Masteroppgaver 2018

Summary of Master's Theses 2018

NTNU
Norges teknisk-naturvitenskapelige universitet
Institutt for elkraftteknikk

NTNU
Institutt for elkraftteknikk

NTNU
Institutt for elkraftteknikk

Fakultet for informasjonsteknologi og elektroteknikk
Institutt for elkraftteknikk

Summary of Master's Theses 2018

We are proud to present this internet published pamphlet, which gives a summary of all Master's theses submitted to the Department of Electric Power Engineering in 2018. The department's vision is to be "At the Center of the Digital, Green Shift," and our Master's students make important contributions to this vision.

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

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

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

NTNU, November 2018

Ole-Morten Midtgård (sign)
Head of Department

Holt, Rakel Alice Utne	Sand, Kjell	Device-level control of microgrids with Master-Slave structure	49
Holvik, Anders Bergheim	Midtgård, Ole-Morten	Virtual Impedance Techniques for Power Sharing Control in AC Islanded Microgrids	51
Johannessen, Sondre Westby	Nilsen, Roy	Power Factor Correction for a Bidirectional On-Board Charger for Electric Vehicles and Plug-in Hybrid Electric Vehicles	53
Karlsen, Henrik Jøssund	Vadlamudi, Vijay	Reliability Evaluation of Energy-Limited Hydro-Electric Generation Systems	55
Karoui, Adrien Sélim	Uhlen, Kjetil	Short circuit capacity improvement techniques for low voltage distribution grid.	57
Kjøsnes, Eivind Magnus Amundsen	Norum, Lars Einar	Adaptive Resonant Controllers in a Modular Multilevel Converter	59
Klippenberg, Anders Hylen	Sand, Kjell	Bruk av nye sensorer og AMS i distribusjonsnettet for a validere nett-topologi	60
Knutsen, Ane Solem	Hansen, Eilif Hugo	Planleggingskriterier for lysstyring basert på dagslystilgang i bygninger	62
Kvammen, Mads-Emil Bratland	Fosso, Olav B	A signal analysis toolbox for power system identification in Smart Grids	30
Kvinnesland, Kasper	Nilssen, Robert	Variable Flux Permanent Magnet Synchronous Machines: Building and Testing Simple Designs with High-Coercivity Magnets	64
Laengen, Øystein Stake	Vadlamudi, Vijay	Application of Monte Carlo Simulation to Power System Adequacy Assessment	66
Lervik, Marie	Hansen, Eilif Hugo	Belysning for produksjon av rognkjeks	67
Lid, Arne Moen	Nysveen, Arne	Analyse av magnetfelt og tap ved enderegionen i direkte vannkjølte generatorer	69
Lillebo, Martin	Farahmand, Hossein	Impact of EV Integration and Fast Chargers in a Norwegian LV Grid	70
Meinich, Audun Matre	Tedeschi, Elisabetta	Harmonic Propagation and Production in Offshore Wind Farms	71
Midttveit, Øystein	Mauseth, Frank	Correlation Between Electroluminescence and Partial Discharges in Silicone Rubber Used for High Voltage AC Subsea Connectors	72
Moen, Torleif Møretrø	Doorman, Gerard	The impact of grid tariffs based on demand charges	74
Mong, Ruben	Mauseth, Frank	Investigation of Electrical Properties of a new low-GWP Insulation Gas	75
Muhirwa, Pascal	Uhlen, Kjetil	Performance of Stability Indicators based on Phasor Measurements	77
Møller, Andreas Blix	Nysveen, Arne	Modelling, Simulation, and On-line Detection of Rotor Eccentricity in Hydropower Generators	78
Mørkved, Emil Hansen	Nilsen, Roy	Sensorless Control of a 6-phase Induction Machine	80
Olsen, Emil Hjelmseth	Sand, Kjell	Analyse av seksjoneringsmetodikker i høyspennings distribusjonsnett	82
Olsen, Marie Sveen	Hansen, Eilif Hugo	Reduksjon av effekttopper i kontorbygg	84
Partha Sarathy, Pankaj Raghav	Sand, Kjell	Analysis and Optimization of Medium Voltage Line Voltage Regulators	85
Pedersen, Mari Andrea	Sand, Kjell	Teknisk-økonomisk planlegging av mikronett	87
Pettersen, Lars Erik	Ildstad, Erling	Dielectric response and electrical conductivity of mass impregnated HVDC cable insulation	88
Reddy, Namireddy Praveen	Peftitsis, Dimosthenis	Optimal design of wind turbine converters using advanced power semiconductor materials	90
Rekdal, Kristin	Peftitsis, Dimosthenis	Battery energy storage integration via DC/AC converter in grid connected wind turbines	91
Rendum, Jørgen	Hansen, Eilif Hugo	El-sikkerhet for ladesystemer med jordfeil i elektriske kjøretøy	93

Stochastic Optimization of Zero Emission Buildings

Student: **Ingrid Marie Andersen**
Supervisor: **Karen Byskov Lindberg**
Co-supervisors: **Pernille Seljom** og **Magnus Korpås**

Zero Emission Buildings (ZEBs) are energy efficient buildings that produce on-site renewable energy to compensate for their consumption. The concept of ZEBs is based the EU's Energy Performance of Buildings Directive (EPBD) of 2010, demanding that all new buildings constructed after 2020 are to reach "near zero energy level. Previous research on energy systems in ZEBs have used *deterministic* linear optimization techniques to determine the cost-optimal design of invested technologies in such sustainable buildings.

The main contribution of this thesis is the development of a *stochastic* two-stage model, formulated as a Mixed Integer Linear Program (MILP), that determines the cost-optimal investments and operations of a ZEB. The model accounts for uncertainty in the short-term operational patterns; the fluctuations in the outdoor temperature, the spot price of electricity and solar irradiation. The two the main objectives are: 1) To compare the optimal technology design of the deterministic and stochastic model counterparts and 2) to investigate the possibilities of the investment of an electric battery. Emissions constraints are formulated to fit the ambition level known as the "ZEB-O" level, only considering emissions caused in building operations.

The model input data is simulated to fit the hourly demand of electricity and heating in a Norwegian passive house. Time series on simulated demand from 2010 to 2014 are used to construct operational scenarios. Realistic investment costs of building technologies are used based on an extensive survey of Norwegian manufacturers' prices. Clustering analysis is used to reduce the computational effort by selecting seasonally representative hours to imitate a full year of operations.

Results show that a stochastic model can better, than its deterministic counterpart, account for the following: (i) Cover the peak heat demand of periods colder than the deterministic input data, and (ii) avoid over-dimensioning of the installed base-load capacity. The net present value of the total costs can be reduced by 1/6, which represents the quantitative value of using a stochastic model in the place of a deterministic model. Furthermore, the stochastic model is used to analyze the impact of a "power subscription" grid tariff scheme and battery operations in ZEBs. The battery is not a cost-optimal technology in ZEBs due to the forced reinvestments every 10th year imposed by the stochastic two-stage formulation. Sensitivity analysis show that the battery specific investment costs (EUR/kWh of storage capacity) must be reduced by 90 \% to become part of the solution.

Impact of Variable-Speed Hydro on Power System Frequency Stability

Student: **Espen Aronsveen**
Supervisor: **Kjetil Uhlen**

There is a growing concern that the decreasing share of rotating masses in the power system, caused by the increasing generation of solar and wind power, will lead to frequency problems. Photovoltaic panels and wind turbines are connected to the grid via power electronic interfaces, and are therefore non-synchronous sources that do not contribute to frequency control. The kinetic energy in the rotating masses is the power system's first defense against disturbances and large faults. If the synchronous generation sources, such as hydropower, are replaced by non-synchronous generation, and a large fault occurs, the power system could experience severe frequency problems. Variable-speed hydro is proposed as a possible solution to this problem.

Primary frequency control in Norway and Sweden is today exclusively performed by hydropower plants utilizing droop control. By connecting a hydropower plant to the grid via a frequency converter, the plant can run on variable speed and release more kinetic energy during frequency drops. In this thesis the impact of variable-speed hydro on the system frequency is studied, by developing a simplified power system model in Simulink based on the swing equation and DC power flow. The model is verified against a higher-order AC model in a test network, before optimal control of the variable-speed plant is investigated.

The control variable for the variable-speed plant is the frequency deviation from the nominal frequency, meaning a large drop in frequency leads to a large contribution during the fault. Only the size of the fault was found to be of importance to the variable-speed plant's contribution to frequency containment, not the location. The location of the variable-speed plant itself did not have significant impact on the results either, only the share of variable-speed capacity. The improved ability to contain the frequency nadir was relatively much larger with small shares introduced. The improvement had a decreasing trend with greater shares of variable-speed capacity in the system. Variable-speed hydro technology shows great promise in the field of primary frequency control, and could play an important role in securing the frequency stability in the future power system.

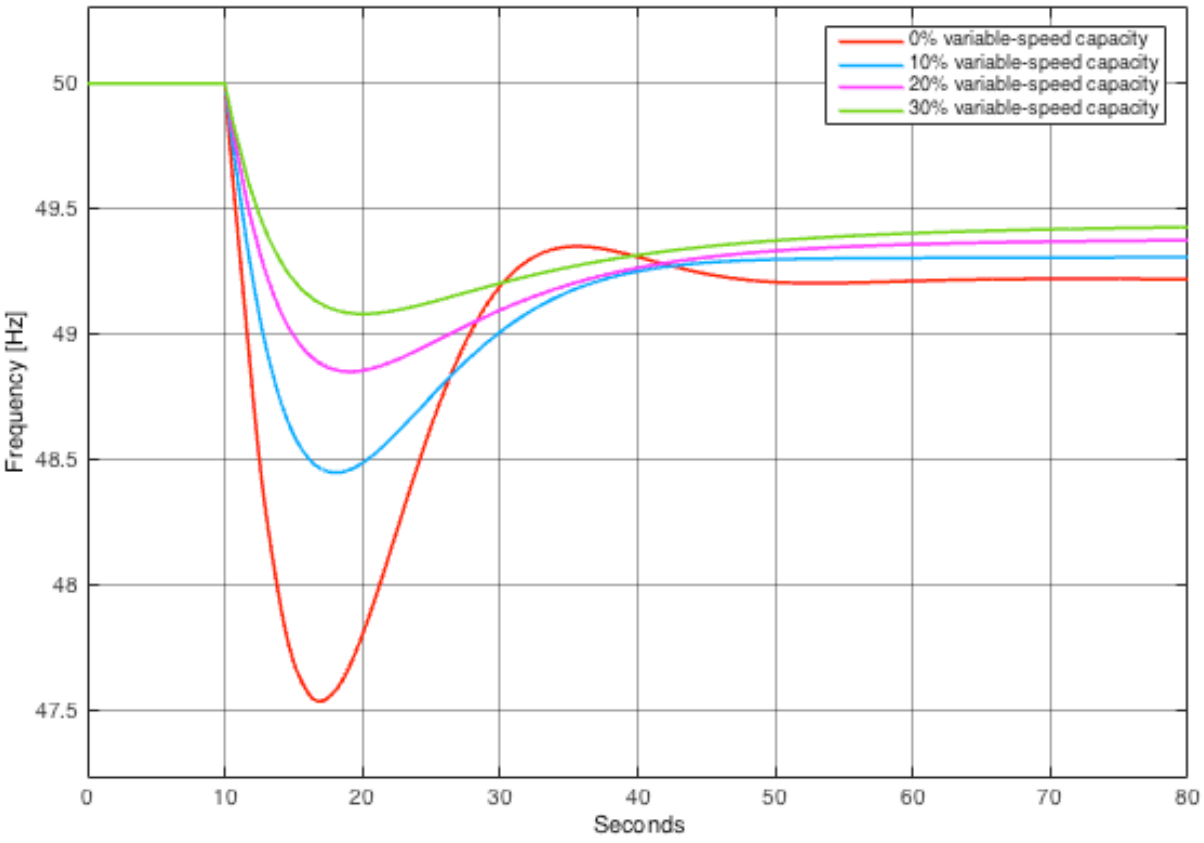


Figure 1: The frequency response following a large disturbance, with different percentages of variable-speed hydro equally distributed throughout the power system.

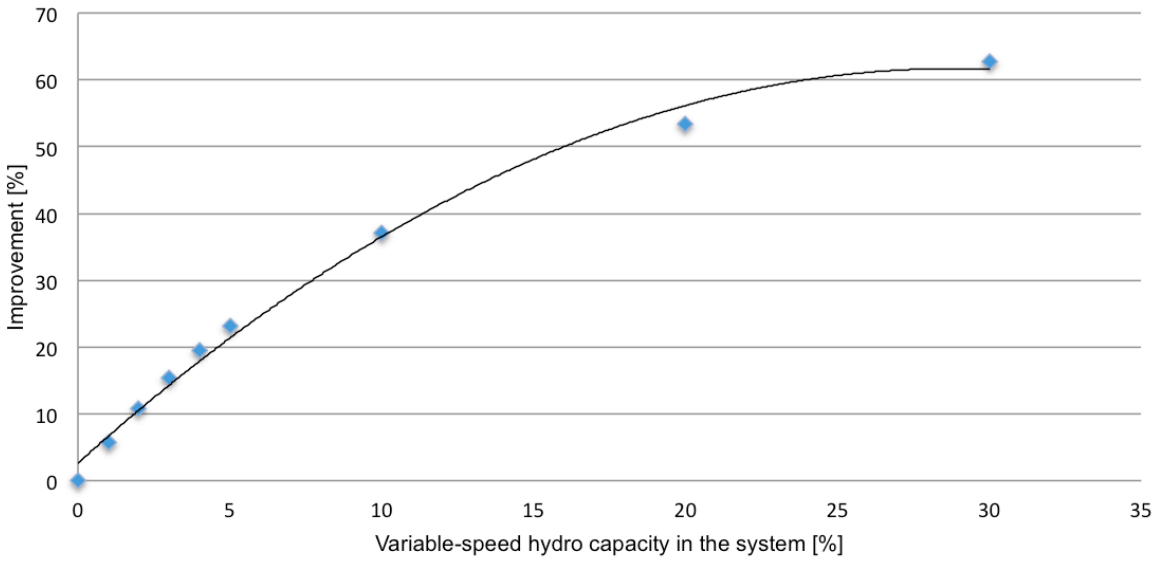


Figure 2: The improvement of the frequency nadir when introducing variable-speed hydro equally distributed throughout the power system.

Effect of filling pressure on Thermal Reignition Performance of free burning ultra-high Pressure Nitrogen arc

Student: **Shashidhara Basavapura Thimmappa**
Supervisor: **Kaveh Niayesh**
Contact: **kaveh.niayesh@ntnu.no**
Co-supervisor: **Fahim Abid**
Contact: **fahim.abid@ntnu.no**
Collaboration with: **SINTEF Energy Research**

Problem description

The arc voltage characteristic of Nitrogen at supercritical pressure have been studied, but the dielectric recovery characteristics of free burning arc after interruption of current in Nitrogen filled chamber at high pressure needs to be studied. The behaviour of remnant charges in arc path and its re strike characteristics after tens of milliseconds needs to be studied. Development of transient recovery voltage or dielectric strength recovery speed to withstand the potential difference between the contact terminals to be explored in detail.

The arc voltage characteristic of nitrogen at supercritical state have been investigated recently. However, thermal reignition and dielectric restrike characteristics of free burning arc after current zero in nitrogen filled chamber at high pressure is yet to be studied. This thesis is limited to the effect of filling pressure on the thermal reignition performance of free burning ultra-high pressure nitrogen arc (including supercritical state).

The task

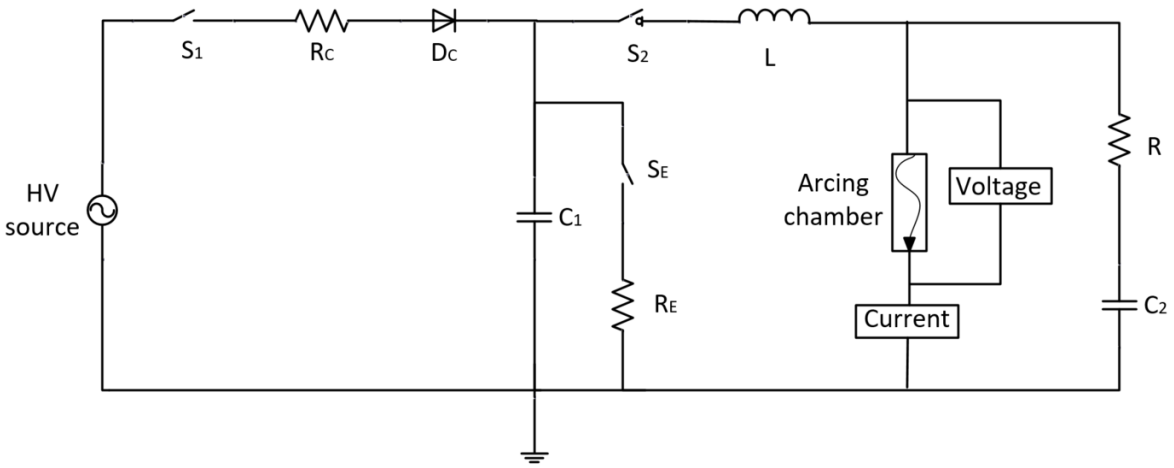
The main objectives of this thesis are

- Literature review on present research studies on this topic and choosing a suitable method to investigate the post arc thermal reignition performance.
- Simple simulation of the behaviour of the circuit in order to understand the circuit.
- Preparation of laboratory circuit to conduct experiments.
- Data collection for varied rate of rise of recovery voltage and varied current slope near current zero at different filling pressure.
- Data analysis and finding the correlation between "re-ignition time" and "voltage when re-ignition occurs" with respect to different di/dt near current zero and dv/dt [RRRV] with different filling pressures.

Model/ measurements

This study is done for different pressure values in a closed nitrogen filled pressure vessel. Ignition wire is tied between copper-tungsten electrodes, where in the copper-tungsten electrodes are separated at fixed distance. The rate of change of current (di/dt) slope is varied by changing the inductance value. The time period (**Δ**t) value is controlled by varying resistance values. As change in resistance values will vary the slope (dv/dt) of the TRV applied. The Voltage and current measurements were carried by HV probe and current shunt respectively. These values are communicated to control room via fiber optics cable and stored in a digital oscilloscope. Capacitor banks are used to supply voltage and current for

interruption and for post arc voltage across the pressure vessel. Inductor in series with capacitor in circuit is used for filtering purpose to achieve fine AC supply.



The test circuit is as shown in figure which consists of HV source (AC), switch (S_1) resistor-diode unit (Rc-Dc), switch (S_2), inductor (L), resistor (R), capacitors (C_1 and C_2), earthing unit (S_E-R_E) and arcing chamber (pressure vessel).

Results

The initiation of thermal re-ignition depends upon rate of rise (dv/dt) of TRV soon after current zero and the time taken to re-ignite the arc is considered as the main parameter to characterise the post arc thermal reignition at different pressure levels. It has been concluded from the results that, for different filing pressures, no strong connection of delay time is observed. For different pressures tested, a common trend of decreased **Δ**t and high increase di/dt and dv/dt is observed for increased dv/dt and decreased di/dt. The observation from the results were expected. The increase in resistance values the rate of rise of TRV increases and increase in inductance decreases the di/dt slope.

The experimental circuit have no control on the delay time to post arc voltage applied. Also, there is no active cooling mechanism present might be one of the reason which limits us from expecting improved restrike performance in free burning arc at SC state. The data recorded from the experiment have the error margin added from voltage and current probes and accuracy of the signal transmitters and receivers.

Conclusion

The objective of this thesis was to study the post arc dielectric recovery characteristics of free burning arc at high pressure filled nitrogen chamber. The experiment is conducted at various pressure levels for different di/dt and dv/dt. Based on the experimental findings following conclusions can be drawn.

1. At atmospheric pressure, a high dv/dt facilitates the reignition earlier, which is expected.
2. At atmospheric pressure, a high di/dt causes faster reignition.
3. At high filling pressure, this general trend of dependency on di/dt and dv/dt is also observed.
4. When compared to different filling pressures, no strong correlation of delay time to restrike and filling pressure was observed.

Solid State Circuit Breakers In Medium Voltage Direct Current Systems

Designing, improving and optimizing solid state circuit breakers for MVDC applications

Student: **Sondre Johan Kjellin Berg**
Supervisor: **Dimosthenis Peftitsis**

Problem description

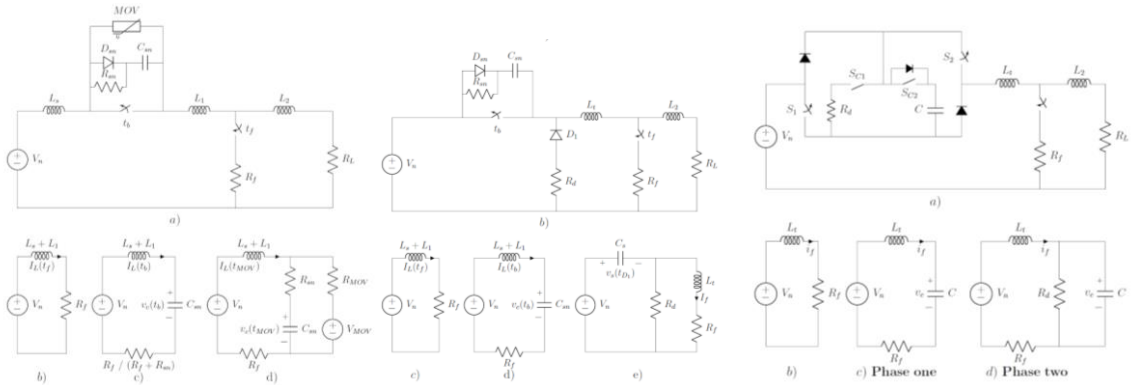
One of the main challenges of implementing MVDC systems that still impedes its development is the design of proper and satisfactory fault handling technology. Due to inherently low cable inductances in the short cable distances related to MVDC applications, fault currents quickly rise to unacceptable values and is in need of very fast fault breaking mechanisms. Traditional mechanical AC circuit breakers (ACCB) are too slow to perform this action and since there is no natural zero crossing in DC systems this technology is not applicable. New SSCBs have been proposed in literature to provide fast current interrupting and isolation.

