simulation results show that the active and reactive power references are followed very well. Energy storage will play an inevitable role in achieving a clean European energy supply. The test system developed in this thesis, although quite simplified, has proven through simulations to be a promising alternative for offering balancing services to Germany (and Europe), and thereby support the integration of variable renewable resources. Many aspects, such as economics and the energy market, will, however, have a major say in how the energy challenges we stand before today are solved.

Magnetic Design for High Temperature, High Frequency SiC Power Electronics

Student: **Torbjørn Sørsdahl**
Supervisor: **Tore Undeland**
Co-supervisor:

Summary

Power electronic components which can operate at high temperatures would benefit a large number of different applications such as in petroleum exploration, aviation and electrical vehicles. Silicon carbide semiconductors have in the recent years been introduced commercially in the market. They are opening up new possibilities to create high temperature devices, due to its superior properties over silicon. Design of high temperature magnetic components is still a tedious process compared to normal temperature levels due to little information and software to simplify this process.

The purpose of this thesis is to develop analytical software for high frequency magnetic design in the temperature range from 130°C, and up to 200°C. Care has been taken into developing temperature dependent loss models and thermal design. The software is primarily for inductors, but most of the theory and discussion are also valid for transformers. Prototypes have been built and tested against the software predictions and good correlation has been observed.

A brief introduction to magnetic materials that can be used at elevated temperatures have been included focusing on powder cores and ferrites, since other high frequency materials could not operate at 200°C. It was found that for most materials, it is the laminations and binder agents that introduce the temperature limit. Materials are designed for specific temperatures which make it likely that when there is a larger commercial interest for higher temperatures, new materials will be developed. Core characterization of ferrites and powder cores was performed with a Brochause steel tester up to 10 kHz, and the losses up to 100 kHz were measured using an oscilloscope and amplifier approach. The characterization was performed at 20°C 108°C and 180°C.

The measurements show that the analytical loss data provided by the manufacturers underestimates the losses in Sendust and MPP materials, while there is a good correlation in High Flux, R-ferrite and N27. New Steinmetz parameters were calculated for MPP and Sendust for 20 kHz. Temperature primarily influences only Sendust up to 180 °C by a factor of 10-20 %, the little temperature dependence is in powder cores due to very high curie temperature.

Winding configurations have been investigated, and Litz wire for 200°C do not seem to exist commercially at this date, however wire for 130°C was successfully used in several 180°C experiments, but permanent degradation was observed in wires which had been exposed for several hours. It was found that the insulation in enamel coated round conductors have problems at elevated temperatures under the rated temperature in the areas where the wire was bent, this was not observed in Litz wire.

It has been shown that parallel connection of smaller powder cores can in some cases be used to obtain smaller designs with better thermal dissipation than with a single core. Leakage capacitance has been measured in several designs and by inserting an air gap between layers the capacitance was reduced in the same order as a Bank winding.

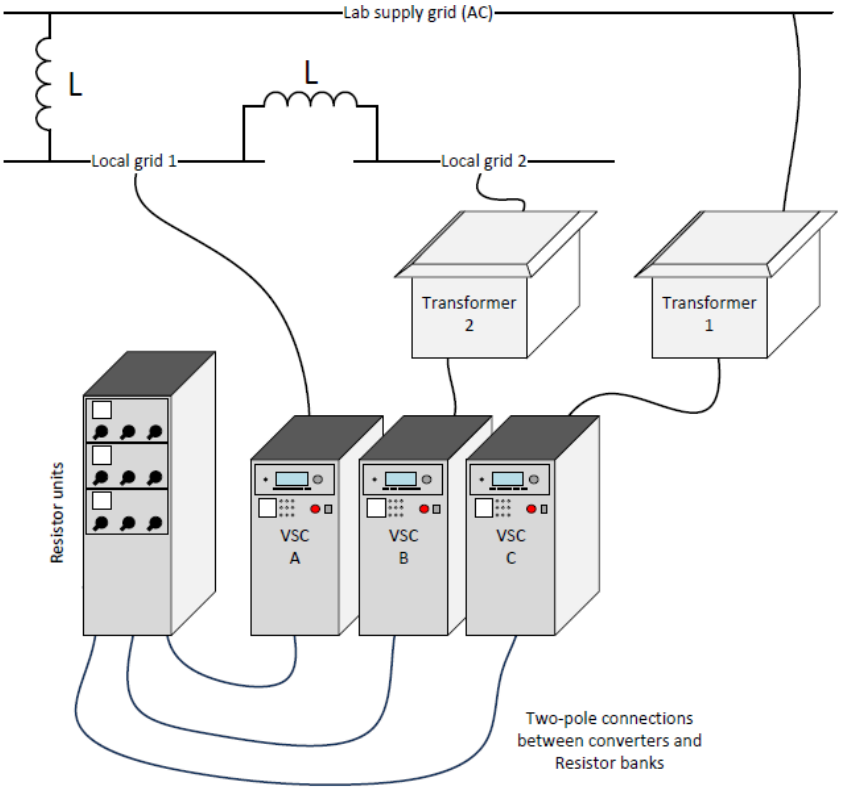
Output filter for dv/dt, Sinus, and a step down converter have been calculated and built. The step down filter has been tested in a buck converter, and compared to analytical data.