The task

In this text three different solid state circuit breakers (SSCB) for medium voltage direct current (MVDC) systems have been investigated, namely the interrupting, the current limiting and the resistive topologies. In particular, design strategies for each breaker topology has been proposed emphasizing the optimal design of passive elements with regard to different design goals.

Models

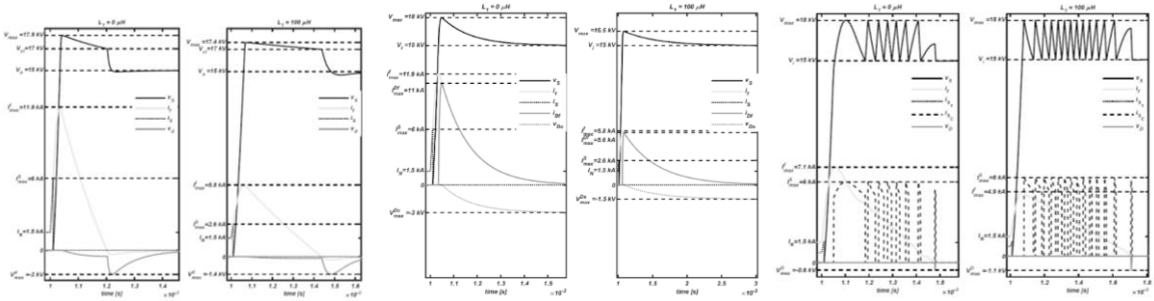
The following figures shows the models considered for the interrupting (left), current limiting (middle) and resistive topology (right) respectively. The equivalent circuits during fault conditions is also seen in these figures.



Using state-space representation, the topologies has been analysed and a design strategies has been proposed.

Results

The following figures shows the simulation results of the base case for the interrupting (left), current limiting (middle) and the resistive topology (right) for faults happening close to the power source (L=0) and close to the load (L=100). Many other cases was also simulated.



Simulations showed results consistent with the analysis and design strategies proposed.

Conclusion

Improving the power electronic device used for switching in terms of Vmax, Imax, Pmax, Ploss, tdelay and tfall will improve the breakers performance.

The interrupting topology is the simplest topology offering the lowest requirements in terms of required power semiconductor devices. it also offers some of the fastest breaking times without the need of further increasing the maximum allowable voltage over the switching device.

The limiting topology offers the largest degree of controllability. It also seems to be the slowest topology, particularly for faults of higher fault inductance. The breaking time of this topology is very sensitive to the increase of Vmax.

While the resistive topology is the most complicated topology requiring a large amount of semiconductor devices, it also seems to be the topology with the highest potential of reducing passive element requirements and total breaking time. It may thus be very suitable for compact fast acting applications.

The power losses in all topologies is governed by the chosen switching device. The key factor in reducing this will thus be the improvement of power semiconductor devices. The implementation of SiC technology thus seems very interesting.

Using SiC MOSFETs further seems to drastically improve all breaker topologies. With current technology however, it seems unlikely that the required current, voltage and power rating of mid-range MVDC.

The results achieved in this paper shows how important it will be to choose a suitable topology and optimize it specifically for the topology to which it is to be used. all topologies have theirs advantages and shortcomings and different topologies may be suitable event within the same system. For example the interrupting topology may be very suitable for reliable and simple interruption of a constant DC grid fault. The limiting topology on the other hand can work as to assuring the deliverance of power to un-interruptible loads or controlling the fault current in sensitive areas of the system. For applications requiring super fast and compact solutions such as under water applications connected to MVDC distribution grids the resistive topology may be a good choice.

Optimal Operation of Battery Storage for Peak Shaving Applications:
A Norwegian Case Study for a Medium-Scale Swimming Facility

Student: **Frida Berglund**
Supervisor: **Kjetil Uhlen**
Contact: **Bjørn Aas**
Collaboration with: **SIAT**

Problem description
With the vast implementation of power-demanding devices, the grid is facing supply challenges in terms of covering the peak power demand. One solution is to expand the existing grid, resulting in large investment costs. Another solution could be to encourage end users to reduce their power demand. Commercial users are subject to a peak demand charge, meaning they are charged for the highest peak power drawn from the grid each month. The demand charge may be high, and the resulting cost of peak power may contribute to a substantial part of the total electricity bill. As such, there is a large incentive for commercial consumers to reduce their power demand.

Sports facilities are a special type of consumer, as they tend to have a high, continuous demand with extreme peak power periods during busy hours or events. Moreover, load shifting is not always an available option. A promising solution for reducing the peak demand is battery storage, where energy can be bought from the grid to charge the battery during off-peak hours, and discharged to supply the load during on-peak hours. This is called peak shaving, and would both relieve the grid of stress and reduce the cost of peak power for the facility. With the introduction of local generation, such as from solar modules, the battery may also be charged by excess production, thus increasing self-consumption. However, due to the high investment cost of battery storage, it is important to operate the battery in a way that ensures longevity such as to avoid early re-investments.

The task
In this thesis, the economic benefits of implementing battery storage into an existing grid-connected PV system for a medium-scale swimming facility is studied. The objective is to minimize the total cost of electricity, including the cost of energy and peak power, while ensuring longevity of the battery. The main purpose of the battery is to shave the peak power demand, as this contributes to a large part of the monthly energy bill.

Model/ measurements
An optimization model based on multi integer linear programming is built. The objective function is to minimize the total system cost, including the cost of energy, the cost of peak power and the operational cost of the battery. The model is written in The General Algebraic Modeling System (GAMS) and solved using Gurobi. Hourly load and PV production data for the test case was found based on a combination between historical data and estimates. The energy price was assumed equal to the hourly spot prices for Oslo from 2017.

Calculation
The simulations are carried out on a one year time horizon with hourly increments. Several sensitivity analyses on important system parameters are also investigated, including sensitivity of the cost of the battery, as well as the energy and peak demand tariffs. Moreover, a 2030 scenario is simulated in order to analyze the impacts of implementing battery storage in the future.

Conclusion
The main results reveal that installing a battery storage system is economically attractive today, with a net savings on the total system cost of 0.64% yearly. The cost of peak power is reduced by 13.9, and the savings from peak shaving operation alone is enough to compensate for the yearly cost of the battery. Moreover, the battery ensures additional revenue by performing price arbitrage operations. The yearly degradation of the battery is found to be 7.15%, and the optimal battery size is 150 kWh. When simulating the system for an assumed 2030 scenario, the battery is found to be even more profitable with a yearly net savings of 4.15%.

Condition Assessment of Service Aged Medium Voltage Cable Joints During Load Cycling

Student: **Ingeborg Bjurholt**
Supervisor: **Frank Mauseth**
Contact: **Sverre Hvidsten**
Collaboration with: **SINTEF Energy**

In order to be able to take maximum advantage of the remaining lifetime of the components in the distribution network, utilities need to know the condition of the equipment as accurately as possible. When partial discharges (PD) are measured in medium-voltage cable systems, it is often chosen to disconnect the cable length and use voltage sources with frequencies of 0.1 or 50 Hz. Temperature dependence of the conductivity in the joints' field grading materials, as well as expansion and contraction of materials could potentially cause PD characteristics to be load dependent. This again means the method and time of testing may affect the results and subsequent assessment of the equipment's condition. There are few studies available in the literature where XLPE cable joints from service are characterised by PD during load cycling.

The purpose of this master thesis is to study PD activity during load cycling of field aged cable joints at 50 Hz. PD measurements are also performed at 0.1 and 50 Hz in room temperature to simulate the conditions during off-line testing. The insulation resistance of the test objects will be measured through both tests.

The conditions during on-line and off-line PD measurements have been simulated in the laboratory, where three phases from a field-age joint have been tested. During the "off-line" measurements, the inception voltage was measured with 0.1 and 50 Hz voltages in room temperature. The measurements were performed with and without voltage conditioning (50 Hz, 6 kV for 1 hour) prior to the PD measurements. On-line measurements were simulated by use of load cycling to temperatures in intervals up to 65 $^\circ$C and voltage conditioning. The inception voltage of the joints was measured at stable temperature. PDs were recorded at 6 kV during the cooling of the test objects to investigate whether the PD sources are temperature dependent.

Towards the end of the experimental work, PDs in the joints were localised acoustically. Then, the break-down voltages were measured, before the dissection of the joints ended the experimental work.

The PDs that were measured appear to depend more on voltage frequency than joint temperature. In room temperature, inception voltages of 3-6 kV and 1-1.5 kV were measured at 0.1 Hz with and without conditioning, respectively. When PDIV was measured at 50 Hz in room temperature, the results were between 5.7 and 7.1 kV without and 6.1-7.6 kV with conditioning. No clear trend of inception voltages was observed when the temperature was increased. With the exception of one (very high) PDIV, all inception voltages measured during load cycling are between 6.0 and 7.1 kV, i. e. in the same range as measured at 50 Hz voltage in room temperature. The break-down voltages of the joints were found to be 65, 65 and 50 kV.

The inception voltages measured at 0.1 Hz are all less than or equal to the operating voltage, and highly dependent on how recently voltage has been applied to the joint. Based on this, it might be concluded that the measurement results at 0.1 Hz can be difficult for the utility to

interpret, thus increasing the risk of misdiagnosis. On the other hand, the off-line measurement results at 50 Hz provide a realistic impression of the condition of the joints, and are also a good representation of the conditions under operation. This is confirmed by the measured break-down voltages.

Weibull analysis of the PD measured during cooling showed a decreasing number of PD sources in 2 of 3 cases. In the joint where a constant number of PD sources were identified during cooling, approximately the same number of sources was detected acoustically. Dissection of the joints after break-down voltage testing showed that 2 out of 3 failures were thermal and that all punctures occurred at the semiconductor cut-off. Traces of discharge spots and ageing due to water ingress were observed by use of microscope.

These findings indicate that the discharge sources may be temperature dependent, but that more investigations are necessary before any conclusions can be drawn.

Generation system adequacy studies in the presence of wind energy resources

Student: **Mads Bjørkeland**
Supervisor: **Vijay Venu Vadlamudi**

Abstract

Variable renewable energy sources like wind power are in exponential growth worldwide. One of the major challenges regarding high penetration of wind energy in the power system is the degradation of generation adequacy due to the intermittent and random nature of wind.

The deterministic approaches applied today to ensure sufficient power system adequacy are ill-fit to handle stochastic generation behaviour. In response, several generation adequacy metrics with probabilistic basis have been developed in literature. Probabilistic methods for generation adequacy assessment are crucial for securing future power system operation and renewable generation integration.

As part of a project to construct a computational framework for power system reliability this thesis focuses on generation adequacy assessment of power systems with the presence of wind power. The applied concepts include generation adequacy metrics (LOLE and EENS)1 and ca-pacity credits (ELCC, EFC and ECC)2. To evaluate the generation adequacy of relevant test sys-tems (Roy Billinton Test System and IEEE-Reliability Test System), MATLAB scripts that compute adequacy metrics and capacity credits have been developed and deployed. To evaluate the re-liability effect from wind power generation, a wind farm has been modelled and integrated in the test systems. Evaluations applying several adequacy metrics and capacity credits have been conducted on the test systems including integrated wind power along with relevant sensitivity analyses.

From the thesis work it has become evident that the myriad of generation adequacy metrics, ca-pacity credits and their combinations provide a powerful means of evaluating different aspects of power system reliability, thereby contributing to optimising renewable energy integration. However, the multitude of possibilities and lack of an established methodological approach makes the process of identifying the optimal metric combination a knowledge-intensive task.

---

1 Loss-of-Load Expectation (LOLE), Expected Energy Not Served (EENS)

2 Effective Load Carrying Capabilities (ELCC), Equivalent Firm Capacity (EFC), Equivalent Conventional Capac-ity (ECC)

A Feasibility Study of Blockchain Technology As Local Energy Market Infrastructure

Student: **Fredrik Blom**
Supervisor: **Hossein Farahmand**

Abstract

The recent surge in renewable energy in the distribution grid could transform the generation side to be more variable, which potentially reduces power quality. This technical local challenge could be compensated by introducing a market solution, which could be realised in the form of a local energy market. Such markets requires a comprehensive infrastructure, where a centralised database solution traditionally have been used. However, blockchain technology have lately been presented as a possible preferable alternative. Blockchain is a decentralised communication platform, which logs all information in a structured and tamper-proof manner. This design makes it potentially suitable for operating a local energy market. However, there have not been performed a lot of research on the feasibility of developing local energy markets using blockchain technology. This will be therefore be the focus of this thesis, where a technical, economic and regulatory analysis are performed. **The task** Concentrate of the text

This thesis address this feasibility by developing a complex local energy market, deploying this on a test blockchain and analyse the results. The market consists of three unique trading mechanisms, where all explores the benefits of flexible loads. These trading mechanisms are then represented as blockchain applications, and simulated over a range of scenarios. The results illustrate a proof of concept, in addition to measure the usage of computational resources of operating blockchain applications.

The market simulation proved the technical feasibility of running several complex mechanisms in a blockchain environment, with an integrated payment solution. The observed computational resource consumption of the market revealed that a complex real time trading with 600 nodes and a trading frequency of 5 minutes requires a blockchain that can process 10.2 standard Ethereum transactions per second. This is considered to be possible for a modern blockchain protocol to process. The blockchain application design is also analysed, where it is identified how applications should be designed in order to lower the resulting computational consumption. In result, this thesis identifies blockchain technology as suited to operate a local energy market, without significant negative computational consequences.

Regarding the economical feasibility, such a solution is considered to be more expensive than a database solution when it comes to development costs. However, a blockchain solution presents new market possibilities, which could result in a more efficient market, and hence be more economically beneficial. Regarding a regulatory analysis, the Norwegian energy market regulations presents several challenges towards decentralised local energy markets. However, the technology behind blockchain could provide arguments for changing these regulations, and hence make it possible for end users to participate actively in an energy market.

Sensorless Control of Synchronous Machines used in Adjustable Speed Hydro

Student: **Magnus Bolstad**
Supervisor: **Roy Nilsen**

Problem description

For some high power application, as for instance in Adjustable Speed Hydro (ASH), synchronous machines are used for power generation. In the specialisation project carried out in the fall semester 2017, flux models and sensorless control methods for such a synchronous generator with damper windings was developed to be able to operate such machines without speed- and position- sensors. The performance of the control system depends on the accuracy of the parameters of the flux models. In this master-project, these flux models and control methods shall be analysed in details. The main focus shall be on sensorless control at low speed operation, and on parameter sensitivity of the flux models. If time available, combinations of flux models to improve the behaviour of the model in the complete speed-torque plane should be analysed. In this Master project the tool to be used for simulation shall be Simulink with the Power System Library.

The task

A drive is classified as sensorless when no sensors are used for measuring the position or speed, but the position and speed are rather estimated based on the measured stator current and stator voltage. In this thesis, the rotor position is estimated based on the estimated stator flux linkage. The stator flux linkage can be estimated by either the voltage model (1) or the current model (2-3), which depend on different estimated parameters. The voltage model is used for estimating the stator flux linkage during sensorless operation, as no rotor position is required in the model. The goal of this thesis is to analyse the sensitivity of these models at different operational points, and how this influence the sensorless control, as both the estimated stator flux linkage, and the estimated rotor position are used as input to the control system. It should also be analysed how the sensorless control performs during different operations. The operation at low speed is of special interest, as the voltage model relies on the induced back emf, which is low at low speeds.

Model/ measurements

$$\underline{\psi}_s = \int_0^t \underline{v}_s - r_s \underline{i}_s \tag{1}$$

$$\psi_d = x_d i_d + x_{md}(i_D + i_f) \tag{2}$$

$$\psi_q = x_q i_q + x_{mq} i_Q \tag{3}$$

Steady state analysis were performed by analytical equations in Matlab, while dynamic analysis, and analysis of the sensorless operation were performed by simulations in the Simulink model implemented in the specialisation project. The stator current and the stator voltage are controlled to be 90º displaced from the stator flux linkage, to achieve unity power factor control. The stator flux linkage is controlled to be 1 pu, to minimise the required current for generating the torque reference. A simplified block diagram illustrating the simulation model implemented in Simulink is illustrated in figure 1.

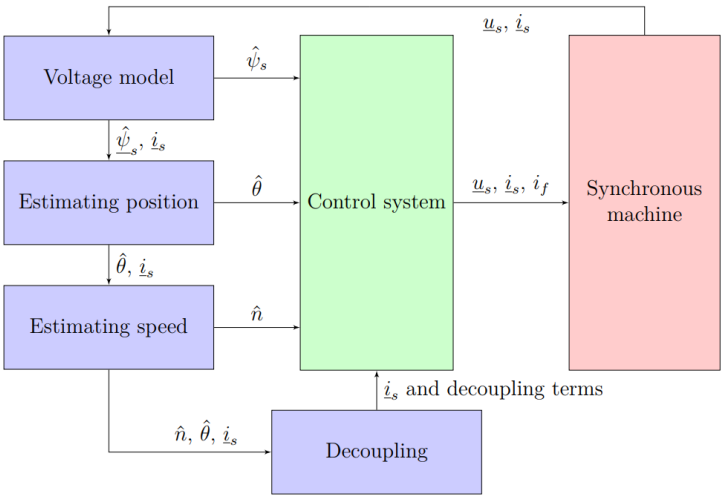


Figure 1: An overview of the simulation model implemented in Simulink

Calculation

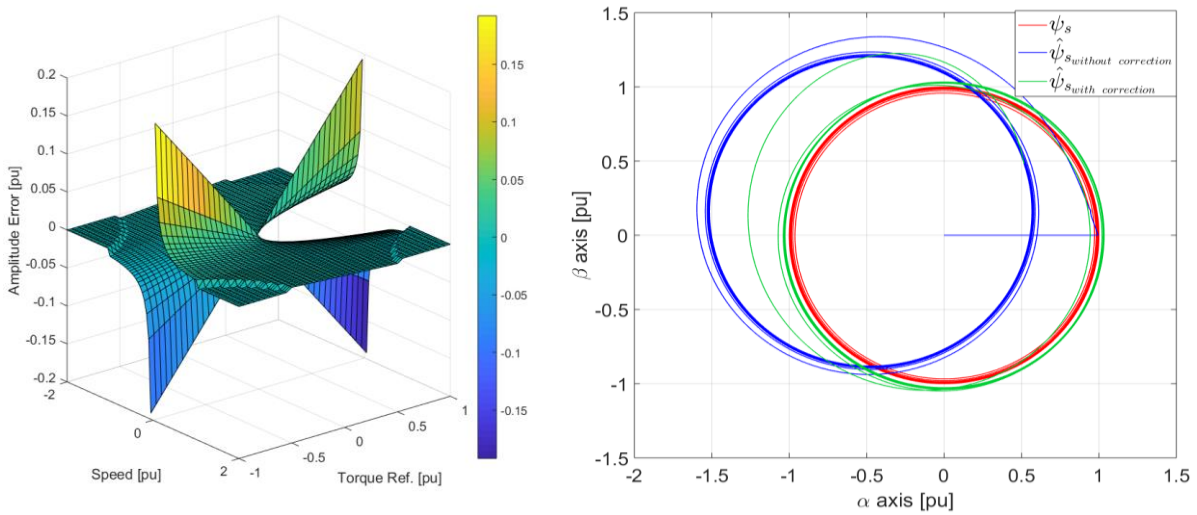


Figure 2 Left: Steady state analysis, Right: Drifting during dynamics

Conclusion

The voltage model is very sensitive to the estimated stator resistance at low speeds, and the sensitivity increases with the generated torque, as seen to the left in figure 2. The model is less sensitive at higher speeds. During steady state, only the stator flux linkage amplitude is affected by an erroneously estimated stator resistance, while during dynamics, drifting occurs. The drifting is due to an offset in the voltage integral, and the estimated stator flux linkage will rotate along a trajectory with a displaced origin, as illustrated by the red circle in figure 2. The blue circle is the trajectory of the actual stator flux linkage. This causes an oscillating error in both the estimated stator flux linkage amplitude, and in the estimated stator flux linkage angle. Neither increasing the speed, nor updating the stator resistance to the actual value remove this offset. Sensorless operation without drift correction yielded unsatisfying control. By applying drift correction, the offset in the estimated stator flux linkage is removed, as observed from the green circle in figure 2, and the error in estimated flux linkage angle becomes zero. This yielded satisfying sensorless control, with a high accuracy for higher speeds. The sensorless performance is reduced for lower speeds, and when generating a high torque while driving through zero speed. It was found that the need for external drift correction was eliminated by using a closed loop observer, correcting the voltage model by the outputs from the models, when the inductances are known with high accuracy.

Exchange Domains for Cross-border Activation of Balancing Bids
-Preventing Internal Congestion in an Integrated European Balancing Activation Optimization

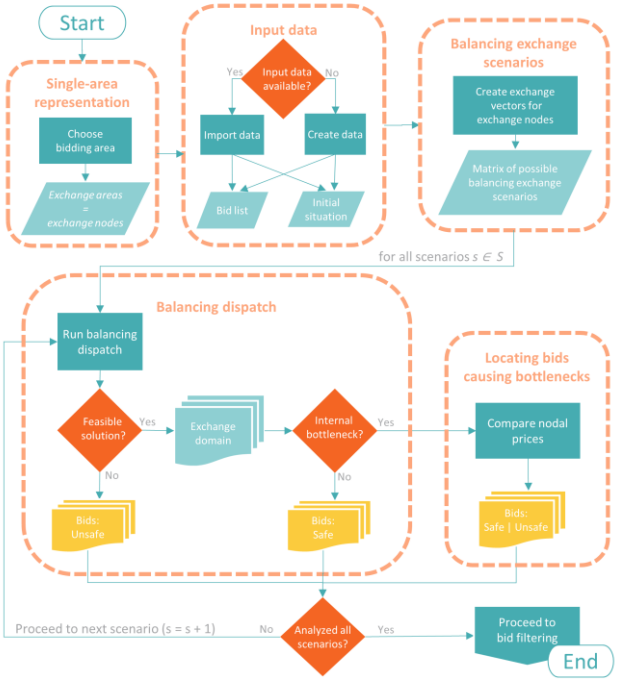
Student: **Hanna Bood**
Supervisor: **Gerard Doorman**
Martin Håberg
Collaboration with: **Statnett**

Problem description
In the near future Europe's power markets and electric power system operation will undergo significant changes. A pan-European central balancing platform is under development that is going to optimize the activation and exchange of balancing energy on behalf of all participating countries. In order for such a platform to operate efficiently, congestion due to balancing actions should be avoided as far as possible. Whereas cross-zonal transmission constraints are considered as part of the platform optimization, each Transmission System Operator (TSO) is responsible for preventing internal congestion within their area. The current proposal is for each TSO to submit to the platform, on a continuous basis, a list with all balancing bids that can safely be activated within its area without causing internal congestion. The methodology to evaluate balancing bids as safe or congesting is still a topic for discussion. At Statnett today the activation of mFRR is a manual process performed by the operators in the National Control Centre, partly based on their experience with the system. Before activating a balancing bid, the operator assesses whether the activation will cause congestion or not. In the future all bids must be evaluated before providing the platform with lists of available balancing bids, and this must be done for every market period, i.e. every 15 minutes. With the assumption that the balancing exchange is unknown at the stage when this is done, doing so manually to cover all possible or even most likely scenarios would be unrealistic.

The task
This main task of this thesis is to develop a method for detecting unsafe balancing bids that may cause internal congestion if activated by the platform. By detecting and withholding bids that are potentially unsafe, a list containing the remaining bids could be viewed as safe activations and be made available to the decision process of the TSO. A mathematical model should be developed for detecting internal congestion from bid activations and a program should be created in MATLAB to implement and test the mathematical model. Criteria that can be used for making bids unavailable should also be evaluated.

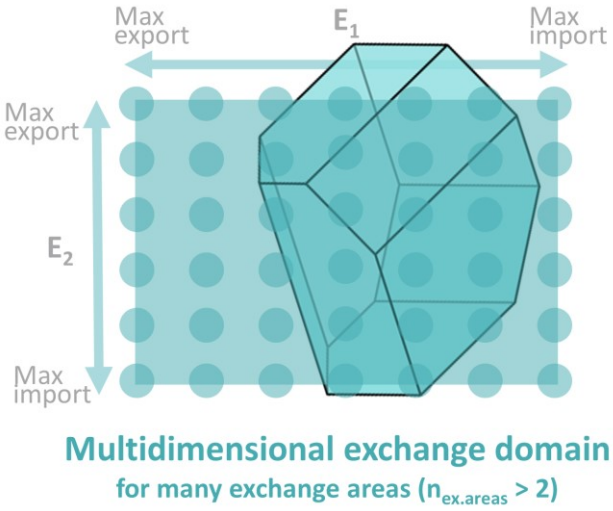
Model

In short, this methodology uses a single-area system representation in which it focuses on one bidding area at the time, and its exchange nodes are converted into node equivalents. A mathematical model was developed that is creating a matrix of all possible exchange scenarios for a bidding area. For each scenario it is performing an OPF based balancing dispatch and using the resulting nodal prices to analyse which bids that may cause internal congestion. It is a multidimensional approach in the sense that it considers different exchange situations and handles requests and activations from different locations simultaneously.



Conclusion

This thesis presents a comprehensive method for identifying balancing bids whose activation could lead to internal congestion. A mathematical model was developed and has been implemented for the purpose of testing and analysis. The developed method and results are not of the same character that what was expected**,** and it has given some important insights. Initially it was believed that the resulting output would be a list with bids that can be activated. The analysis has shown that the output should rather be in the form of a domain, where all bids within this domain can be optimally activated in merit order. For a bidding area with more than two exchange areas this creates a multidimensional exchange domain illustrated by the figure. The method demonstrates the potential complexity of evaluating whether bid activations lead to congestion, especially considering the uncertainty in balancing exchange flows decided by the platform. As a complement to making bids unavailable, this thesis therefore introduces a new concept of balancing energy exchange domains, enabling more bids to be made available for the platform optimization by reducing the uncertainty for the TSO.



Harmonic Sharing in Microgrid Applications

Modeling, Developing and Elaborating a Microgrid Control System
With Harmonic Sharing Capability

Student: **Ruben Buchmann**
Supervisor: **Olimpo Anaya-Lara**
Contact: **Raymundo E. Torres-Olguin**
Collaboration with: **SINTEF Energy Research**

Problem description

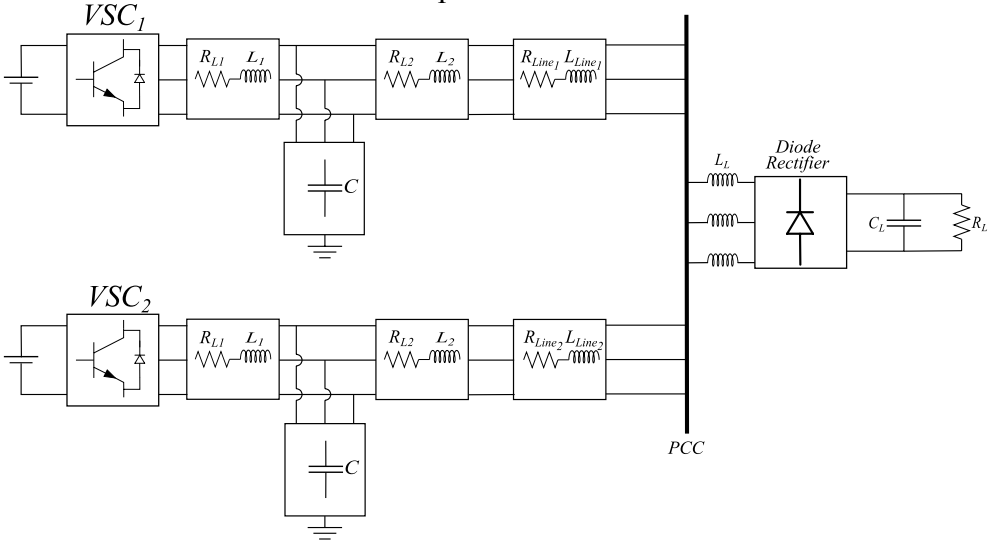
Several renewable energy sources, such as wind and photovoltaic, utilize power electronic converters, representing distinctly different characteristics compared to the technology used in the conventional power system of today. Among several traits, the converter's inherent ability to compensate harmonics is a cost-effective solution to meet the persistent challenge of harmonic distortion, which is a typical power quality issue in microgrids. However, uneven line impedances between the converters and the PCC lead to imbalance between the harmonic currents supplied by the converters, potentially harming the converter supplying most of the harmonic load.

The task

This master's thesis investigates a harmonic sharing scheme to meet the challenge of harmonic current sharing imbalance. Several case studies are provided to verify the applicability of the proposed scheme, as well as test its resilience to system alterations.

Model

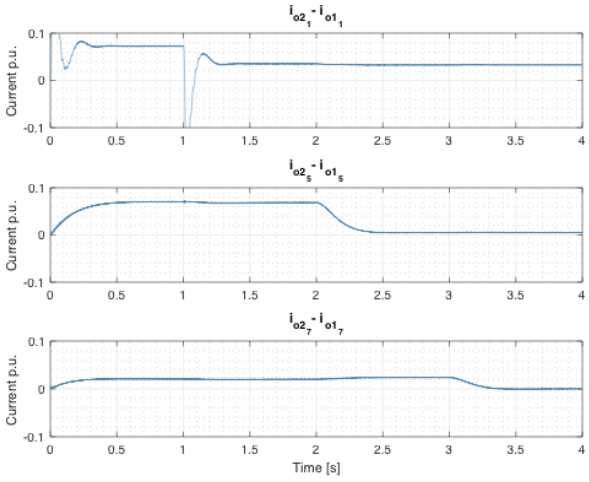
A simple AC microgrid in island mode is developed, consisting of two converters, their individual LCL filters, uneven line impedances and one non-linear load. In addition, the control system of the microgrid's converters is developed and elaborated. It consists of primary control, including current, voltage and droop control, as well as control measures to achieve harmonic compensation of the capacitor voltage for both converters. This way, the issue of uneven harmonic current sharing is displayed, as the converter facing the lowest line impedance supplies themajority of the harmonic load. A virtual impedance-based harmonic sharing scheme is then implemented in the control system of the converter facing the lowest impedance, to achieve better sharing of the harmonic load. Specifically, the sharing of the 1st, 5th and 7th harmonic current component is studied.



Results

The implemented harmonic sharing scheme is displayed with simulation results in a case study, proving the feasibility of the elaborated control system. The 5th and 7th harmonic currents are observed to be shared almost perfectly, while the fundamental current sharing is improved substantially, but still has a value of 0.033 p.u. in constant offset. This indicates the need for a secondary control layer in order to update the power references, thus achieving perfect fundamental current sharing. Additional key performance indicators (KPIs), namely apparent power, THD and load parameters, are simultaneously monitored to give a broad assessment of the harmonic sharing scheme. In this case, all KPIs are deemed adequate, resulting in assessing the harmonic sharing scheme as successful, but with room for improvement in terms of fundamental current sharing.

Three additional cases are displayed to evaluate the control system's resilience towards certain system alterations. The first of the three additional cases investigates harmonic compensation of the PCC voltage. Isolated, the scheme is successful, as the THD of the PCC voltage is lowered from 16.2% to 8.20%. However, the system as a whole is not compatible with this configuration, ending in inadequate performance of all other KPIs than the THD. The second of the additional cases studies the effect of implementing opposite droop compared to a conventional droop scheme. The difference in system responses between the twoimplementations is observed to be marginally different, with the opposite droop delivering an improvement of fundamental harmonic current sharing. Specifically, opposite droop achieves a mismatch in fundamental current sharing of 0.013 p.u., compared to the corresponding number of 0.033 p.u. for the conventional droop.
The last of the additional cases simulates the connection of a linear load to the PCC. The harmonic sharing remains efficient, showing only a decrease in performance for the fundamental current component. However, the load experiences large ripples. E.g., the voltage has a ripple of approximately 131 V, constituting a suboptimal loading scenario. Hence, as a whole, the control system is not compatible with connecting an additional linear load between two phases.



Conclusion

The harmonic sharing scheme proposed and developed demonstrates efficient harmonic sharing. However, it has been found that the proposed scheme may reduce its effectiveness when system conditions change substantially. Hence, recommendations for further work are provided which include enhancing robustness of the harmonic sharing approach.

Power electronic converters for work class remotely operated vehicles

Student: **Håvard Edvardsen**
Supervisor: **Dimosthenis Peftitsis**

Abstract

Remotely operated vehicle (ROV) is considered a key component for the subsea industry. Not only for the oil and gas industry, but also for inspection of underwater installations, subsea installations of HVDC cables, object location and recovery, diver observation and assistance and so on. The ROV will play an even more important role in subsea development in the future, as the depths of interest are getting deeper.

Most commercialized ROVs today, utilizes hydraulic systems for the propulsion and tooling equipment on board. However, the industry is starting to shift focus over to fully electric ROVs and the possible advantages it presents. Lower maintenance cost, higher reliability and efficiency, and thinner and cheaper umbilical are the main driver for this shift. As the industry is moving towards operation in deeper waters than today, the shift to fully electrifying the ROVs is even more crucial.

This thesis investigates the converter suited as the main converter for the ROV. The main converter is supplied with medium voltage from the umbilical and it distributes a low voltage to the equipment on board the ROV. The converter must be dimensioned to handle the entire load of the ROV. Since the hydraulic power unit, which is the biggest load, is removed from the ROV when fully electrifying the ROV, the power rating for the ROVs does not need to be as high as the hydraulic ROVs. After discussion with the industry, a 100 kW power rating has been used for this thesis.

In the literature study leading up to this thesis, a new electrical system was proposed for the fully electric ROV. The study points to several benefits for the electric ROV and suggests that the ROV is supplied with a MVDC at 3 – 15 kV through the umbilical and a LVDC at 0.4 – 0.7 kV as the power supply on the ROV. The study also suggest that a galvanic isolation is needed to ensure safe operations and obtain higher reliability. This means that the main converter should be designed as an isolated DC/DC converter.

Five different converter topologies have been presented and discussed. They all have their advantages and disadvantages. One of the most important criteria for ROV application is weight and volume. Converter efficiency is second priority. This means that the converters should be optimized to avoid high capacitances and inductances.

Two of the presented topologies are further designed, simulated and evaluated for the ROV application; the dual active bridge and the modularized dual active bridge. Since the voltage or switching frequency is not clear at this point, several voltage and frequencies ranges has been tested in order to optimize the design.

The result from calculation and simulation shows that by choosing the modularized dual active bridge the volume can be decreased by more than 57 % compared to the dual active bridge. The reason for decreased volume is that the modularized dual active bridge can operate with a much higher switching frequency due to low voltage switches. By increasing the frequency, the passive components such as capacitors, inductors and transformers can be

significantly reduced. However, this thesis has not been able to identify the complete volume of each converter. This means that the total volume of the converters in this thesis may be higher. Still, the conclusion from this thesis gives an indication for further research and development for the ROV application.

Probabilistic Load Flow Studies: Analytical and Approximate Methods

Student: **Mari Holtet Eie**
Supervisor: **Vijay Venu Vadlamudi**

Abstract

The power system is, in an increasing manner, subject to uncertainties, and the traditional method of analyzing power systems using the deterministic load flow (DLF) is increasingly proving to be insuÿcient to handle the challenges of the modern power system. The modern power system is characterized by integration of renewable energy sources whose generation is fluctuating and uncontrollable in nature; even on the demand side, an increased flexibility related to the development of smart grids and power systems is expected to increase the uncertainties. Probabilistic load flow (PLF) techniques provide engineers the opportunity to include these uncertainties in the analysis of power systems.

In this thesis, a review of the current state of the PLF research is presented, with focus on analytical and approximate methods available today. Two of the most commonly used and promising methods are the Cumulant method (CM) and the Point estimate method (PEM). These methods are studied in further detail and demonstrated on three di˙erent test systems. A major contribution of this study has been to provide a pedagogical presentation of the theoretical framework and methodogical procedure, and thus one of the test cases includes thorough step-by-step illustrations of both methodologies. The aim of this master's project has also been to create in-house tools with which to conduct probabilistic load flow studies. This tool has been applied to yet another two test systems, in order to provide validation and to demonstrate the application on two test systems that are widely used in reliability studies.

The scope of this study has been the analytical and approximate methods of PLF, hence no simulation methodologies such as the Monte Carlo (MC) methods have been implemented. This has restricted the validation of the results from case studies in this thesis to comparison with results from previous research, whose availability is often limited.

The case studies of this thesis address uncertainties associated with load demand, as well as conventional and renewable generation. Correlation between di˙erent random variables in the system is an important part of these uncertainties, and is also studied in detail. Uncertainties related to outages and resulting changes in the network topology are aspects of the PLF that are not considered in this thesis, but rather left as a possibility of future work on the subject.

Breakdown at Multiple Protrusions and Surface Roughness in SF6 and CO2

Student: **Odd Christian Feet**
Supervisor: **Kaveh Niayesh**
Co- Supervisor: **Frank Mauseth**
Contact: **Martin Seeger, ABB**
Collaboration with: **ABB**

Summary

Gas insulated components are important in the modern transmission system. The most common gas used in high pressure insulation is Sulphur Hexafluoride (SF6). SF6 has been classified as a greenhouse gas and a potential replacement is CO2, either by itself or in mixtures with other gases. The insulation properties of gas insulation depends on several parameters, e.g. surface roughness. An electrode with a built-in precision motor was used in a quasi-uniform gap. This thesis aims to investigate the impact of needle protrusions with lengths in the range 0.05 – 2 mm in SF6 at 4 bar absolute pressure and CO2 at 6 bar absolute pressure. Another aim is to investigate the applicability of the enlargement law. The results with a single needle were used to create predictions, according to the enlargement law, for 20 and 100 identical needle protrusions. The electrode used allowed needle arrays of 20 and 100 needles to be tested with needle lengths in the range 0.05 – 2 mm. The enlargement law was also investigated for two sandblasted surface areas.

The results in SF6 showed a decrease in the 50 % average background breakdown field, E50, with increasing needle lengths for both polarities. With 20 needles E50 decreased from the single needle results and agreed well with the predictions for both polarities. With positive polarity and 100 needles, there was no significant change in the results between the 20 and 100 needles and there was a discrepancy with the predictions. With 100 negative needles there was a good agreement between predictions and results, showing a decrease from the results with 20 needles. The sandblasted surfaces showed a decrease from the small area (2.383 cm2) to the large area (64.465 cm2). The reduction in E50 showed good agreement with predictions with negative and disagreed significantly with positive polarity.

The obtained results in CO2 showed an insensitivity to single needle protrusion with nee-dle lengths shorter than 1 mm with positive and 0.75 mm with negative polarity. With 20 needles, there was an increased sensitivity and reduction for both polarities. E50 with pos-itive polarity decreased with increasing needle lengths. Negative polarity had a significant decrease of E50 from 0.1 to 0.5 mm where it seemed to saturate between 0.5 – 2 mm needle lengths. For 20 needles both polarities agreed well with predictions. With 100 needles, there was no longer an agreement between predictions and results for either polarities. the results with positive polarity decreased further. With negative polarity similar behavior as with 20 needles was seen, where the saturation occurred at 0.2 mm needle lengths and ended at the same field strengths as with 20 needles. The sandblasted surfaces showed much more of a decrease than what was predicted based on the small area.

The experimental results were analyzed with Turnbull’s algorithm to determine the em-pirical cumulative distribution function, which was fitted with the three parameter Weibull

distribution. From the distribution functions the 2 % average background breakdown field was found. Possible physical explanations and breakdown mechanisms of the results were discussed. The results showed that SF6 was more sensitive to the needle protrusion than CO2. The main conclusion is that the enlargement law must be used with care. It is possi-ble that the mechanisms involved in breakdowns scale differently than just with increased number of needles or area and require further investigation to understand.

Investigation of various solutions for improved voltage quality in a weak distribution network

Student: **David Fellner**
Supervisor: **Kjetil Uhlen**
Contact: **kjetil.uhlen@ntnu.no**
Collaboration with: **TrønderEnergi Nett AS, Vienna University of Technology**

Problem description

Keeping voltages in acceptable limits is a challenge for every grid operator and utility, especially in weak rural distribution networks and on the end of feeders. In rural parts of the grid farms are predominant. These show varying loads especially when starting motors which can lead to problems with assuring voltage stability. These fluctuations in voltage are very undesirable for customers as they can lead to inconveniences as flickering lights or also shorten the lifespan of appliances. The local utility TrønderEnergi is facing issues operating rural distribution grids and is therefore looking for solutions to improve the performance of the grid. These solutions are preferably easy to implement, durable and cost efficient.

The task

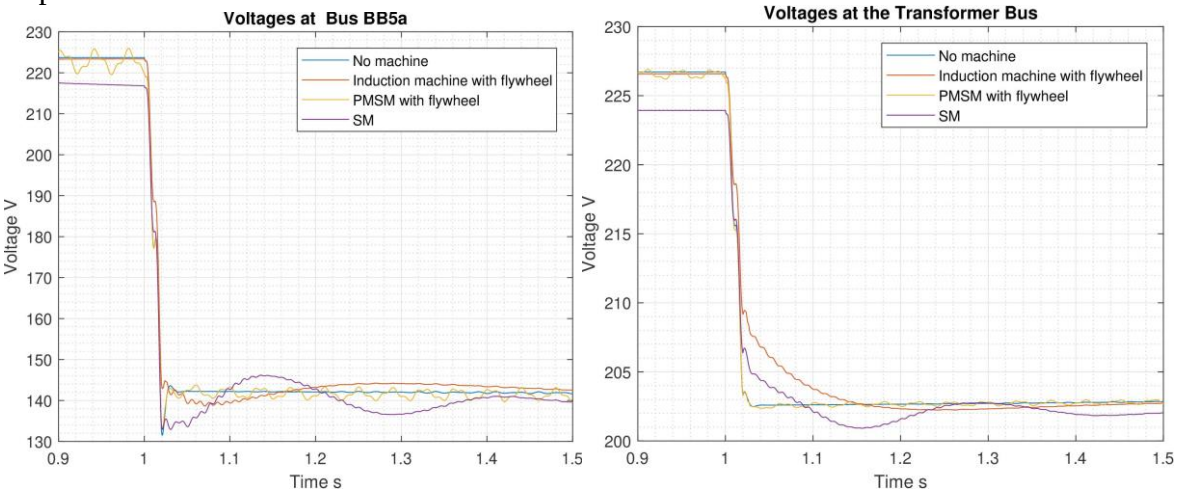
Voltage instability and low short circuit capacity are a main issue for utilities when operating weak, mostly rural, distribution grids. Especially voltage dips caused by start-ups of induction motors, which are frequently found in rural grids, are problematic. This thesis is investigating several solutions to improve voltage stability and the short circuit capacity of distribution networks like these.

Model/ measurements

Electric machines are added to the grid and their impact is analysed. First a realistic grid is modelled using actual data provided by a utility and two induction machine models are implemented. In addition to the induction machine an electrically excited synchronous machine, a PMSM and an additional flywheel linked to the machines are examined as solutions as well. Typical parameters are chosen for all parts of the model. Finally, a start-up of an induction machine and a short circuit simulation is conducted.