Laboratory Testing of Multi-terminal VSC-HVDC

Student: Kalle Teearu
Supervisors: Kjetil Uhlen, Kjell Ljøkelsøy
Collaboration: Sintef Energi AS

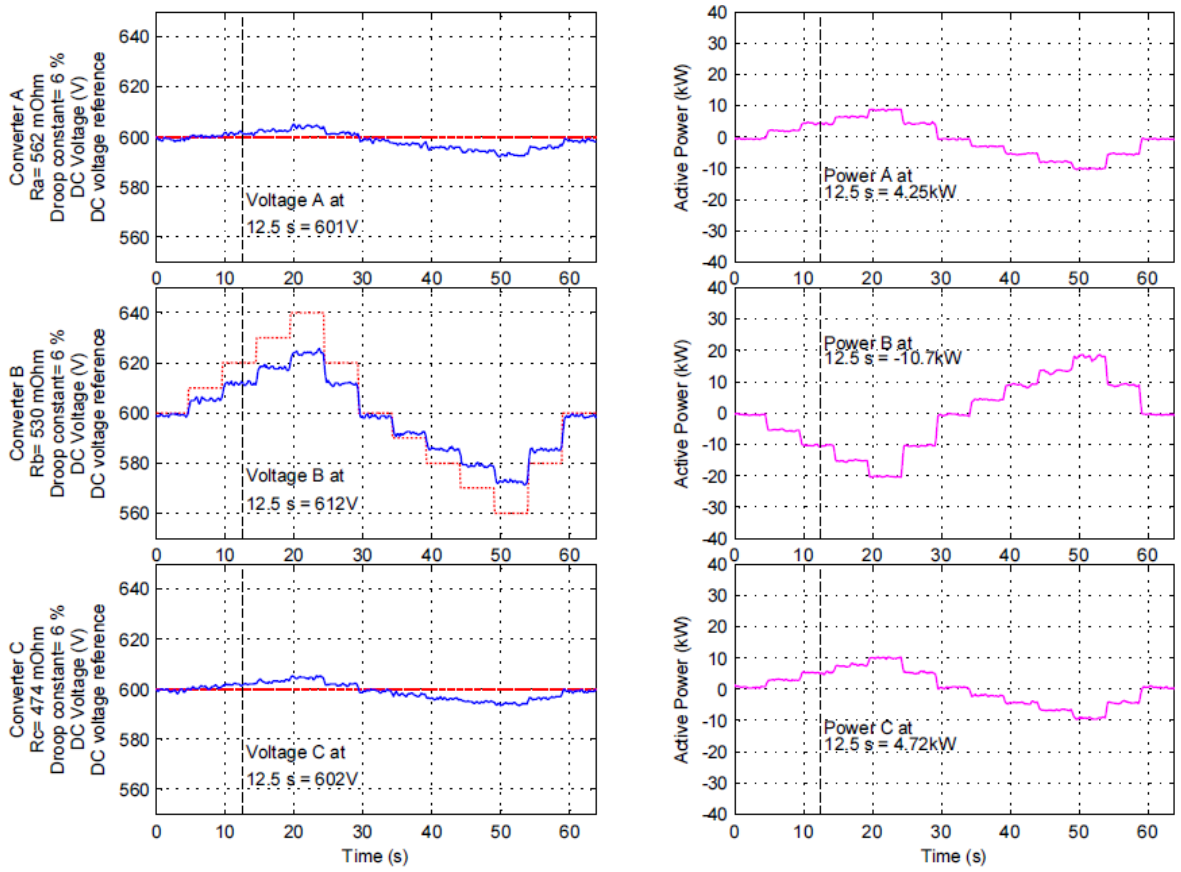
Problem description

This thesis reports laboratory testing of voltage source converter based multi-terminal HVDC system. Multi-terminal HVDC systems have become more of interest due to ambitious plans for interconnecting remote generation sites to ever-growing electricity consumption. Offshore wind energy holds a great potential of covering a great deal in Europe's future energy portfolio. Moreover, interconnection between remote areas with different generation and consumption characteristics, helps to improve overall efficiency on any energy system. Conventional AC transmission lines have too high losses and become economically unpractical for long subsea connections. HVDC connections, on the other hand, do not have



practical limits in how far from the shore an offshore wind farm can be built. DC voltage droop control has been proposed as suitable method for controlling Multi-terminal VSC-HVDC systems.

Laboratory test system consisting of three voltage source converters was set up. Three resistor banks were used as DC line models and control and monitoring system for the converters was developed. DC voltage droop control was implemented for all of the converters and laboratory test results were compared with the analytical power flow results. Multi-terminal DC system was tested in multiple different configurations. Tests differed from one another with respect to droop values and resistances in the DC line models.



			RESULTS at t=12.5s	
$\rho_a = 6\%$ $\rho_b = 6\%$ $\rho_c = 6\%$	$R_a = 562m\Omega$ $R_b = 530m\Omega$ $R_c = 474m\Omega$		Laboratory	Power flow
Converter A	$P_{a,ref} = 0kW$ $U_{a,ref} = 600V$	Power Voltage	4.25 kW 601.2 V	4.28 kW 602.6 V
Converter B	$P_{b,ref} = 0kW$ $U_{b,ref} = 620V$	Power Voltage	-10.7 kW 612.3 V	-9.19 kW 614.5 V
Converter C	$P_{c,ref} = 0kW$ $U_{c,ref} = 600V$	Power Voltage	4.72 kW 601.8 V	4.73 kW 602.8 V

Conclusion

Comparison between expected and laboratory test results confirmed previously studied theory. DC voltage droop control allowed adjusting active power flow between the converters without modifying references to voltage source converters. Converters with higher DC droop constant were having smaller impact on active power flow. Higher DC line resistance in between converter and network's star-point caused less active power flow through this converter.

Stabilitetsproblemer i regionalnettet i Sør-Rogaland

Student: **Ole-Morten Thu**
Faglærer: **Kjetil Uhlen**
Veileder: **Trond Toftevaag**

Denne masteroppgaven omhandler pendlingsproblematikk i regionalnettet i Sør-Rogaland. Problemstilling er gitt av Lyse Energi AS, som til tider opplever pendlinger i aktiv og reaktiv effekt i 132 kV regionalnettet. Under pendlingene er det observert at Flørli kraftverk (et aggregat på 89 MVA) og Lysebotn kraftverk (seks aggregat på totalt 264 MVA) er involvert. Årsak til pendlingene, eller hva som initierer dem har så langt ikke vert kjent.

Arbeidet består i hovedsak av stabilitetsstudier ved hjelp datasimulering i programmet Simpow. Studien er i stor grad rettet mot småsignalstabilitet ved hjelp av lineæranalyser som egenverdi-, sensitivitet-, og modalanalyser. Dynamiske analyser er benyttet for å verifisere resultater fra lineæranalysene, samt for sammenligning av målinger i regionalnettet og simuleringer.

Det blir sett på fire forskjellige caser, hvor case A, B, og C er basert på undersøkelser av hendelser med pendling, og case D tar for seg sammenligning av simuleringsresultater og målinger gjort i Lysebotn 13.05.2013.

Simuleringer har avdekket en potensielt dårlig dempet mode med svingefrekvens rundt 1,2 Hz, bestående av samtlige synkrongeneratorer i Lysebotn, Flørli og Jøssang. Demping til denne moden vil være avhengig av antall tilkoblede generatorer, hvor lavest demping oppstår ved samtlige maskiner tilknyttet nettet med full produksjon.