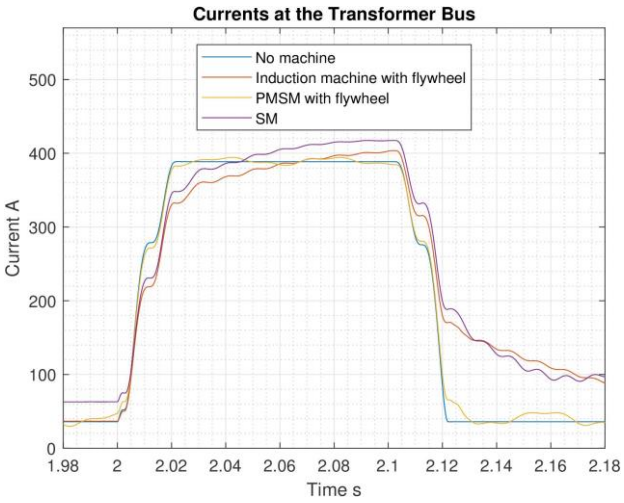
Calculation

At the motor start the various electric machines simulated provide different degrees of improvement as shown below:



Both at a local load and at the transformer the voltage is supported to a certain extent.

In the fault scenario the various solutions differ in their impact also as the following figure points out. The short circuit currents at the transformer have lower or higher magnitudes with respect to the machine applied. Effects of blinding can be observed:



Conclusion

The induction machine including a flywheel solution shows the best performance in an increased load scenario, as the motor start-up, as well as in a fault case, the 3-phase line to ground short circuit. It provides voltage support both at the transformer bus and the local load for a limited time and especially for the transient time frame. In regard to these aspects the proposed solution shows preferable behaviour in comparison to the electrically excited synchronous machine, the PMSM and just the induction machine without a flywheel. Only the big short circuit currents fed into the fault by the induction machine including the flywheel pose a disadvantage regarding protection schemes.

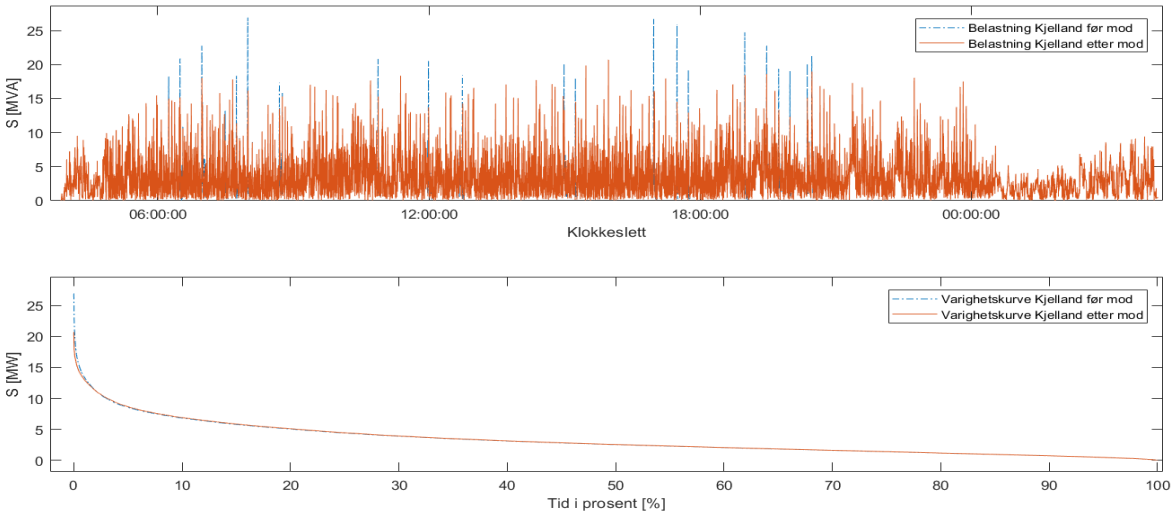
Energiøkonomisk togfremføring vs dimensjonering av jernbanens strømforsyningsanlegg

Student: **Øyvind Frantzen**
Veileder: **Trond Toftevaag**
Utføres i samarbeid med: **Bane NOR**

Problemstilling
Denne rapporten tar for seg hvorvidt det foreligger en mulig teknisk/økonomisk motsetning mellom energiøkonomisk togfremføring og dimensjonering av jernbanenes strømforsynings-anlegg. Med energiøkonomisk togfremføring menes kjøring med hurtig akselerasjon, med tilhørende høyt effektuttak under akselerasjon. Det gjennomføres også en mulighetsstudie som omhandler bruk av batterier i den norske banestrømforsyningen. Målet med bruk av batteri er i hovedsak håndtering av topplast, slik at omformerstasjoner kan dimensjoneres med mindre ytelse.

Det er her gjennomført en casestudie, der trafikken på Jærbanen er simulert ved bruk av programmet µPas. Trafikken er simulert med og uten seksjonering (øy-modus), samt med og uten pådragsbegrensninger på togene for begge tilfeller. Når togene er ilagt pådragsbegrensning kan togene kun kan trekke inntil 2/3 av nominell effekt. Videre er samtlige simuleringer re-simulert etter at rutetabellen er modifisert. Det innebærer at tidspunktet der de høyeste effekttoppene oppstår er avdekket, og justeringer i rutetabellen er gjennomført slik at samtidig akselerasjon er unngått. Samtlige avganger på det tidspunktet er forskjøvet med 10 sekunder hver, slik at samtidig akselerasjon unngås.

Resultatene viser at for case 1 (base case) reduseres effekttoppene til Kjelland og Stavanger med henholdsvis 21.78 % og 23.03 % etter at rutetabellen modifiseres. For case 2 (pådragsbegrensing) reduseres effekttoppene tilnærmet 1/3, og modifseringen gir reduksjon i effekttoppene med 22.01 % og 13.54 % for Kjelland og Stavanger. Videre reduseres energibruken for alle togene over ett døgn med 1.66 MWh, og kjøretiden økes med 6.48 minutter. Case 3 (seksjonering) gir enda høyere effekttopper, og tilsvarende høyere reduksjon etter modifisering. Case 4 (seksjonering og pådragsbegrensning) gir redusert energibruk på 1.81 MWh og økt akkumulert kjøretid for alle tog med 8.82 minutter. De største effekttoppene skapes av at 5-6 tog akselererer samtidig, noe som finner sted klokken 07.59, 16.58 og 18.59.

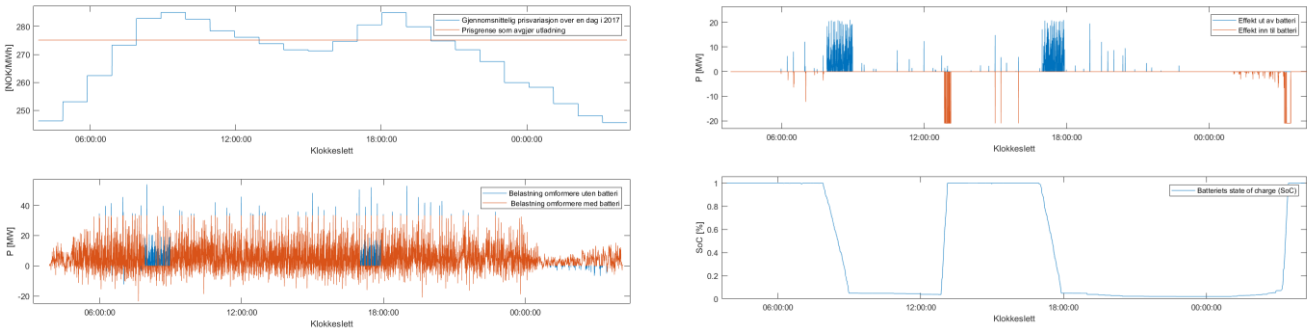


Figur 1 – Belastnings – og varighetskurve for Kjelland omformerstasjon over ett døgn, før og etter mod (Case 1

Videre er det gjennomført en økonomisk analyse der tre ulike dimensjoneringsalternativer for Kjelland omformerstasjon vurderes. I analysen er kostnaden knyttet til investering, energiforbruk og tap medtatt. Resultatet er som følger:

- Alternativ 1 - 2 x 35 MVA - 526.50 MNOK
- Alternativ 2 - 2 x 25 MVA - 490.60 MNOK
- Alternativ 3 - 2 x 45 MVA – 557.38 MNOK

I denne rapporten er det også gjennomført en mulighetsstudie som omhandler bruk av batterier i den norske banestrømforsyningen. Målet er at batterier brukes til håndtering av toppbelastning (effekttopper), slik at omformerstasjonene kan dimensjoneres med lavere ytelse. Det er her gjennomført simuleringer i Matlab, der lasten er konstant og hentet fra case 1 fra simulering i µPas. Her simuleres fire ulike alternativer som ansees teknisk likestilt. Samtlige alternativer sammenlignes med nullalternativet, som er å investere i en 2 x 35 MVA omformer. Figur 2 viser sammenhengen mellom strømpris, belastning omformerstasjon, belastning batteri og batteriets state of charge.



Figur 2 – Strømpris, belastning omformerstasjon før og etter batteri samt batteriets belastning og state of charge.

Tabell 1 viser resultatet fra den økonomiske analysen. Alternativ 1 innebærer å utsette investeringen av ny omformerstasjon med 20 år ved å kjøpe batteripakke i år 0 av analyseperioden. Ved en nedgang på 13 % av batteriprisen vil detet alternativet være like lønnsomt som å investere i en ny, 2 x 35 MVA omformerstasjon. Riktignok er det her medtatt kostnader knyttet til vekselretter og transformator. Da omformerstasjonene i dag har et mellomledd er det mulig å koble batteripakken på det, via en DC/DC omformer. Den vil være billigere enn vekselretter. Det vil også være mulig å koble batteriene slik at ønsket spenning oppnås, og transformator unngås. Det vil gjøre bruk av batteri mer økonomisk fordelaktig, men per i dag er prisen på batterier for høy til at det skal være lønnsomt.

		Omformerstasjon Kjelland	Batteri		
Alternativ	Batteri	S [MVA]	P [MW]	E [MWh]	Netto nåverdi [MNOK]
1	Toshiba	2 x 7	21	5.25	-5.14
2	Toshiba	2 x 15	14	3.5	-49.10
3	Tesla	2 x 20	9	18	-73.85
4	Tesla	2 x 25	4.5	9	-41.17

Isolated Full-Bridge DC-DC Converter Configurations for Photovoltaic Applications using Modular Multilevel Converter

Student: **Guro Watten Furu**
Supervisor: **Lars Einar Norum**

Abstract
Traditionally, photovoltaic (PV) systems have used two- or three-level converters in conjunction with a step-up transformer in the connection to the grid. The transformer provides isolation at the point of common coupling to protect the PV system from the grid, however, this necessarily increases the total cost of the plant.

Recently, the Modular Multilevel Converter (MMC) inverter got introduced as an attractive topology for PV plants due to a high scalability that facilitates a direct connection to medium voltage grid without the use of a step-up transformer. The required voltage level is achieved by designing the MMC with the correct number of submodules. It also provides high MPPT tracking, which gives the MMC several advantages over conventional PV inverters. The isolation in such a configuration can be provided between the PV strings and the submodules of the MMC by utilizing isolated DC-DC converters.

In this study, different isolated full-bridge DC-DC converter configurations with high efficiency rate are presented. The single-unit configuration provides a simple structure, but requires high voltage and current ratings on equipment due to the high power transfer. By utilizing a parallel- or series-connection of converters, the bulk transmission of power to the submodules is distributed, which increases the overall reliability of the system. If the PV string operating voltage is not equal to the submodule capacitor voltage, then a step-up in voltage is necessary. However, the PV strings are in this study designed such that the HF transformer turns ratio is 1:1 in all configurations.

The parallel-arrangement avoids the parallel-connection of switching devices in the DC-DC converter in order to handle the high currents. In case of the series-arrangement, the voltage stress on the switching device is reduced considerably. Due to the reduced voltage, an utilization of GaN devices is possible, resulting in a higher switching frequency range of operation. Simulations are performed in order to find the efficiency of the different isolated DC-DC converter configurations.

Furthermore, the obtained efficiency curves are utilized in a simulation model in order to find the overall energy efficiency and the levelized cost of energy (LCOE) of the MMC PV plant configurations. These configurations are also compared to a central inverter (CI) PV configuration and a multi-string central inverter (MSCI) PV configuration in order to state the benefits of utilizing the MMC as inverter in medium voltage PV plants.

The simulations verifies the improved energy efficiency and the lowered LCOE when utilizing MMC over the CI and the MSCI configurations in medium voltage PV plant applications. They also presents the high efficiency of the isolated DC-DC converter configurations. When utilizing the GaN HEMTs in the series-arrangement, high efficiency is obtained at high-switching frequency. However, these simulations and calculations do not address losses in the HF transformer.

A signal analysis toolbox for power system identification in Smart Grids

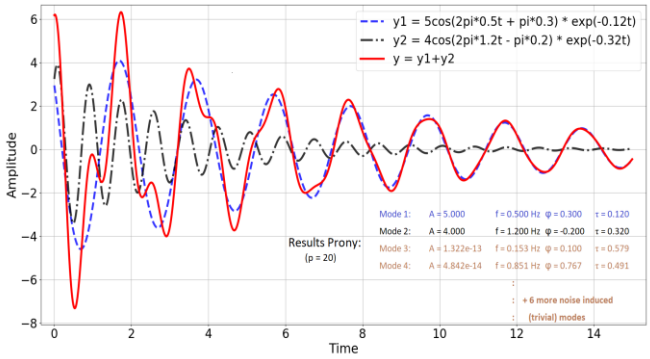
Student: **Mads-Emil B. Kvammen & Sjur Føyen**
Supervisor: **Olav Bjarte Fosso**
Contact: **Jalal Khodaparast**

Motivation

Dynamic stability is a major concern for power system operators, and may prove to be increasingly challenging with less inertia and more power electronic converters in the Smart Grid. If this issue is neglected, the risk of large area blackouts increases.
However, operators today are good at keeping the system well within the stability limits. The challenge is mainly to keep investment costs as low as possible, by operating the system close to the limits while still maintaining stability. Increased awareness and real-time monitoring of system damping will aid in pushing this limit and move towards a Smarter Grid.

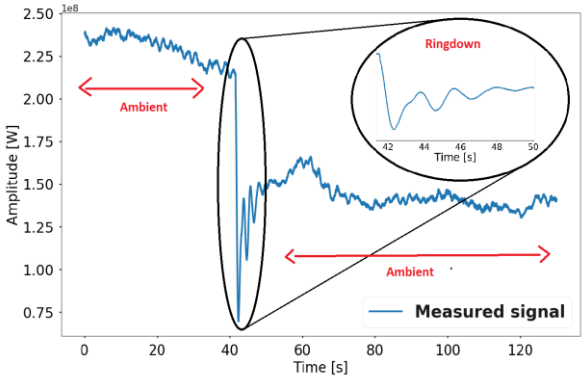
Objective

Small-signal stability has for a long time been assessed by component-based models, i.e. classical eigenvalue analysis of a linearized power system. Prony's method attempts to evaluate the same small-signal stability, by fitting postdisturbance (ringdown) measurements to a sum of damped sinusoids.



Correct estimation of the modal content of a multi-modal sine wave is a trivial matter, as long as the signal does not exhibit non-linear, non-stationary and/or noisy features. However, power system measurements are often just that. The task is to obtain the linear characteristics in a somewhat distorted signal.

Additionally, "ambient" data can be used for evaluating the small-signal stability of the power system. In normal operating state, currents, voltages and power flows (amongst others) vary as a consequence of millions of customers turning their electric equipment ON and OFF. Aggregated, this is assumed to behave like continuous small-amplitude, random disturbances. The system response to these variations are described as ambient data and contains distorted information of the system's oscillatory behavior.
The focus of this thesis is to estimate the modal content in both ambient and ringdown data.



Method used:

Prony's method, Robust Recursive Least Squares (RRLS), Empirical Mode Decomposition (EMD), Clustering, Welch's method.

Conclusion:

- The applied methods establish a signal analysis toolbox for power system identification in Smart Grids. Appropriate combination of the tools enables analysis of a variety of power system measurements.
- A comprehensive study of several techniques is presented in this thesis. Although their application is narrowed down to power system identification, most of the shown characteristics also hold true in the general field of signal analysis.
- EMD is successfully implemented and evaluated as a band-pass filter.
- Clustering automatically and accurately identify true, dominant modes in a signal for both Prony and RRLS.

Synthetic Inertia from a Converter-Fed Synchronous Machine in a Hydro-Electric Power Plant

Student: **Mathias Gallefoss**
Supervisor: **Trond Toftevaag**
Collaboration with: **HydroCen**

Problem Description

Increasing integration of variable renewable energy sources in the electric power system raises the demand for balancing technologies to compensate for fluctuations in production. Of all the balancing technologies available, pumped-storage hydroelectricity is by far the most mature technology. In recent years, the interest for adjustable speed drives has increased due to the ability to adjust power consumption in pumping mode. However, decoupling generators from the grid using power electronic converters reduces the total inertia of the power system. In grids with high penetration of power electronic controlled production, this can reduce the overall system stability.

Model

The thesis focus on deriving and analyzing control methods which emulate inertia for a convert-fed synchronous machine in a hydro-electric power plant. Two separate methods are derived; classical torque control with supplementary inertia controllers and virtual synchronous machine control which emulates the dynamic operation of a synchronous machine. These methods are tested and compared in a system consisting of a converter-fed hydro-electric machine connected to a simplified power grid using simulation software.

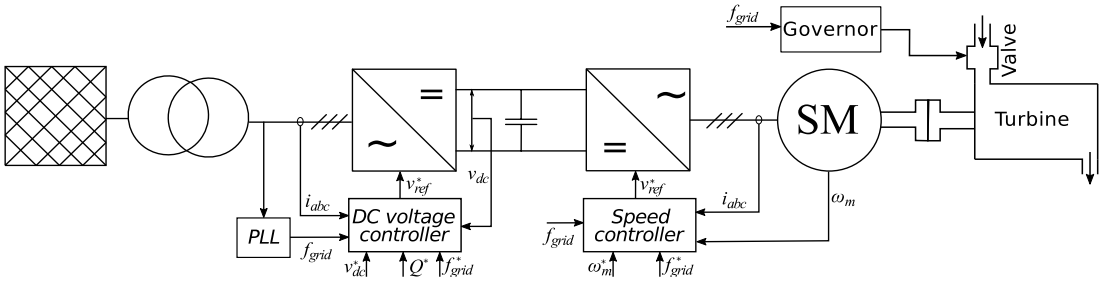


Figure 1: Classical torque control with supplementary inertia controllers

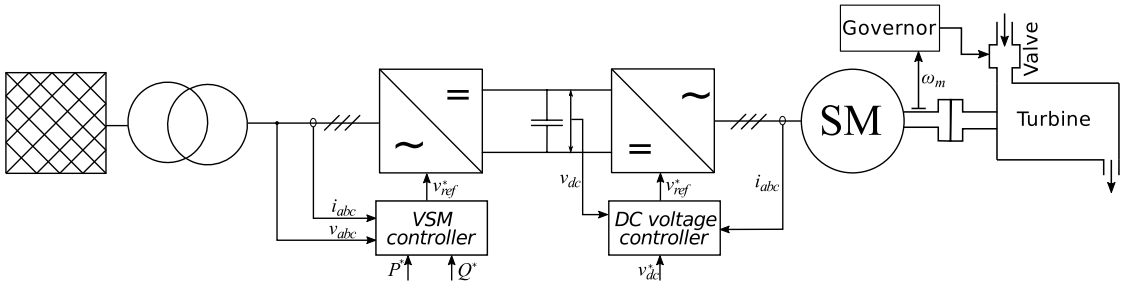
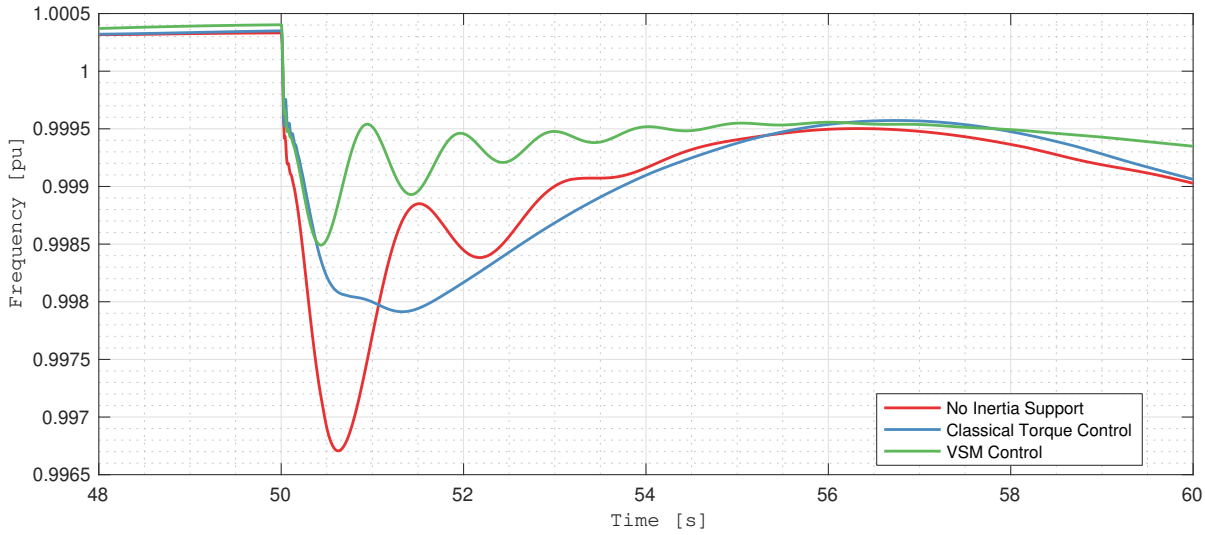


Figure 2: Virtual synchronous machine control

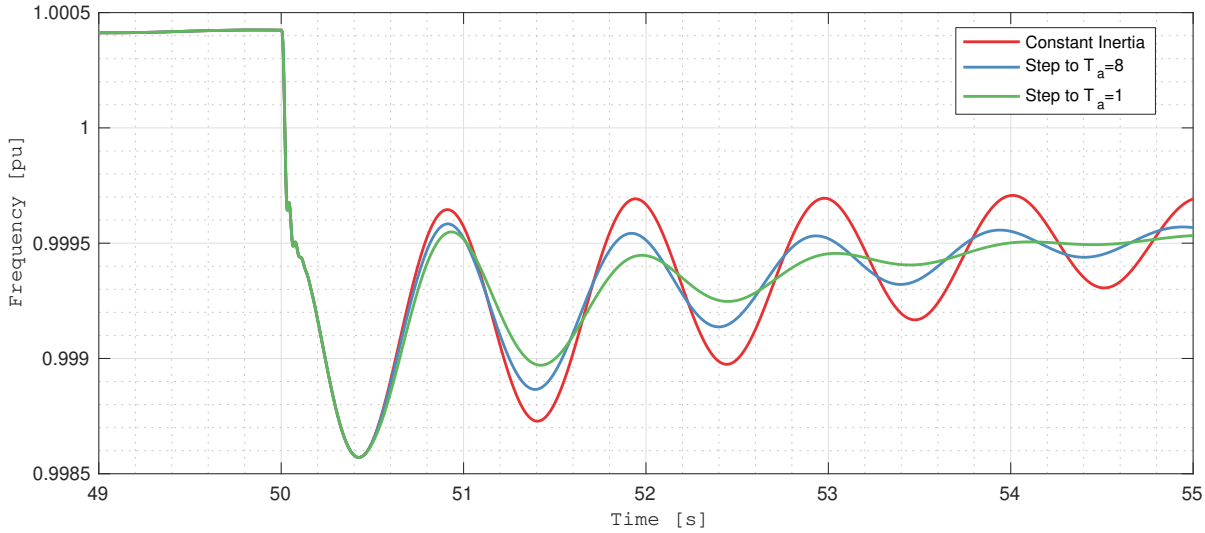
Case 1: Comparison of Control Methods

The figure below shows the initial frequency during a disturbance for the two different control methods described above.



Case 2: Dynamic Inertia from a VSM

Using the VSM control method, it is possible to control the inertia time constant during operation, as shown in the figure. Doing this, better performance is achieved as the inertia is set high during steady-state to improve frequency stability and reduced after the load event to achieve improved small-signal stability.



Conclusion

It is shown that both methods performed as intended, emulating the effect of inertia during a power imbalance event. The classical torque control and VSM control improve the frequency nadir by 36.4% and 54.5% respectively based on the steady-state frequency for a given test case. The VSM method is found superior in the context of inertia support due to fast power control. Also, the VSM inherits a number of other advantages such as the possibility for dynamic inertia support. Dynamic inertia support allows the VSM to change the amount of synthetic inertia in the grid during operation, which can improve small-signal stability.

Integrasjon av sol i det norske kraftsystemet

Student: **Signe Eika Gjørven**
Faglærer: **N/A**
Veileder: **Magnus Korpås**

Problemstilling

Distribuerte energiløsninger, herunder særlig sol, blir mer og mer populære, også i Norge. En av de kjerneegenskaper av fremtidens smarte nett er å kunne ta imot elektrisitet fra distribuerte energikilder uten store forstyrrelser i nettdriften ellers. Dette krever en del tiltak i det eksisterende nett, blant annet for å sikre spenningskvaliteten til enhver tid og funksjonaliteten av vern.

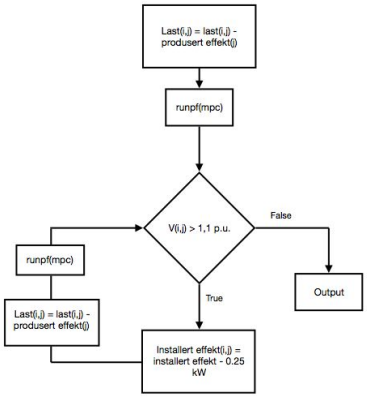
Oppgaven

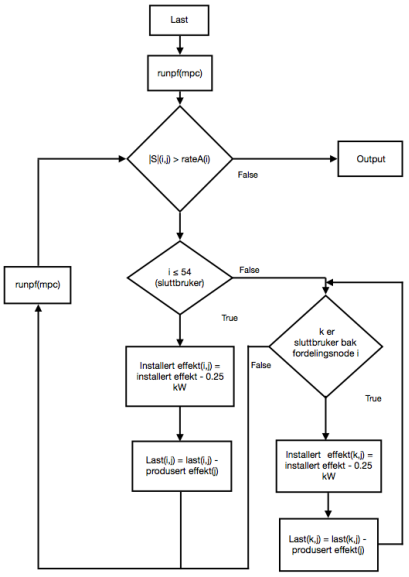
Ved å utføre lastflytanalyse i simuleringsverktøyet MATPOWER har spenninger og effektflyt i et lavspent distribusjonsnett blitt undersøkt. Nettet som er testet er en del av NTE sitt nett i Trøndelag, med måledata for hver time i 2012. Det har blitt undersøkt hvordan nettet påvirkes når det installeres solcelleanlegg med ulike størrelser, jevnt fordelt utover nettet. Produksjonen fra solcellene hver time i 2012 har blitt bergenet i MATLAB.

Ved å innføre en effektbegrensning fra solcelleanleggene de timene det oppstår for høye spenninger eller for høy effektflyt, kan en større solcellekapasitet installeres. I effektbegrensningen har først effekten blitt redusert slik at ingen noder i nettet får for høye spenninger. Deretter har effekten blitt ytteligere redusert for å unngå overbelastninger i overføringslinjer og kabler. Det har også blitt sett på hvordan tapene i nettet påvirkes av integrasjon av solceller, og hvordan LCOE for solcelleanleggene påvirkes av effektreduksjonen.

Modell

Flytskjemaer for hvordan effektreduksjon fra solcellene har blitt utført i MATLAB:





Konklusjon
Nettet som har blitt undersøkt er et sterk nett. Ingen spenninger overskrider 1,1 p.u. før 15 kWp installert effekt hos hver sluttbrukernode. Da er det kun to av de 54 sluttbrukernodene som opplever for høy spenning. En fordelingslinje får for høy lastflyt ved 12,5 kWp solceller installert hos hver sluttbruker. Nettet tåler høy grad av installert solcellekapasitet. Overbelastning i linjer og kabler oppstår ved lavere installert effekt og skjer i flere flere ganger i løpet av året, enn for for høye spenninger. Mer effekt begrenses på grunn av for høy effektflyt enn på grunn av for høye spenninger.

Effektbegrensning tillater at mer solceller kan installeres i nettet med tanke på spenninger og effektflyt. Men høy installert effekt gjør at tapene i nettet øker. Først vil tapene synke til minimumsverdien ved 270 kWp installert effekt i nettet, før tapene begynner å stige med økt installert effekt. Ved 1620 kWp installerte solceller totalt, er tapene dobbelt så høye som de er på det laveste. Minimumsverdien for tapene er 1,28 \% av det totale forbruket i nettet, sammenliknet med 1,41 \% når det ikke er installert solceller.

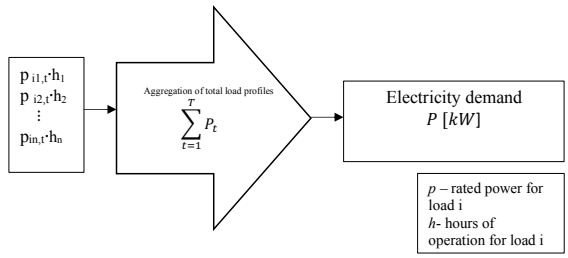
LCOE øker når produsert effekt fra solcelleanleggene må reduseres. Når det antas at systemkostnaden på solcelleanleggene synker med økt installert effekt, har LCOE et minimum på 1,5641 kr/kWh ved 675 kWp installert effekt. Tapene i overføringslinjene er ikke tatt med i beregningen av LCOE. LCOE vil øke når tapene øker.

Metoden virker, men mer effekt enn nødvendig blir redusert ved effektflytbegrensning fordi effekten reduseres hos alle sluttbrukere bak aktuell overføringsgren.

Model for Load Analysis at Granåsen

Student: **Maren Haugland Hansen**
Supervisor: **Eivind Solvang**
Contact: **N/A**
Collaboration with: **SIAT**

Problem description
During the next years, Granåsen is facing a comprehensive expansion, which will lead to increased energy and power demand. The purpose of this thesis is to ensure Granåsen to be a sustainable facility, with respect to eventual energy self-sufficiency. This work includes analysis of current load profiles, load modelling and assessment of solar cells.



A bottom up approach to load modelling is used in order to construct load prognoses, involving both engineering and statistical methods. Retrieval of data is therefore emphasized. The system boundaries have been chosen to encompass four central loads of a Granåsen: Lights, snow production, elevator and buildings.
The energy consumption prognoses for the buildings are based on reference data from buildings in Norway with similar functions. A constructed scenario where events, weather, and temperatures are the determining variables, provides an annual energy consumption which corresponds to approximately the double of the current consumption.

PV production potential is found to be 652790 kWh/year when all future available roof is utilized for PV modules. That furthermore corresponds to a 750. 8kW plant. A 30 °tilt provides the highest annual output, while a 90°tilt leads to a higher yield during the winter. PV can, with respect to a 30 ° tilt, contribute to decrease the forecasted load profiles by 35%. With no energy storage, however, 69,442 kWh excess energy would go to waste during the summer months. PV can also, with no energy storage implemented, to a small extent remove power peaks.

Energy storage together with PV can be very relevant to implement in a sports facility as Granåsen, especially to function as a peak shaving unit.
A battery with capacity 720 kWh suggested for this purpose can work as a peak shaving unit for 250 kW for two hours. However, just below 100 batteries are required in order to store all the excess energy for the installed PV and given load scenario. Mobile Energy storage, which works as peak shaving units other places on a daily basis but collected at Granåsen for special events could be a relevant execution model to get a smoother load profile during the year.

Anvendelse av elektriske maskiner for økt kortslutningsytelse og redusert utløsningstid av vern i lavspent fordelingsnett

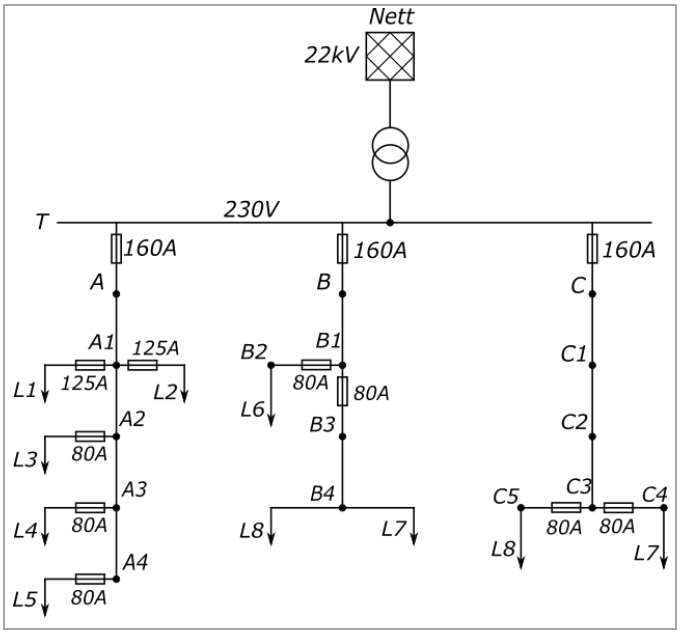
Student: **Martin Hantveit**
Faglærer: **Trond Toftevaag**
Veileder: **Trond Toftevaag**

Oppgaven

I svake nett er det et problem at det er for lav kortslutningsstrøm ved feil langt ute i nettet. I denne oppgaven skal det bli foretatt en vurdering på om det kan være gunstig å legge inn elektriske maskiner som kjører uten last, nær de problematiske områdene. Ved kortslutning vil maskinene være med på å øke kortslutningsstrømmen og dermed redusere utløsningstiden til vern.

Modell/målinger

Det er foretatt simuleringer som er basert på et virkelig nett. Figuren under viser nettet lik det er bygget opp, med valgte sikringsstørrelser.



Beregninger

Tabellen under gir et eksempel på resultater fra simuleringene. I eksempelet er det én maskin tilkoblet hver av radialene med unntak av forsøket uten maskin («Ingen»), med maskin tilkoblet nær trafo («AS1 trafo») og maskin kun tilkoblet B1 («AS1 i B1»). Tabellen viser kortslutningsstrøm og utløsningstid for lokalt vern ved topolet kortslutning i lastpunktet med lavest kortslutningsytelse, L6. Eksempelet gir et inntrykk av hvilke forbedringer som oppnås ved bruk av de forskjellige maskinløsningene.

	I_{lokal} (tran) [A]	Tid [s]	Endring tid [s]	Redusert tid [%]
Ingen	263,0	10,046	-	-
AS1 trafo	262,2	10,234	-0,188	-1,9
AS1 i B1	332,7	5,742	4,304	42,8
AS1 i alle	333,5	5,926	4,120	41,0
AS2 i alle	408,3	4,379	5,667	56,4
SM1	373,6	4,734	5,312	52,9
SM1 EXAC4	373,8	4,494	5,552	55,3
SM1 AC8B	373,8	4,410	5,636	56,1
SM2	484,0	3,232	6,814	67,8

Kortslutningsbidraget fra både synkronmaskinen og fra asynkronmaskinen har vist seg å kunne være av stor betydning for utløsningstiden til vern dersom maskinen er plassert nær lastpunktene. Dersom maskinen er tilkoblet nettet for langt unna lastpunktene, kan det oppstå for lavt spenningsfall på motorklemmene til at den gir bidrag. En elektrisk maskin kan føre til betydelig reduksjon av utløsningstid så lenge feilen skjer i et lastpunkt på samme radial som maskinen er koblet til. I de fleste tilfeller vil en maskin føre til høyere strøm gjennom sikringen nærmest feilen, enn gjennom sikringen for radialen. Tilkobling av maskiner har derfor ikke ført til problemer med selektiviteten i nettet. Avhengig av maskinens størrelse kan den bidra til en betydelig reduksjon av utløsningstid. Økt ytelse på synkronmaskinen kan tyde på å føre til raskere utløsning av vern, men dette er avhengig av hvilket lastpunkt feilen oppstår i. I noen tilfeller kan en økt maskinytelse føre til at maskinen gir dårligere utløsningstid enn uten maskin tilkoblet, men dette er bare testet for synkronmaskin.

Topolet feil fører til ubalanse i nettet og sammen med maskiner kan det føre til at det går forskjellig strøm gjennom hver fase i sikringen. Dette kan føre til at bare én fase løses ut i sikringen. Simuleringene tyder på at maskinene da, uavhengig av maskintype, leverer bidrag til feilen selv etter at én fase er koblet ut i radialens vern. Sikringene i nettet bør derfor koble ut begge de resterende fasene dersom én fase løses ut.

Konklusjon

Når lav kortslutningsytelse fører til at utløsningstiden for vern er for lav, vil bruk av elektriske maskiner kunne være en gunstig løsning for reduksjon av utløsningstid. Ved bruk av både asynkronmaskiner og synkronmaskiner kan det oppnås en betydelig reduksjon av utløsningstid. Valg av maskinløsning er avhengig av kostnad og netteiers behov og ønsker.

Tackling Variability in Renewable Energy Production and Electric Vehicle Consumption with Stochastic Optimization

Student:	**Sondre Flinstad Harbo**
Supervisor:	**Magnus Korpås, IEL**
Co-supervisors:	**Alexei Gaivoronski, IØT**
	Zechun Hu, Tsinghua University

Summary

The work presented in thesis investigates different applications for implementing the Stochastic-Quasi Gradient (SQG) model to solve stochastic multistage AC-OPF problems, and com-pares it with a Stochastic-Dynamic Programming (SDP) approach and an Evolutionary algorithm.

Where the SDP quickly becomes too cumbersome to solve, the thesis also shows the other two as more appropriate tools, where the SQG method works better in larger cases, the Evolutionary algorithm in smaller.

Hence, to analyze how energy storage may optimally be used for incorporating variable renewable energy sources to bigger grid networks, the SQG method may be of academic and practical interest.

Evaluation of Power Losses and Ruggedness of SiC MOSFETs for use in High-Power High-Frequency Induction Heating Generators

Student:	**Knut Haukelidsæter**
Supervisor:	**Roy Nilsen, IEL**
Co-supervisors:	**Subhadra Tiwari, IEL**
	Tore M. Undeland, IEL
Contact:	**John K. Langelid, EFD Induction AS**
Collaboration with:	**EFD Induction AS**

Abstract

As the Si IGBTs are confronting its physical limitations when it comes to high-frequency high-power ap-plications, the SiC MOSFET sails up as a promising substitute due to its material properties. However, in the process of developing next generation induction heating generators based on SiC technology, power loss and reliability considerations should be evaluated thoroughly .

Soft-switching is mandatory to keep losses low in high-frequency high-power applications. In this thesis the power losses and reliability of a 1.2 kV FCA120A50 DioMOS half-bridge device from SanRex Panasonic for use in induction heating generators are evaluated. The power losses are measured with both an elec-trical and calorimetric approach. Where the electrical loss measurements results in an overestimation of 28.28 % to 34.50 % of total power losses, in relation to the measured calorimetric losses.
Further, measurements of the on-state resistance as function of current and as function of temperature are carried out, where a moderate increase in on-state resistance are observed in both cases. Further-more, by increasing the gate-source voltage the on-state resistance are reduced, and hence the conduc-tion losses. By increasing the gate-source voltage from 19.1 V to 21.23 V at 128 kW 247 kHz the total losses are reduced by 8.95%, obtaining an inverter efficiency of 99.4 %.
As a consequence of increased gate-source voltage, the risk of very high short-circuit currents is severe. An increase from 648 A to 1134 A of the short-circuit current are measured when increasing the gate source-voltage from 19 V to 21 V. However, the device limits the short-circuit current and turns off safely after 1.34 µs. Moreover, when operated out of soft-switching conditions a moderate increase of 12.12% in total losses is observed. Thus, the 1.2 kV FCA120A50 DioMOS half-bridge device from SanRex Panasonic proves to be extremely efficient and robust for industrial induction heating applications.

Analysis of frequency stability:
How wind power and HVDC connections affect the future power system

Student: **Håkon Hellebust**
Supervisor: **Kjetil Uhlen**

Problem description

The main objective of this master thesis is to study how increased HVDC capacity and wind power generation affects the frequency stability of the power system in the future. The thesis also aims to investigate how the new technologies can be used to contribute to system inertia, and how this may affect the dynamic frequency response. In addition to frequency responses, power flows and system voltages will be briefly examined to detect possible critical implications.

The primary emphasis has been on the Nordic system which was the base for the simulation model.

Approach

Simulations were conducted in DIgSILENT PowerFactory to examine the contribution from HVDC and wind power both without measures to improve the frequency response and with additional controllers providing synthetic inertia. A set of frequency response indicators were introduced to facilitate examination of the frequency responses to disturbances. The major parts of the simulations were conducted in an existing Nordic simulation model called N44. Simulations have also been conducted in a smaller and more transparent model.

Four main scenarios have been investigated: Situations with very high and low inertia in the present system (2017) and the future (2030). Five disconnection events and one short-circuiting have been studied for all the scenarios. The events along with the scenarios have been extremes, meaning that they are representing the grid under extraordinary conditions. For the future scenarios, additional controllers have in turn been enabled for wind power production and HVDC connectors to explore their possible contribution the frequency support.

Conclusion

The expected increase in wind power capacity and HVDC connections do reduce levels of inertia during scenarios where the consumption is low. This deteriorates the system frequency stability significantly. The main reason seems to be the new technologies replacing the conventional production that inherently provide inertia to the system. During high load operational hours, both levels of inertia and system stability stay at approximately the same levels.

As the frequency response was deteriorated considerably, measures to enhance system stability should be considered. Simulations conducted where suitable controllers were implemented to HVDC connection and wind turbines indicated that their provision of

synthetic inertia could improve the frequency response significantly. However, this must be investigated and tested further.

Significant voltage dips and power flow changes (both with large oscillations) were detected. Some voltages were dipping more than 10% of nominal value. However, the oscillations died quickly, and the system remained stable for all disturbances in all scenarios.

Spenningsregulering i regionalnett med stort innslag av vindkraft

Student: **Per-Olav Henriksen**
Faglærer: **Hans Kristian Høidalen**
Veileder: **Hans Kristian Høidalen og Hilde Stangeland**
Utføres i samarbeid med: **TrønderEnergi Nett**

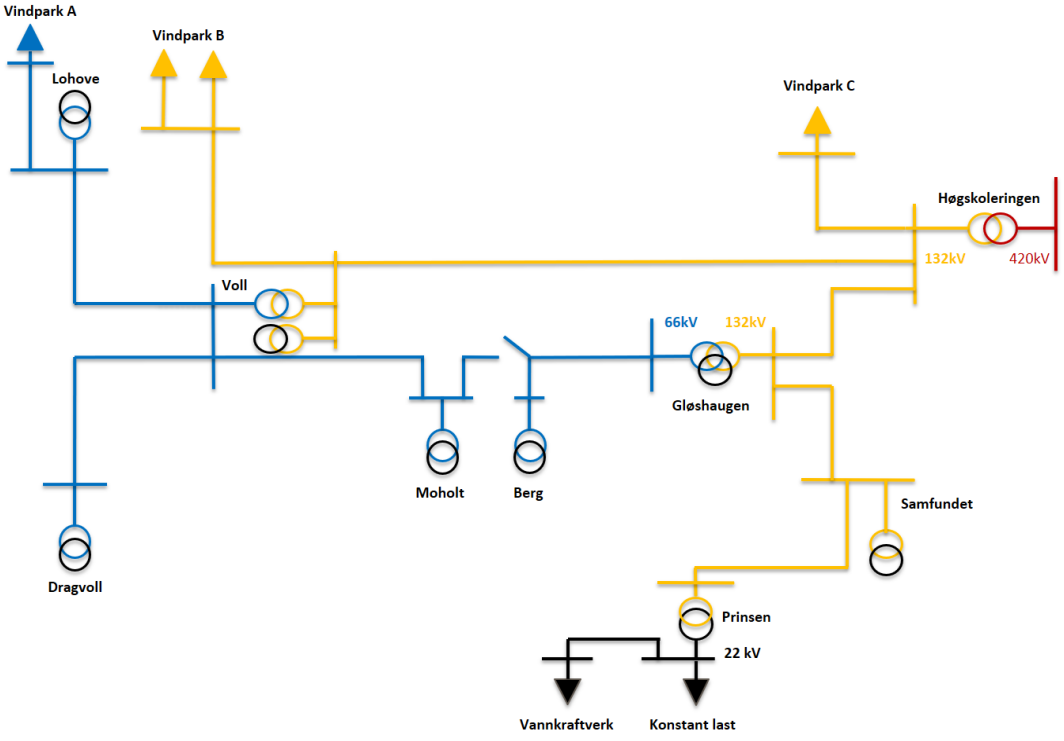
Problemstilling

I dag er det ett vindkraftverk i området som har vært i drift siden 2004. Frem til 2020 vil det komme tre nye vindkraftverk i området og deler av regionalnettet blir oppgradert fra 66 til 132 kV. Netteier kan møte ulike utfordringer ved tilknytning av de nye vindkraftverkene. Vindkraftverkene kan ha innvirkning på spenningskvalitet og stabilitet i området.