Målinger i regionalnettet bekrefter at mode med svingefrekvens rundt 1,2 Hz blir eksitert ved en forstyrrelse i regionalnettet. Respons i aktiv effekt etterfølgt forstyrrelsen viser en initial dårligere dempet respons i forhold til simuleringer med relativ demping lik 4,97 % for målingen, og 7,66 % for simuleringen.

Det konkluderes med at systemet i utgangspunktet var småsignal stabilt for hendelser med pendling i 2007 og 2008, men med lave stabilitetsmarginer, og hvor hittil uavklarte årsaker har påvirket demping slik at systemet blir ustabilt.

Det blir ansett som en mulighet at feltstrømsbegrensere i Flørli og/eller Lysebotn kraftverk kan ha en negativ innvirkning på demping i systemet ved spesielle driftstilfeller, og krever ytterlige undersøkelser.

Electromagnetic Transient Modelling of Grounding Structures

Student: **Irina Tikhomirova**
Supervisor: **Professor Hans Kristian Høidalen**
Contact: **Dr. Bjørn Gustavsen, SINTEF Energy Research**

Abstract

Grounding is traditionally modelled as a pure resistance. This is a good approximation at low frequencies, but as the frequency gets higher, inductance starts to play an important role. To acquire accurate transient response of the system it is desirable to consider this fact. Special computer programs like CDEGS are required to analyse grounding structures, but this is not directly compatible with other programs for analysis of over-voltages and transients. The main objective of this project is to create a database containing frequency response for some common electrode types with different parameter combinations. This frequency response can be further used to create an equivalent time - domain grounding impedance that can be exported to EMTP programs.

Three types of ground electrodes were analysed in this project; earthing rod, counterpoise grounding with four radials, and horizontal ring electrode. A uniform soil model with variable values of resistivity and relative permittivity was used in all simulations. Geometrical dimensions of the electrodes were varied as well. All conductors were modelled as bare copper conductors. Parameters were determined based on the results of simulations in CDEGS and general recommendations for grounding of transmission towers given by Statnett.

Unit current at different frequencies was injected into ground electrodes through a 0.1 meter long copper conductor. Ground potential rise of this conductor, which is equal to impedance to earth of the ground electrode, was extracted from HIFREQ in text format. Frequency resolution in the simulations is 10 points per decade between 0 and 0.1 MHz, 40 points between 0.1 and 1 MHz, and 80 points between 1 and 10 MHz. As a result of the project a database containing impedance and admittance as function of frequency for three types of electrodes has been created. Total number of responses stored in the database is 2268.

Vector Fitting is used to convert frequency domain responses to time domain state - space models or RLC - networks. Vector fitting is a method to approximate measured or calculated frequency domain responses with a sum of rational functions.

A Matlab routine *interfit.m* was developed to extract response of an electrode with given parameters. For parameters between the points in the database, linear interpolation is used. As a second step the function calls vector fitting that creates a time – domain model from the frequency response of the defined ground electrode. Order of approximation in vector fitting should be adjusted for each case, starting with a low value and gradually increasing it till a sufficient approximation after passivity enforcement is achieved.

Time – domain simulations in CDEGS and ATPDraw gave similar results when order of approximation in vector fitting was chosen correctly. Negligible deviation was observed between the responses in time range between 0 and 5 μs in some cases. The results indicate that frequency - dependent models created by this method can be used in EMTP programs.

Low switching frequency modulation scheme for high power three level converters: FPGA based implementation

Student: **Biruk Bekele Yenore**
Supervisor: **Professor Tore M. Undeland**
Contact: **Dr. Eng. Roy Nilsen**
Collaboration with: **Wärtsilä Norway AS**

Problem description

Increased power rating and higher efficiency are some of the qualities a modern application requires from the electric motors it employs. Fulfilling these requirements needs a different approach in the PWM techniques, and a new modulation technique should be proposed. In addition, a low switching frequency implementation of PWM strategies is also an important requirement to alleviate harmonic problems. One of the ways to do this is programming the pulse patterns so that the total harmonic content fulfills the maximum tolerable harmonic content.

The task

In this master's thesis, techniques to produce the optimal pulse patterns for the motors were studied. First, the mathematical relations that govern the relation between optimal patterns and the required output voltage level were dealt with.