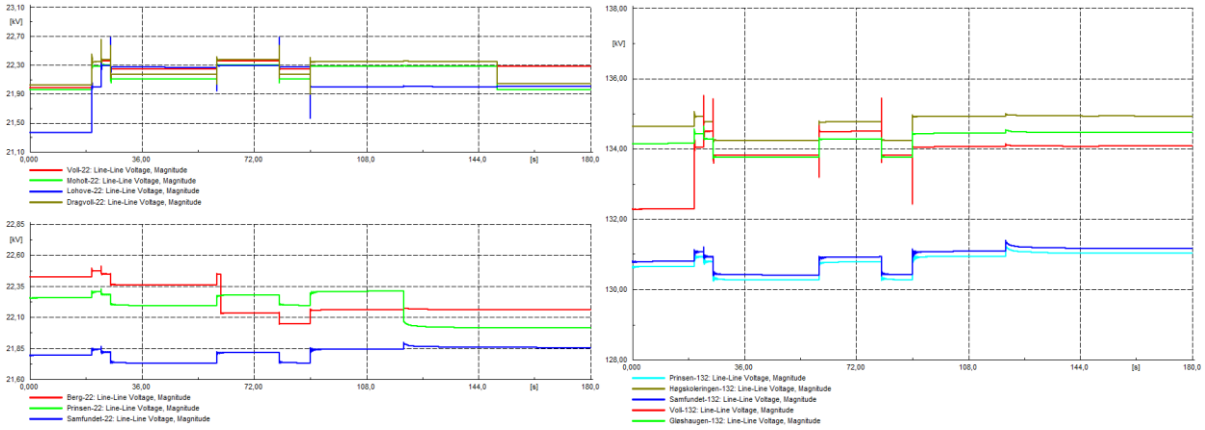
Nettekvivalenten skal modelleres i DIgSILENT PowerFactory for dynamiske analyser av spenningsvariasjon ved varierende vindkraft og belastning. Det er av interesse å avdekke om vindkraftverkene vil regulere mot hverandre eller mot trinnkoblere i regionalnettet. Virkninger av store last- og produksjonsendringer skal analyseres, samt begrensninger for produksjon når 132 kV forsyningslinjen er ute og området forsynes via en svakere 66 kV forsyningslinje.

Modell

Det er laget en modell i PowerFactory ut fra det enkle enlinjeskjemaet nedenfor. Det blir utført lastflytanalyser og dynamiske analyser ved forskjellige scenarioer som f.eks. utfall av vindkraftverker, variert produksjon i vindkraftverkene, utfall av laster og variasjon i lastene. Det er gjort analyser av to forskjellige oppbygginger av systemet. Den ene oppbyggingen er slik figuren under viser, og en hvor 132 kV linjen mellom Høgskoleringen og Voll er ute av drift og 66 kV linjen mellom Moholt og Berg er koblet inn.



Beregninger
Nedenfor vises spenningene på 132 og 22 kV samleskinnene i nettet ved variert produksjon i vindkraftverkene med 132 kV linjen inne.



Gjennom de forskjellige lastflytanalysene er det undersøkt hvordan en variasjon i settpunktsspenningen i Høgskoleringen og Voll vil variere den reaktive utvekslingen med transmisjonsnettet. I tabellen under vises resultatene av lastflytanalysene.

Settpunkt i Høg.ringen [kV]	Settpunkt i Voll [kV]	Produksjon i vindpark A [MVAr]	Produksjon i vindpark B [MVAr]	Produksjon i vindpark C [MVAr]	Uttak fra Statnett [MVAr]
132	**132**	0	-3,6	-4,8	63,9
136	**132**	-0,4	-7,8	54,6	6,8
132	**136**	-0,8	18,9	-9,3	45,9
136	**136**	-1,2	14,6	50,2	-11,4

Konklusjon
En forandring av settpunktspenningen i Høgskoleringen til 136 kV gjennom hele året vil bli mest gunstig med tanke på reaktiv effektutveksling med transmisjonsnettet. En variasjon mellom 132 kV og 136 kV i Voll er ønskelig for å holde utvekslingen av reaktiv effekt under grensene gitt i Sentralnettstariffen. Under vinterperioder bør Voll ha 136 kV som settpunkt og i sommerperioder bør den være 132 kV.

Tilknytningen av tre nye vindkraftverk vil ha en innvirkning på spenningen i området, men ikke nok til å gi store utslag i spenningskvaliteten på 22 kV. Q-droop innstilling på 4\% i alle vindkraftverkene vil gi de beste resultatene for spenningsvariasjon. En strengere Q-droop vil gi mindre variasjon av spenning, men det må undersøkes hvor lavt vindkraftverkene kan stille inn regulatorene. En innstilling av dødbåndsområdet på 1,6*trinnstørrelsen vil gi få trinninger på 22 kV samleskinnene i nettet under variert produksjon og ved utfall av vindkraftverk og laster. Høyeste spenningsvariasjon på 22 kV samleskinnene er ved utfall av vindpark A da spenningen på 22 kV i Lohove vil synke med nesten 1 kV. Høyeste spenningsendring etter dette er ved et utfall av Lohove når det er ingen produksjon. Da vil spenningen i Dragvoll og Moholt øke med rundt 0,8 kV.

Modell for nøyaktig posisjonering av kraftledningsfeil

Student: **Malin Helen Hestø**
Faglærer: **Gerd Kjølle**
Veileder: **Christian Sundal Melaaen**
Utføres i samarbeid med: **Statnett**

Sammendrag

I denne masteroppgaven har det blitt utarbeidet en foreslått modell for beregning av feilposisjon. Denne modellen ble utarbeidet gjennom funn fra prosjektoppgave skrevet av samme forfatter. Ved bruk av verktøy og data fra Statnett har 42 historiske feilhendelser fordelt på 9 kraftledninger med bekreftet feilsted blitt analysert. Det har blitt beregnet feilposisjon med samme algoritme Modifisert Takagi, for alle feil med ulike kilder til impedans. I denne oppgaven er det kun sett på feil i 300 kV og 420 kV nett i Statnetts anlegg, og det er kun feiltypen fase-jord som er undersøkt. Ved hjelp av beregningsalgoritme i AutoDig har avstand til feil beregninger blitt gjennomført og forbedret i foreslått modell.

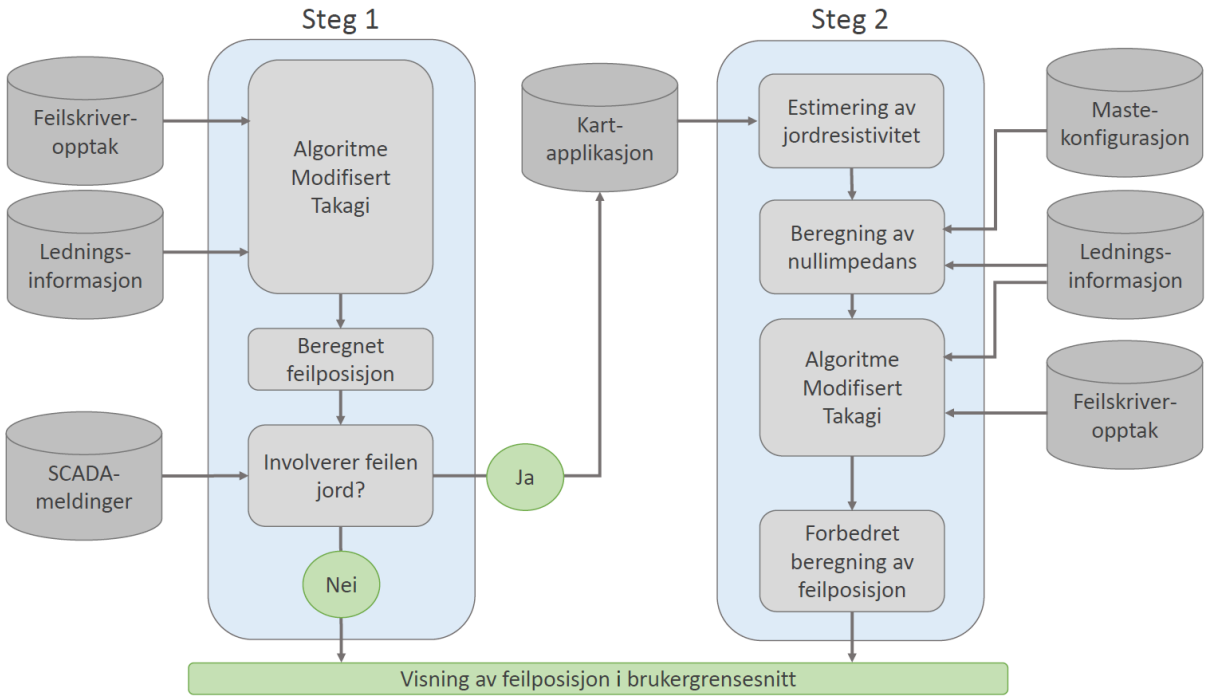
Det har blitt beregnet feilposisjon med tre forskjellige kilder til nullimpedans, og to forskjellige kilder til ledningsimpedans. I foreslått modell beregnes nullimpedans med en mer tilpasset verdi av jordresistivitet, sammenlignet med en konstant verdi på 100 ohm*m som SINTEF Planbok benytter i beregning av nullimpedans. Ledningsimpedans i foreslått modell er målt eller beregnet. Ved bruk av foreslått modell med individuell tilpasning av jordresitivitet til beregning av feilposisjon for de 42 feilhendelsene, blir gjennomsnittlig avvik 0,70 km og 1,17 %. Når en konstant verdi for jordresitivitet benyttes alle luftledninger i foreslått modell, blir gjennomsnittlig avvik høyere sammenlignet med individuell tilpasning av jordresitivitet.

Ved bruk av nullimpedans og ledningsimpedans basert på data fra SINTEF Planbok blir gjennomsnittlig avvik for alle feilhendelser lik 3,73 km og 4,43 %. Sammenlignet med foreslått modell, vil altså bruk av impedans fra SINTEF Planbok gi et vesentlig større gjennomsnittlig avvik. Tilsvarende blir gjennomsnittlig avvik av beregnet feilposisjon for alle feilhendelser lik 2,0 km og 2,4 % med målt og beregnet nullimpedans og ledningsimpedans. Målt impedans benyttes der de er tilgjengelige, ellers er beregnet impedans fra SINTEF Planbok brukt. Det er en halvering i avvik ved bruk av målt og beregnet impedanser sammenlignet med beregnet fra SINTEF Planbok. Tilsvarende vil en halvering skje med gjennomsnittlig avvik når foreslått modell sammenlignes med bruk av målt og beregnet impedans. Foreslått modell vil derfor gi avstand til feil beregninger med lavest gjennomsnittlig avvik.

I foreslått modell gjøres det en individuell vurdering av jordresistivitet for hver enkelt luftledning. Jordresistivteten blir bestemt etter hva slags beregnet nullimpedans med tilhørende jordresistans som gir lavest gjennomsnittlig avvik av beregnet feilposisjon, for alle feil knyttet til en kraftledning. Foreslått modell er derfor ikke egnet for å alene beregne en eksakt jordresistivitet, men til å gi nøyaktig beregning av feilposisjon.

Jordresistansen som brukes i avstand til feil beregninger er en gjennomsnittlig verdi av resistiviteten langs hele kraftledningsstrekningen. Dette er basert på teori om returstrømmen til feilstrømmen. Ettersom det er vanskelig å bestemme helt eksakt hvor stor andel feilstrøm som vil fordeles i jordline og jord, må det benyttes flere forenklinger. Det er derfor i foreslått

modell gitt en tabell som velger ut jordresistivitet basert på inngangsparameterene gjennomsnittlig høydemeter over havet og andel myr i % langs kraftledning. Dette er en forenklet modell, som inkluderer en del usikkerhet. I fremtiden anbefales det at en mer nøyaktig av bestemmelse av jordresistivitet utarbeides, og den foreslåtte modellen i denne oppgaven bør testes og vurderes på fremtidige feilhendelser. En illustrasjon av foreslått modell er vist under.



Integrasjon av distribuert fornybar energi og energilagring i Trøndelag

Student: **Jarand Hole**
Faglærer: **Magnus Korpås**
Veileder: **Magnus Korpås**
Utføres i samarbeid med: **Trøndelag fylkeskommune og TrønderEnergi Nett AS**

Problemstilling
Hvordan kan distribuert fornybar energi og energilagring integreres i Trøndelag, og hvilke konsekvenser for det for Trøndelags kraftsystem.

Sammendrag

Distribuert energiproduksjon vil spille en betydelig rolle i fremtidens kraftsystem. Tilstrekkelig med fleksibilitet i nettet vil også være en nøkkel for å takle overgangen til et mer volatilt kraftnett, med større variasjoner i spenning og effektflyt som følge av uregulerbar fornybar energiproduksjon. Elektriske batterier vil, i tillegg til å øke fleksibiliteten, kunne tjene nettet globalt med blant annet aktiv effektkompensering for frekvensstabilisering.

Den økende elektrifiseringen av transportsektoren er viktig for utviklingen mot lavutslippssamfunnet, men stiller krav til kraftnettets effektkapasitet. Både akkumulert effektforbruk fra lading av elbiler og individuelle effektuttak for kraftkrevende elektriske kollektivtransportmidler er noe som må tas hensyn til av netteiere og regulatoriske myndigheter når det fremtidige kraftsystemet i Trøndelag og resten av landet planlegges.

Modell/målinger

Resultatene fra nettanalysen gjennomført i softwaren MATPOWER av kraftnettet rundt Heimdal videregående skole, impliserer at nettet virker å være godt nok dimensjonert for å ta i mot overskuddsproduksjonen fra skolens distribuerte energiressurser, uten store konsekvenser for spenningsnivå eller risiko for overbelastning. Radialen når termisk overbelastning av kablene før spenningsnivåene i nettstasjonene blir uakseptable i henhold til EUs anbefalinger på pluss/minus 6%. For at kablene skal nå maksimal termisk driftsstrøm på 345 A, må lasten i systemet øke med 595\% i forhold til verdiene som ligger i TrønderEnergi Nett sine databaser i NETBAS.

Heimdal videregående skole vil derimot bli begrenset av plusskundeavtalen mellom skolen og TrønderEnergi Nett, når det kommer til kraft eksportert ut fra systemet. Eksportbegrensningen på 99 kW fører til at 1% av all energien skolen produserer, strupes vekk og dermed ikke blir utnyttet. Dersom skolens energiproduksjon antas å nå merkeeffekt i den timen med høyest produksjon i løpet av året, øker denne dumpingen av energi til 6% av total produsert energi. Dette er en direkte konsekvens av eksportbegrensningen i kombinasjon med offseten mellom skolens lastprofil og produksjonsprofilen fra de distribuerte energiressursene.

Energilagring kan benyttes til å øke fleksibilitet i energisystemer ved load-shifting. Det finnes mange ulike alternativer for energilagring, blant annet pumpekraftverk, komprimert luft(CAES), kinetiske energilager(flywheel), superledende magnetiske lagre(SMES), lagring av energi i hydrogengass og elektriske batterier. Endringer i programmet WINDHYDTOOLS, har muliggjort en analyse av Heimdal videregående skoles energibalanse med integrasjon av et elektrisk batteri.

Beregninger

Resultatene fra analysen viser at andelen strupet distribuert energi over et år reduseres fra 5,516% til 5,318% ved installering av et 150 kWh batteri med C-rate C/3. Videre viser sensitivitetsanalyser at dersom batteriet skal kunne påvirke andelen dumpet energi bør forholdet mellom batteriets effektkapasitet og energilager, kalt C-rate, være mindre enn 1/1. Lading- og utladningseffekten til batteriet bør i tillegg være større en 20 kW.

Konklusjon

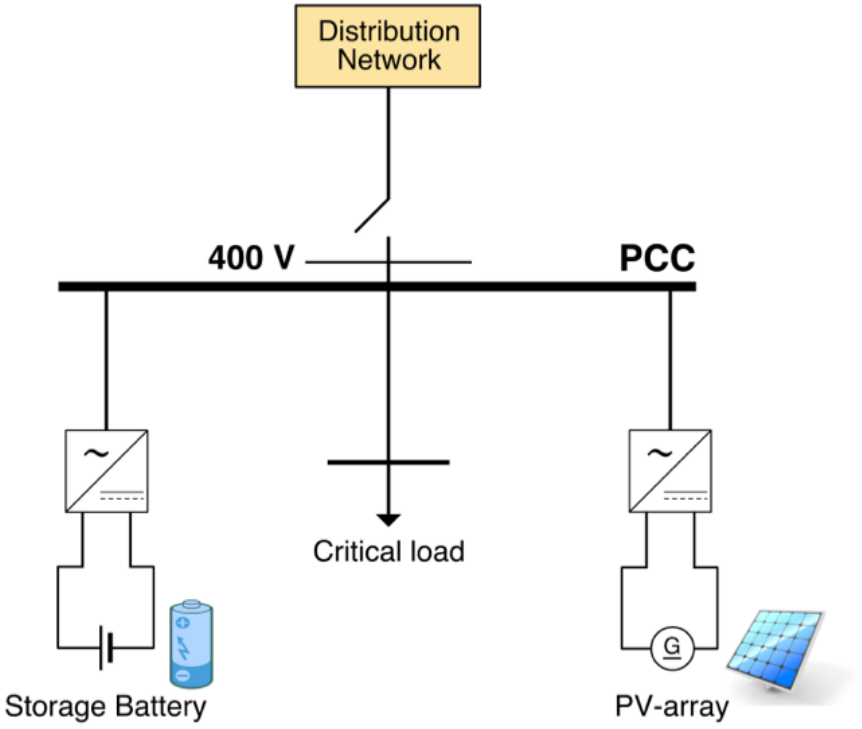
En økonomisk analyse resulterer i at de sparte strømkostnadene som følge av batteriets utnyttelse av tidligere dumpet egenprodusert energi, ikke er store nok til å dekke batteriets kapitalkostnad. Dersom batteriet skal være lønnsomt i denne case-studien, må prising av effekt utgjøre en stor del av skolens strømkostnader, kontrollstrategien må forbedres og batterikostnadene må sannsynligvis subsidieres.

Device-level control of microgrids with Master-Slave structure

Student: **Rakel Alice Utne Holt**
Supervisor: **Kjell Sand**

Summary
Microgrids are low voltage distribution networks comprising various distributed generators, storage devices and controllable loads that can operate as a controlled entity, either interconnected or isolated from the main distribution grid. Successful operation of microgrids can increase the reliability and efficiency of the energy system, lower operational costs and facilitate the implementation of renewable energy sources. However, long-established regulation strategies used in conventional power systems might not be feasible in microgrids, due to the new system configuration, the variety of resources utilized, and the considerable presence of power electronics.

A control system for a microgrid model has been developed. The model consists of a generating unit (PV-array), a storage unit (battery), a distribution system and loads, as well as the power electronic interfaces between the AC- and the DC- components. The control is performed through inverter control of the microgrid units in a master-slave structure. The control functions implemented are current control, power control, voltage control, and maximum power point tracing of the PV-array. The control system was developed using the rotating dq-frame coordinate system, and implemented in the MATLAB/Simulink simulation tool. Most simulations concerned events that spanned less than 3 seconds, and it took approximately 5-10 seconds to perform the simulations.



The control system was shown to enable optimized efficiency of the PV-array, while at the same time regulate the amplitude and frequency of the load voltage in the presence of a variable load condition and a variable supply. The control system was feasible during both grid-connected and islanded operation, and was able to adapt to islanding events with the microgrid stability preserved.

An advantage of the master-slave structure utilized is that it enabled reference tracking with zero steady-state error. A disadvantage with the strategy is the need for two distinct controllers on the master unit (the battery), with following dependence on proper coordination of battery controller modes. The application potential of the developed simulation model was demonstrated. Simulations concerned transient dynamics during important events, such as the islanding of the microgrid during power exchange with the utility, and islanding that did not coordinate with the microgrid master controller. It was also demonstrated how the current controller time constant affected the battery's voltage reference tracking ability. As the time constant increased, the reference tracking ability became more sensitive to the load conditions.

Virtual Impedance Techniques for Power Sharing Control in AC Islanded Microgrids

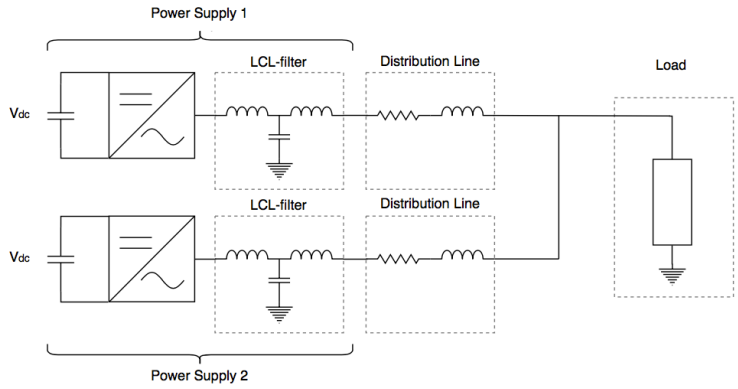
Student: **Anders Bergheim Holvik**
Supervisor: **Ole-Morten Midtgård**
Contact: **Raymundo E. Torres-Olguin**
Collaboration with: **SINTEF Energy**

Problem description

This project will focus on developing power sharing control techniques for ac microgrids with multiple distributed generation units. The power sharing within these generation units will be studied when the microgrid is operating in island mode. In order to provide improved power sharing in such a grid, the use of virtual impedance will be explored using a decentralized approach. The performance will be assessed through simulations.

Abstract

This thesis focuses on power sharing in low-voltage, islanded ac microgrids. It is motivated by the challenges related to climate change. To achieve a successful integration of renewable energy resources in the power grid, it is likely with an increased use of small distributed generation units. A promising way of organizing these units is by the use of microgrids. With microgrids disconnected from the main grid, several challenges related to current, voltage and power flow control arise. These challenges are studied in this thesis, where a microgrid with two distributed generation units and one load is investigated while operating in island mode. The two distributed generation units in the system are implemented with significantly different output impedances, in order to examine the unequal power distribution.



Distributed control systems are developed for this system, especially focusing on the use of virtual impedances for improved power sharing. Proposed virtual impedance methods are presented. These methods reduce the effect the virtual impedances have on the voltage level.

Three different cases are considered, each of which divided into two subcases. In case 1, the microgrid system is assumed to have predominantly resistive output impedances. The subcases 1 a) and 1 b) consider the use of opposite and conventional droop control algorithms for controlling the voltage and frequency levels. The microgrid considered in case 2 is similar to the one in case 1, but with predominantly inductive output impedances. As in case 1, the conventional and opposite droop control algorithms are utilized in case 2 a) and 2 b), respectively. Case 3 is a reproduction of case 2, but in the selection of virtual impedances, the physical output impedances are estimated to be 25% lower than the actual values.

Simulation models are carried out in all of the cases by utilizing the software MATLAB/Simulink. Each simulation case considers the use of physical output impedance only, an existing virtual impedance method and a proposed virtual impedance method. The proposed virtual impedance methods show promising results in all cases, where the power sharing performances are the same as for the existing methods. The voltage drops due to the use of virtual impedances are however significantly reduced. All of the simulation cases show a reduction of at least 90 %.

This master's thesis is a part of the research project FME CINELDI, and the results of this thesis are planned to be verified through laboratory experiments.

Conclusion

An islanded microgrid system is modelled in order to investigate power sharing between paralleled DG units with different output impedances. In the studied system, two DG units connected through inverters are modelled to feed one linear load. This thesis shows the distributed control structure, including the inner- and primary control. The inner control includes voltage and current control, while the primary control contains a droop control algorithm which takes care of voltage and frequency levels. In this loop, the output impedances of the inverters are modified by use of virtual impedances, which contribute to improved power sharing among the inverters. Six different cases are considered, and it is investigated how virtual impedance can be used to utilize different control systems in grids with mismatching physical output impedances. The system is validated through simulations, divided into three main cases.

This thesis presents promising results, where virtual impedance methods show well-working power sharing performance, in addition to minor effects on the output voltage level. The results should still be seen as a preliminary study, due to the assumptions that are done. For further work, it is suggested to perform laboratory experiments in order to validate the simulations in a more realistic sceanario. In addition, expansions of the microgrid, the use of non-linear loads and inclusion of more application oriented simulations can be part of future research on the topic of power sharing in islanded ac microgrids.

Power Factor Correction for a Bidirectional On-Board Charger for Electric Vehicles and Plug-in Hybrid Electric Vehicles

Student: **Sondre Westby Johannessen**
Supervisor: **Roy Nilsen**
Contact: **Tore Undeland, Torbjørn Sørsdahl**
Collaboration with: **Valeo Siemens eAutomotive**

Problem description

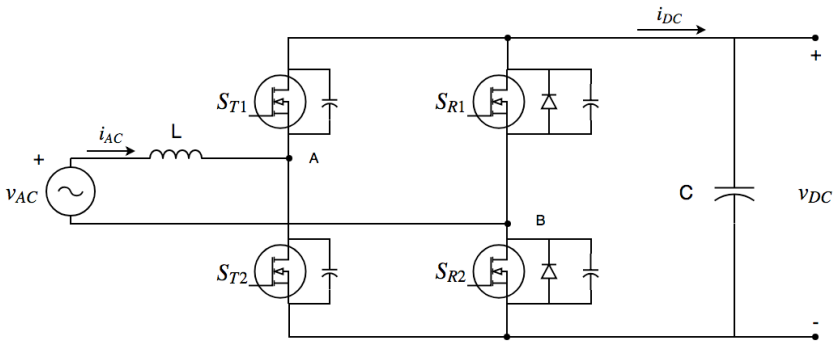
Bidirectional on-board chargers (OBC) could see an increased interest over the next years, as the growing implementation of the smart grid is enabling dynamic control of power flow on the consumer side, empowering the possibility of vehicle-to-grid (V2G) charging. Furthermore, any grid connected power supply is in need of power factor correction (PFC) sinusoidally shaping the AC current in phase with the AC voltage, to comply with the grid limitations for current and voltage harmonics. Thus, such a bidirectional OBC would require a bidirectional PFC. Such a bidirectional PFC could be the bidirectional totem-pole PFC.

The task

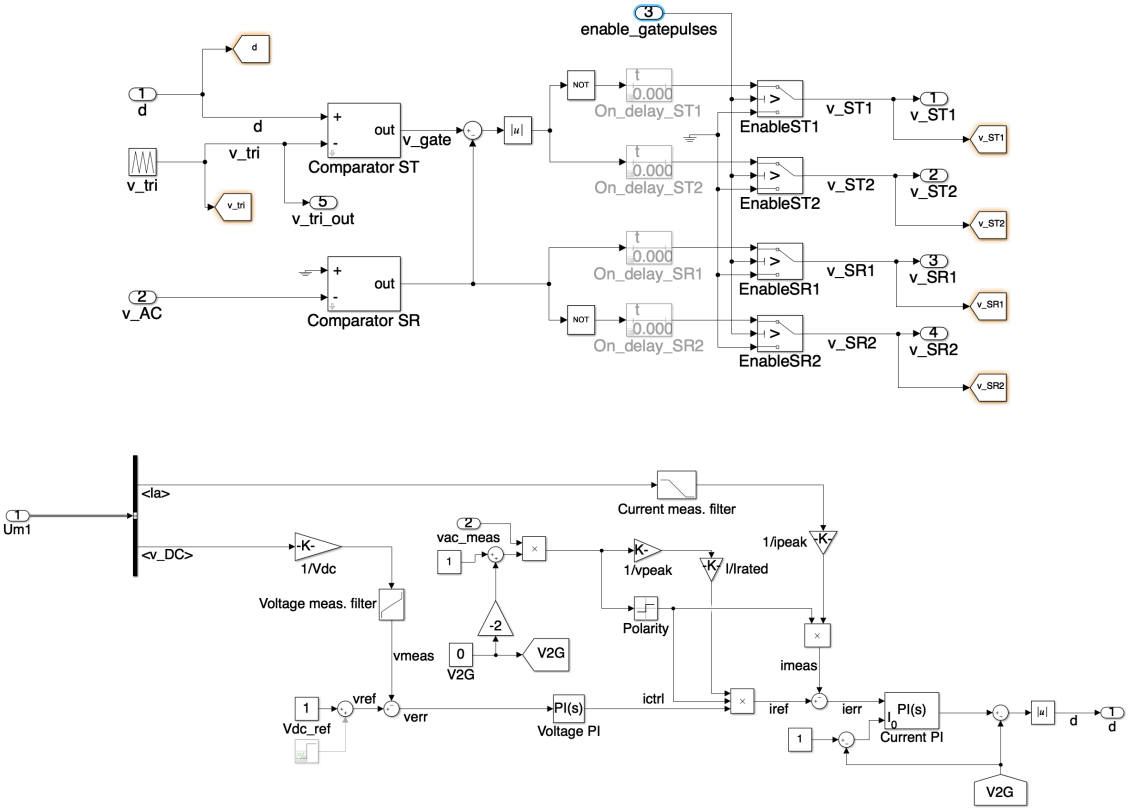
In this master's thesis, a simulation model is developed for a bidirectional totem-pole PFC, attempting to verify the use of this topology as the mentioned bidirectional OBC PFC. The work is focused on describing the basic bidirectional operation of the bidirectional totem-pole PFC, deriving expressions for currents, voltages and losses, as well as for the gate logic and control system. Average current mode control is used, with cascaded current and voltage control including PI controllers and Symmetrical optimum tuning. To verify the simulation model for the power levels and demands of an OBC, the main components are dimensioned to achieve 98% efficiency at 230Vrms, 3.5kW and 90kHz switching frequency, implementing GaN eHEMTs in the fast-switching leg of the totem-pole.

Model/ measurements

The topology of the eHEMT-based bidirectional totem-pole is as following, where ST1 and ST2 are interchangeably working as boost switch or imitating boost diode every mains half cycle and SR1 and SR2 are interchangeably conducting for every half cycle:

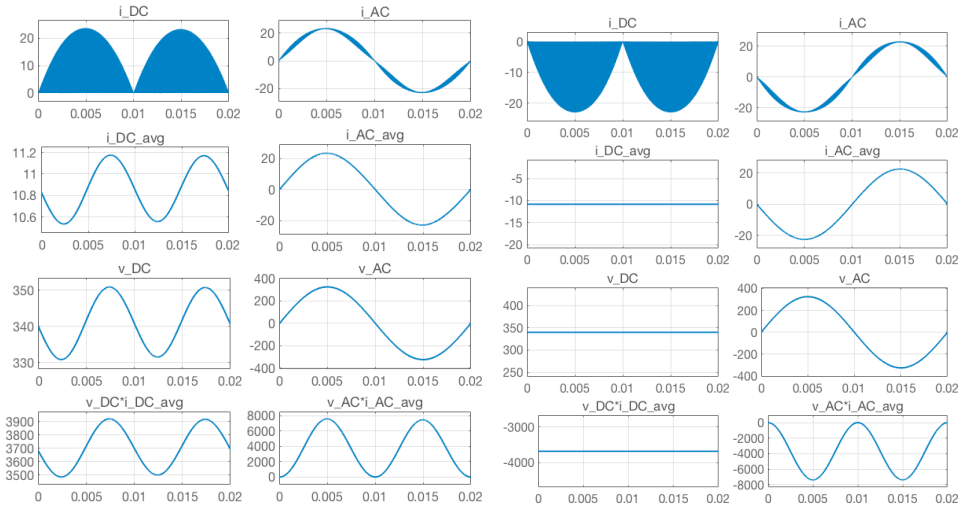


The gate logic and control system implemented in Simulink are as follows:



Results

At last, simulations were performed, showing that the PFC is able to achieve a power factor of 0.998 and a THD of 5% in both G2V and V2G, without a DM filter on the AC side. The simulation results were as follows:



Conclusion

The simulation model is operating as desired, with 0.998 power factor in both G2V and V2G mode, but in order to completely verify the bidirectional totem-pole PFC, a prototype should be made. Furthermore, it was interesting to find that the conduction losses of the bidirectional totem-pole PFC are independent of the power due to symmetry, and that it out-performed the conventional boost PFC under normal operating conditions.

Reliability Evaluation of Energy-Limited Hydro-Electric Generation Systems

Student: **Henrik Jøssund Karlsen**
Supervisor: **Vijay Venu Vadlamudi**

Abstract
Reliability studies are an essential part of power system planning and operation studies. A wide range of reliability indices is used by system planners and operators to ensure successful operation of power systems against random failures both in the planning and operational horizons. In generation system reliability studies, it is usual to consider the energy source for generation as always available. This implies that unavailability of generation is solely on account of a generation unit of the power plant; in the case of hydro generation, if the reservoir is sufficiently large enough to guarantee the availability of energy, through a constant regime of inflows, such modelling is correct. However, stochastic nature of inflows and reservoir limitations make hydro generation energy-limited.

In this thesis, multiple methods for incorporating energy-limited hydro generation units in generation system reliability studies, from the literature, have been examined. Three of the methods have focused on hydro generation units with reservoir limitations, meaning that each hydro unit only has a fixed amount of water available for generation. The *capacity modification method* (CMM) treats the limited hydro units as non-limited, but with a modified capacity depending on the capacity-probability table and the energy distribution of the unit. The same applies to the *forced outage ratio* (FOR) *modification method*, only with a modified probability instead of capacity. The massive benefit of these methods is that they treat the units as non-limited, which means the energy-limited units can easily be implemented in reliability test systems. The *load modification method* (LMM) makes use of the energy-limited units to reduce the load duration curve (LDC), and with the remaining non-limited units calculates the reliability indices. The method produces accurate results, but gets complicated as the number of energy-limited units is increased as this also increases the number of load steps. The methodological approaches are illustrated for simple systems for conceptual clarity.

A model of a run-of-the-river (ROR) power plant for evaluating power system reliability, from the literature, is also examined. The model considers the uncertainties of both river inflows and component failures, where the river inflows and component failures are modeled as a stationary stochastic process by a multiple state Markov model. The stochastic system is solved with linear algebra, and the steady-state probabilities of all capacity states are obtained. The final capacity-probability table represents a ROR power plant well, and can be used in other reliability evaluations. The river inflow values at Solbergfoss in the river Glomma in Norway are used in a case study, and the vast number of river inflow values are reduced by the statistical clustering technique *k*-means. The ROR model is then extended, again based on suitable existing literature, to also take into account the modelling of failure rates of all the components of a typical ROR plant.

The CMM and the extended ROR model are utilized on two reliability test systems, the Roy Billinton Test System (RBTS) and IEEE Reliability Test System (IEEE-RTS), to demonstrate the impact on system reliability from energy-limited units. The results show a significant effect from reservoir limited hydro units on the system reliability, and the energy-limited

hydro units should thus be included in reliability evaluation. The ROR unit is compared to a conventional unit of the same size. The ROR unit strengthens the reliability, but not as much as the conventional unit; this means if the same reliability output is desired, a larger ROR unit must be used.

Short circuit capacity improvement techniques for low voltage distribution grid

Student: **Adrien Sélim Karoui**
Supervisor: **Kjetil Uhlen**
Collaboration with: **TrønderEnergi**

Problem description

Some part of the Norwegian low voltage distribution grid suffers from voltage dips during short term event such as motor start and short circuit fault. Since these voltage dips can leave the admissible voltage range for some seconds, it is critical to search for some cheap solutions to regulate continuously the voltage.

Model

This thesis compared two voltage regulation devices, namely the Magnetic Voltage Booster (MVB) developed by the company Magtech™ and the STATCOM which is part of the Flexible Alternative Current Transmission System and analyse their performance during motor start and fault events. The diagram of the two devices are depicted in Figure 1.a-b.

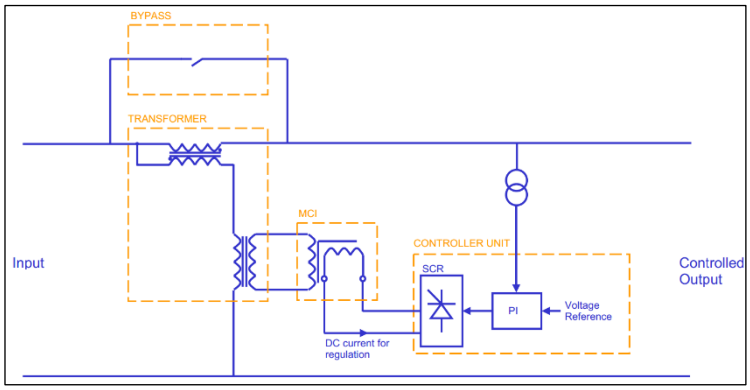


Figure 1.a: Electrical model of the MVB.

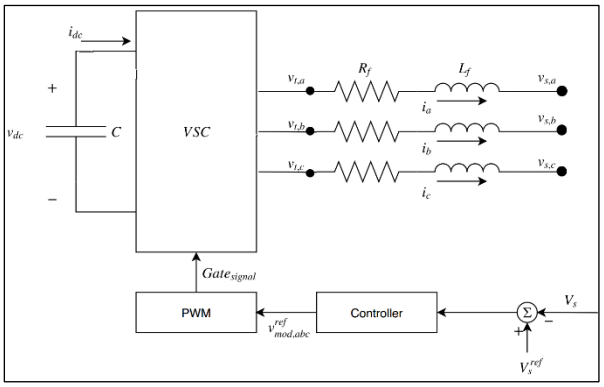


Figure 1.b: Electrical model of the STATCOM.

Result

The simulations of the short circuit and the motor start are runned for each voltage regulation devices using the Test grid showed in Figure 2 .

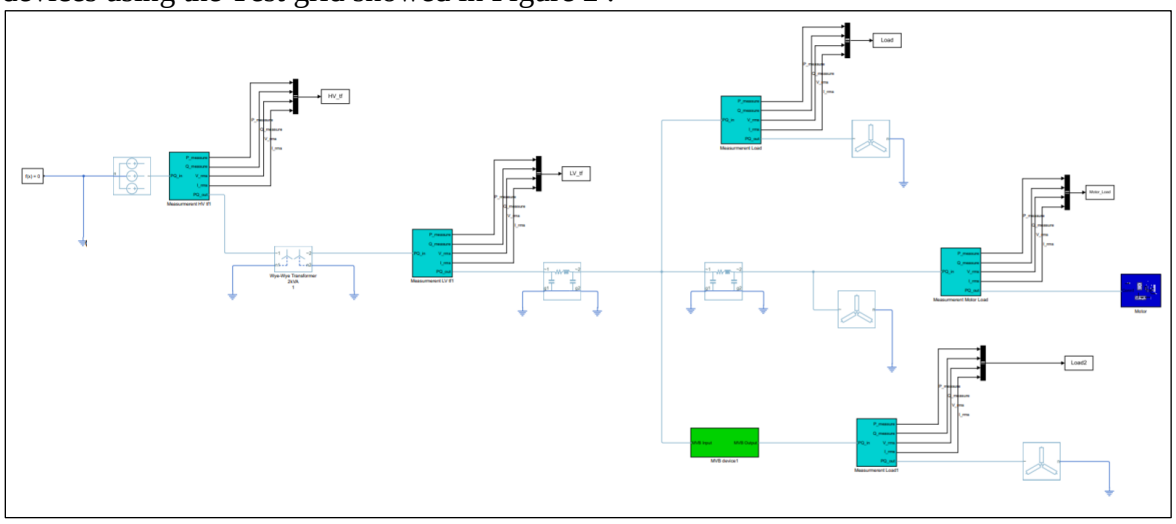


Figure 2 Single Line diagram of the Test Grid modelled with Simscape/Simulink

The simulation result depicted on Figure 3 show the transient evolution of the controlled voltage when (left figure) a 3 phase short circuit occurs and (right figure) an induction machine is started. The short circuit fault is modeled on feeder of *Load* while the motor is connected in the center feeder.

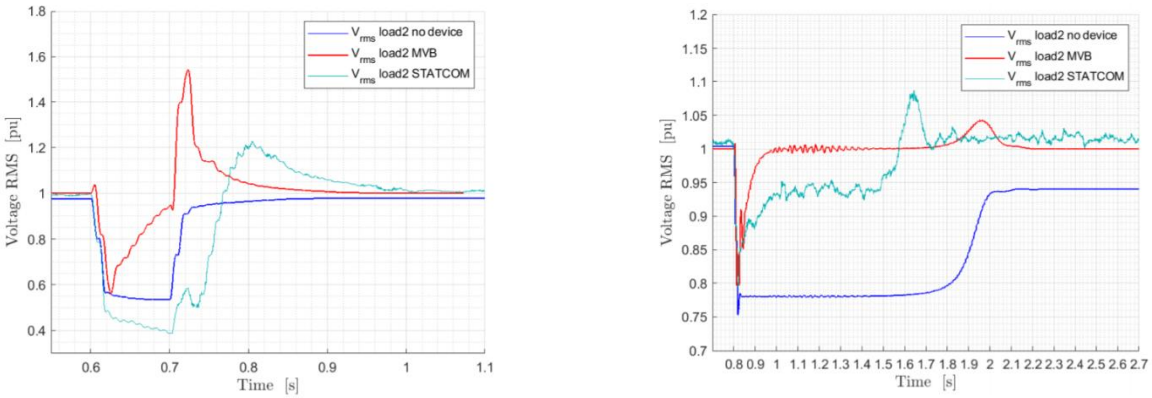


Figure 3: The left figure compares the evolution of the voltage during a 3 phase short circuit when the STATCOM, the MVB and no device are connected to the grid. The right Figure compare the same devices but in the case of a motor start.

Conclusion

The STATCOM which has been used to compare the MVB technology is modelled with a capacitor, a voltage source converter and a filtering inductance. Additionally, a control scheme composed of a inner and a outer controller has been implemented and the corresponding reference tracking test have been conducted to validate the proper operation of the STATCOM in case of event. One drawback of the STATCOM over the MVB is the high amount of noise its injects into the grid which result in very fast voltage oscillation. Nevertheless, the simulation analysis of the STATCOM during the motor start have shown two advantages over the MVB. The first advantage is that the STATCOM is able to injects reactive power and thus is able to compensate for the large reactive power consumption of the motor during its start. Consequently, the duration of the voltage dip is reduced since the motor can start faster. The second advantage of the STATCOM over the MVB is its shunt connection to the grid that allows the STATCOM to regulate the terminal voltage independently of the nearby voltages to some extent.

Adaptive Resonant Controllers in a Modular Multilevel Converter

Student: **Kjøsnes, Eivind Magnus Amundsen**
Supervisor: **Norum, Lars Einar**

In this thesis work, the modular multilevel converter was investigated. More specifically, an analytical study of circulating current suppression methods for low-bandwidth systems was undertaken. A comparative study of two frequency adaptive digital controllers proposed in earlier research papers has been evaluated to check which yields the most efficient controller.