Second, a brief study of the Digital control technologies for the implementation of the modulation principle was made with focus on Xilinx FPGA. The flexibility of FPGA based system together with its ability to execute instructions at hardware level made it an ideal choice for the implementation of the proposed modulation scheme. After having mastered the overall development environment of Xilinx FPGA through the studies, the project design, both software and hardware, for the problem in hand was done using the tools.

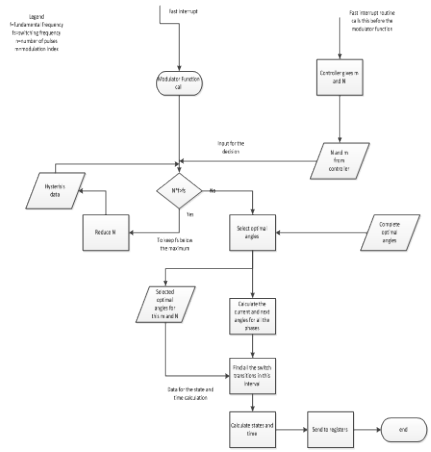
Last, the software program that produces the optimal patterns for a certain variation of number of pulses and modulation indices was successfully developed on the FGPA processor.

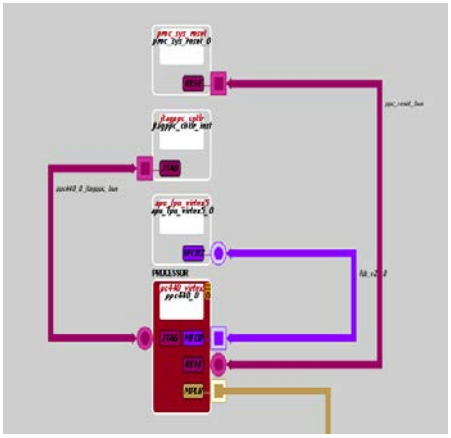
Finally, an investigation was done on the output waveforms produced by the optimal patterns.

Model/ measurements

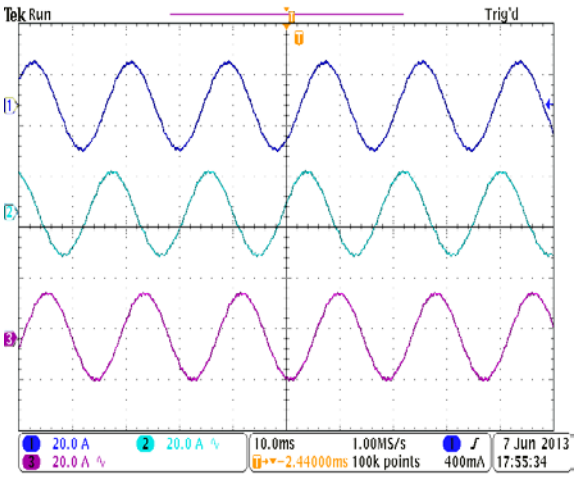
Hardware and software design of the proposed modulation scheme was done on Xilinx Virtex5 FPGA based system.

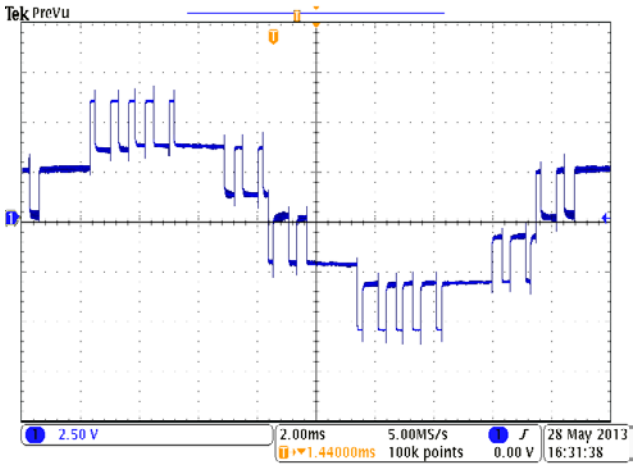
The language used to design the hardware is VHDL, while the software implemented was programmed using C++.





Results





Modulation technique	THD
SPWM	53.88%
Trapezoidal	52.7%
SVPWM	52.7%
Programmed modulation	24.4%

Conclusion

Measurements of the voltage and current waveforms produced by the proposed modulation system indicate that the proposed modulation scheme gives a very good quality output signal in terms of harmonic content. The total harmonic distortion of the output current is well below that of the conventional sub-oscillation modulation method.