The modular multilevel converter (MMC) is a converter aimed for high voltage direct current applications. Compared to other voltage source converters, the MMC has several distinct advantages; high efficiency, scalability, modularity, and superior harmonic performance. One of the key advantages is its modular design. The redundancy is proportional to the number of submodules, and having multiple submodules in series gives high redundancy. If one submodule were to fail, the converter could continue to operate with high efficiency by bypassing the failed submodule.

However, its modular design does also have some drawbacks. First, the more submodules, the higher switching losses. However, the switching losses can be reduced by lowering the switching frequency. By reducing the switching frequency, the system's bandwidth reduces as well. Consequently, the controller's ability to suppress disturbances reduces. Second, a circulating current is introduced to the system. The circulating current is responsible for transferring power from the dc-link to the ac-side, and also balance the energy of the capacitors. If not controlled, the circulating current will be predominant of a second harmonic, which results in higher resistive losses. The additional resistive losses affect the lifetime of semiconductor devices and passive components due to the temperature rise.

To suppress the second harmonic during grid frequency fluctuations, studies of a digital frequency adaptive controller was undertaken. A proportional resonant controller was digitally realised in an infinite impulse response (IIR) filter. By only changing one variable, the filter adapts its resonant peak according to the measured grid frequency. A phase-locked loop was used in combination with a look-up table to measure the grid frequency and to give a new parameter for the IIR filter.

A comparative study of two frequency adaptive digital PR controllers has been undertaken. Both methods are used to change the resonant peak of the IIR filter. The first method proposed in [1] focuses on changing ω_0, while the second method proposed in [2] focuses on changing the sampling time. Both controllers were simulated in a system where the grid frequency changed from 50 Hz to 52 Hz, resulting in a 4 Hz jump in the second harmonic. A *fast Fourier transform* (FFT) analysis reveals that both methods work with high efficiency. However, in medium- and low-bandwidth systems the method proposed in [1] was able to suppress the second harmonic more effectively.

Bruk av nye sensorer og AMS i distribusjonsnettet for å validere nett-topologi

Student: **Anders Hylen Klippenberg**
Faglærer: **N/A**
Veileder: **Kjell Sand**
Utføres i samarbeid med: **Trønder Energi Nett, ved Arnt-Magnar Forseth**

Problemstilling
Norske nettselskaper har utfordringer med til enhver tid å ha en oppdatert oversikt over kob-lingsbildet i lavspenningsnettet. Lavspenningsnettet er omfattende og utsatt for hyppige end-ringer, og det er derfor utfordrende å ajourholde dokumentasjonen av nett-topologien. Ved inn-føringen av AMS og nye sensorer i lavspenningsnettet tilgjengeliggjøres nye data som potensielt kan nyttiggjøres av nettselskapene til å ha en bedre oversikt over lavspenningsnettet.

Trønderenergi Nett har installert nye målere i nettstasjoner og hos abonnenter i et par lav-spenningskretser. Disse kretsene egnes for testing, og kan benyttes i praktiske case i oppgaven. Oppgaven adresserer følgende punkter:

- Hvilke måledata er tilgjengelig fra de nye målerene?
- Hva er typiske feil i nettdokumentasjonen og hva er typiske feilkilder?
- Hvordan kan disse dataseriene utnyttes for å forbedre nettdokumentasjonen?
- Gjennomfør et litteratursøk og sammenlign mulige metodikker som er kandidater til å bli implementert i norske nettselskaper
- Foreslå en metodikk som kan bli implementert
- Gjennomfør praktisk case der tilgjengelig måledata anvendes. Benytt valgt metodikk og vurder hvorvidt den bidrar til å forbedre nettdokumentasjonen

Oppgaven
Først gjennomgås de nye målerene i lavspenningsnettet. De tilgjengelige måleseriene blir presentert, før de blir sammenlignet med reell måledata som er målt i de aktuelle testkretsene. Disse dataseriene vil være inngangsdata i metodene som blir foreslått senere i oppgaven.

Videre presenteres typiske feil i nettdokumentasjonen og typiske feilkilder. Deretter gjennomføres et litteratursøk der resultatene av dette sammenlignes med egenutviklede metoder som kan bidra til å løse utfordringen med dårlig nettdokumentasjon. Resultatet av disse vurderingene blir videreutviklet til algoritmer som kan benyttes på reelle måledata.

Algoritmene blir så anvendt i et praktisk case på testkretsene og benytter reell måledata. Avslutningsvis drøftes resultatene og det gis forslag til forbedringer og videre arbeid.

Modell/målinger
Det ble foretatt praktiske tester av en utvalgt lavspenningskrets. Dette var lavspenningskretsen under NS00638 som ligger på Reppe i Trøndelag. Følgende metoder ble testet:

- Energibalansemetoden
- Jordfeilmetoden
- THD-metoden
- Spenningsfallmetoden

Testkrets som ble brukt til å gjennomføre spenningsfallmetoden

Beregninger

Energibalansemålinger gikk ikke opp. Dette indikerte at multimåleinstrumentet i nettstasjonen var feilkoblet. Dette ble oppdaget og måleren ble koblet om. Måleverdiene som avslørte dette var for energimålingene:

- AMS-målere: 5713,2 kWh
- Nettstasjon: 3000 kWh

Her sier målingene at det oppstår energi i kretsen. Dette går ikke, så derfor var måleroppsettet galt. Dette førte til omkobling av måler og dermed nye måledata.

Konklusjon

Totalt sett ble ikke metodene gjennomført med godt nok datagrunnlag. Energibalansemetoden viste likevel lovende resultater og spenningsfallmetoden ga tilsynelatende riktige resultater. Det er heller ingen åpenbar grunn til at THD-metoden ikke lar seg gjennomføre. Jordfeilmetoden fungerte ikke i dette caset, men kan fungere for andre nettselskaper med annerledes måleroppsett og nettkonfigurasjon. Den er likevel overflødig dersom THD-metoden fungerer.

Dersom metodene fungerer betyr det at hovedalgoritmen vil være godt egnet til å validere lavspenningskretsene til TEN. Hvis nettselskapet vil benytte seg av nye måledata for å forbedre eksisterende arbeidsprosesser eller opprette nye lønsomme arbeidsprosesser må de per juni 2018 utrede lavspenningskretsene manuelt for å få oppdatert dokumentasjon av topologien. Dersom den foreslåtte metodikken i denne oppgaven gjennomføres, kan det potensielt kutte drastisk ned på ressursbruken til manuell utredning og potensielt føre til store besparelser for bedriften.

Planleggingskriterier for lysstyring basert på dagslysstilgang i bygninger

Student: **Ane Solem Knutsen**
Veileder: **Eilif Hugo Hansen**

Sammendrag
Dagslyssensorer er et energibesparende tiltak i bygninger som skal redusere den kunstige belysningen etter innkommende dagslys. En forutsetning for at styringen skal kunne føre til energibesparelse er at dagslystilgangen i bygningen er god store deler av arbeidsdagene gjennom året. Sensorene blir i dag installert sammen med bevegelsessensorer i nye bygninger eller ved oppgradering av lysanlegg, som oftest uten noen forundersøkelser.

Hensikten med dette masterprosjektet er å vurdere energisparepotensialet i ulike type bygninger med dagslyssensorer og vurderer komfortforholdene for brukere i disse bygningene Det skulle utføres energi- og effektmålinger på lyskursene i Abels hus og Trondheimsporten, i tillegg til spørreundersøkelser som omhandlet brukerens komfort i Abels Hus. Måleutstyret på Trondheimsporten måtte tas ned på grunn av forstyrrelser på resten av bygningens styresystem, og det ble derfor ingen måledata som kunne benyttes til videre analyse fra denne bygningen.

Energi- og effektmålingene ble utført i 3.etg i C-blokken på Abels hus og resultatene viser en total energibesparelse på *58,2 %* sammenlignet med at lysanlegget hadde stått på for fullt over arbeidsdagene (kl. 0745 – 1715). Av denne besparelsen står konstantlys-styring (dagslys) for ca. *16,9 %* og bevegelsessensoren for ca. *41 %*. Resultatene fra spørreundersøkelsen tyder på at brukerne legger merke til styringen, men de opplever den ikke som en stor ulempe. Enkelte opplever at tenningen av armaturen er mer brå enn neddimmingen.

Statiske simuleringsverktøy er de mest utbredte i prosjektering av lys og dagslys. Disse simuleringsverktøyene beregner dagslyset ut fra en konstant overskyet himmel. Denne vurderingsformen vil ikke vise hvordan lyset er inne i rommet til enhver tid, fordi den blant annet ikke inkluderer sollys og bruk av solskjerming. For å kunne estimere energibesparelsen og optimalisere bygningers dagslystilgang bør prosjekteringen ta i bruk dynamiske simuleringsverktøy som inkluderer reelle værdata og himmelforhold.

I prosjektets oppstartsfase var det også tenkt å foreslå beregningsmetodikk for dagslystilgang i bygninger, ved å gjennomføre dynamiske simuleringer (CBDM) i Daysim. På grunn av manglende veiledning i simuleringsverktøyet ble det ikke mulig å gjennomføre. I stedet ble det utført en undersøkelse for å finne ut hvordan dynamiske vurderinger kan inkluderes i prosjektering av dagslys.

I denne undersøkelsen ble prosjekterende av lys i rådgivende bransje kontaktet. Resultatene viser at det finnes få dynamiske verktøy på dagens marked. Verktøyene forutsetter gode forkunnskaper og forståelse av lysets egenskaper. I tillegg er simuleringstiden betydelig høyere enn for statiske simuleringsverktøy.

For å kunne estimere en mer nøyaktig energibesparelse ved å utnytte dagslyset bør det inkluderes krav om mer dynamiske beregninger i Byggteknisk forskrift (TEK). For å få innført CBDM i dagens prosjektering bør det inkluderes i et allerede utbredt statisk simuleringsprogram på det Europeiske markedet. I tillegg bør det innføres separate

reduksjonstall for ulike styringsprinsipp i SN/TS 3031. Reduksjonstallet i dag skiller ikke på separat eller kombinert styring av dagslys og bevegelse.

Variable Flux Permanent Magnet Synchronous Machines: Building and Testing Simple Designs with High-Coercivity Magnets

Student: **Kasper Kvinnesland**
Supervisor: **Robert Nilssen**

Problem description

Permanent magnet synchronous machines (PMSMs) offer high efficiency and high torque density, which have made them increasingly popular over the last few decades. In certain applications, however, a significant disadvantage of PMSMs is limited operation above rated speed. Since the rotor magnetomotive force (mmf) is constant, high speed operation may induce too large back-emf in the stator windings and cause overvoltage, potentially damaging the windings or inverter. In the main competitor of PMSMs, the induction machine, the rotor mmf can be controlled freely, such that excessive back-emf will not become a problem.

A common method to achieve high-speed operation of PMSMs is to inject continuous negative d-axis current, i.e. field weakening current, to lower the emf induced by the rotating rotor flux. This extra stator current increases copper losses and, therefore, the efficiency decreases when conventional PMSMs is operated above rated speed.

A novel idea to avoid this deterioration of efficiency at high speeds is based on the idea of manipulating the magnetization state of the PMs by injecting large current pulses in the stator windings. The ability to control the level of magnetization in the rotor magnets allows manipulation of air gap flux to optimally correspond with the operating point, without more circuitry or continuously feeding loss-inducing current. Machines using this method are called variable flux permanent magnet synchronous machines (VF-PMSMs).

The task

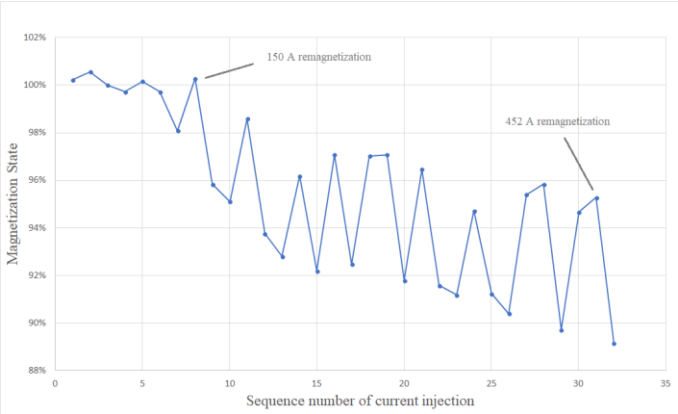
The paper uses the lessons from existing literature to develop a new, simple VF-PMSM design and describes the building process. In contrast to most other published VF-PMSM designs, this design uses high-coercivity samarium-cobalt magnets on the rotor. The machine is investigated in finite element analysis and tested experimentally for its ability to manipulate the magnetization state (MS) of the magnets.

Experimental approach

In order to achieve a magnetization current that is sufficiently large to affect MS, a capacitor bank is used as the current pulse source. After the capacitors have been charged to a given voltage level by a secondary source, they are discharged through the stator windings, causing a large current pulse. This pulse will give rise to a magnetic field that, if strong enough, will change the MS of the PMs. After a magnetization current pulse injection, a change in MS is detected by measuring the induced back-emf in open-circuited stator windings when a secondary motor is used to rotate the rotor at rated speed.

Results

The built VF-PMSM was found to have a very limited ability to control MS. While theoretical calculations suggested that the magnets would be significantly demagnetized for a given demagnetization current, the actual demagnetization that seemed to take place was much lower. Even when the injected current was increased far beyond that predicted necessary, the change in MS remained very small. Furthermore, it was found that the demagnetizations that did take place were partly irreversible in the sense that a remagnetization current was not able to return the MS back to its previous level. This is displayed in the figure below, showing the chronological development of MS as re- and demagnetization currents were injected.



It was concluded that limited MS manipulation capability was due to the rotor core not being laminated. Since the MS changes must take place during the short duration of the injected current pulses, the magnetic flux in the rotor core must change very quickly. Thus, since the core is not laminated, excessive eddy current will be induced, working against the applied stator field. The resulting field over the magnets is therefore reduced and the expected MS change does not occur.

Conclusion

- Using a capacitor bank as the sole current pulse source is sub-optimal to investigate the magnetization behavior of VF-PMSMs.
- High-coercive SmCo magnets may be inappropriate for this application due to the large current needed to change the magnetization.
- Due to the rapid changes in flux, lamination of the rotor core is essential to achieve magnetization changes using current pulses of reasonable length.
- Not laminating the rotor core may defeat the VF-PMSM's purpose of reducing operational losses.

Application of Monte Carlo Simulation to Power System Adequacy Assessment

Student: **Øystein Stake Laengen**
Supervisor: **Vijay Vadlamudi**

This thesis examines three Monte Carlo Simulation methods that can be used in power system reliability studies. Through application of the methods to both generation- and composite system adequacy assessment, an understanding of the methods was built. The field of probabilistic methods in power system reliability studies is a highly developed field with a lot of written material. However, it can be difficult for an inexperienced reader in the field to understand the small, but important, steps along the path for building Monte Carlo Simulation based applications for generation- and composite system adequacy assessment. Thus, the motivation for this thesis has been to present a transparent and detailed methodology for both levels of adequacy assessment.

The thesis elaborates on the details of obtaining power system adequacy indices through three fundamental Monte Carlo Simulation methods: state sampling, state duration and state transition methods. All the three simulation methods are applied to generation system adequacy assessment, while only the state sampling and the state transition methods are applied to composite system adequacy assessment. A detailed methodology on how to create a DC based contingency solver and an AC based contingency solver for composite system state evaluation, is also proposed in the thesis. The developed scripts created by implementation of the proposed methodology are tested on two test systems (Roy Billinton Test System and IEEE-Reliability Test System). Comparisons of three adequacy indices, viz. loss of load expectation, expected energy not served and loss of load frequency, are made against corresponding benchmark results from literature.

It was observed that the state sampling method provides estimates with a higher precision than the two sequential methods when equal sample sizes are used. The state sampling method, however, is unable to provide distributions of the indices. It was also observed that the state transition method requires less computation time than the two other methods to simulate a year.

A dependency for the bus indices on choice of load curtailment philosophy was observed in the study. The Roy Billinton Test System is found to be more reliable than the IEEE-Reliability Test System. It was also observed that the estimates of the latter's indices are more influenced by the choice of DC based or AC based system representation.

Belysning for produksjon av rognkjeks

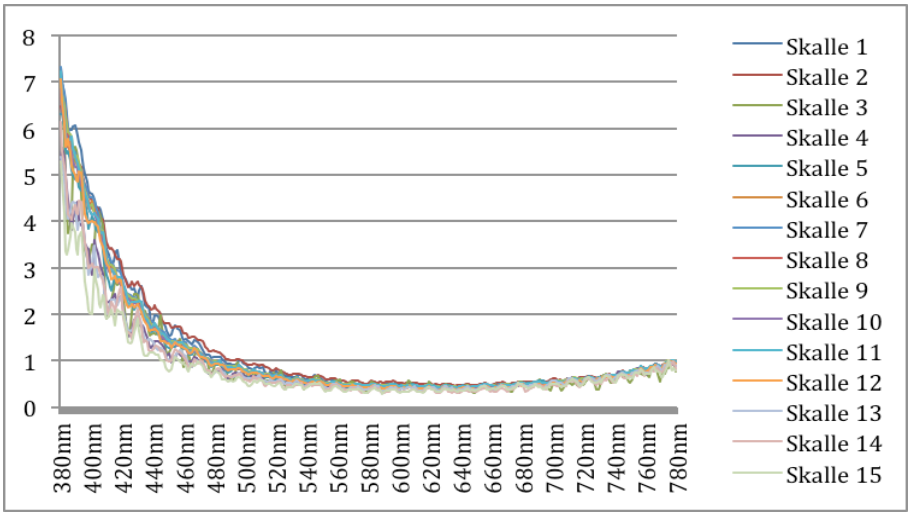
Student: **Marie Lervik**
Veileder: **Eilif Hugo Hansen**
Utføres i samarbeid med: **Institutt for biologi**

Lys har stor betydning for både mennesker og dyr, og er viktig med tanke på syn, generell velferd og den biologiske klokka. Det er dermed et potensial når det gjelder belysning og optimalisert produksjon innen akvakultur, som kan få stor framtidig betydning. Norsk fiskeoppdrett omsatte i 2016 for over 64 milliarder NOK, der laks sto for 60 milliarder NOK. Innen norsk industri og på regjeringshold er det et mål at virksomheten skal øke i framtiden, men det er utfordringer knyttet til næringens videre ekspansjon. Lakselus er i dag en stor utfordring, som det siste året har kostet næringen mer enn 3 milliarder NOK.

Det er gjennomført flere tiltak for å finne en løsning på lakselus-problemet, som for eksempel spyling, medisinering og kjemisk behandling. De siste årene er det sett på muligheten for biologisk avlusning ved hjelp av lusespisende rensefisk, blant annet rognkjeks. Flere oppdrettsselskap har etablert anlegg for oppdrett av rognkjeksyngel, der det er kontroll på tilførsel av fôr og vannmiljø. Et problem er at det er kunnskapshull knyttet til rognkjeks og rognkjeksproduksjon, og millioner av yngel dør under prosessen.

Gjennom forsøk er det etablert kunnskap om virkningene lyset har på blant annet laks og hvordan den bearbeider lys. Denne kunnskapen mangler i dagens rognkjeks-produksjon, og det var derfor nødvendig å utvikle kunnskap om hvordan blant annet lysintensitet og lysfarge påvirker rognkjeksens liv i vekstanlegg. I denne sammenheng var det ønskelig å vurdere belysningen på anlegg for rognkjeks, lysets spektrale transmisjon gjennom rognkjeksens hodeskalle (da det har effekt på biologiske rytmer) og lysets påvirkning på rognkjeksyngels adferd.

Det ble gjennomført forsøk på spektral transmisjon gjennom rognkjeksens hodeskalle. Det var interessant å finne ut hvor mye og hvilket lys som transmitterer gjennom skallen på rognkjeksen under ulike forhold. Dette for å vite hvilke bølgelengder som kan påvirke fiskens pinealkjertel. Resultatet er vist i Figur 1. Det ble også gjennomført to typer lysforsøk for å se hvordan lys påvirker rognkjeksens adferd. Forsøkene omhandlet lysets farge og intensitet.



Figur 1: Spektral transmisjon for 15 rognkjeksskaller

Resultater ga indikasjoner på at rødt lys transmitterer dårlig gjennom rognkjeksens skalle, i tillegg er det vist at rognkjeks ikke ser i rødt lys. Dette gjør rødt lys mindre aktuelt som produksjonslys, men det kan brukes som arbeidslys eller lys i hodelykter. Observasjoner viste at rognkjeksen hadde et høyt aktivitetsnivå i grønt lys, og at fisken virket stresset i dette miljøet. Rognkjeksen hadde også en tendens til å trekke bort fra det grønne lyset. Grønt lys er dermed mindre aktuelt som produksjonslys. Rognkjeksen hadde et rolig og naturlig aktivitetsmønster i blått og hvitt lys, men i fargeforsøkene hadde fisken en tendens til å trekke mot det blå lyset. Resultatene tyder på at blått lys har høy transmisjon gjennom rognkjeksens skalle, i tillegg til at rognkjeksens øyne har høy følsomhet for blått lys. Blått lys kan derfor være aktuelt som produksjonslys. Ut fra resultatene kunne det ikke dokumenteres at lysintensitet har stor betydning for rognkjeksen. Det anbefales derfor å uniformere belysningen og planlegge lysintensitet på rognkjeks-anlegg ut fra menneskers behov.

Analyse av magnetfelt og tap ved enderegionen i direkte vannkjølte generatorer

Student: **Arne Moen Lid**
Faglærer: **Prof. Arne Nysveen**
Veileder: **Mostafa Valavi**
Utføres i samarbeid med: **Statkraft AS**

Sammendrag

Denne masteroppgaven er i samarbeid med Statkraft AS. Oppgaven går ut på å undersøke og analysere magnetfeltet som treffer statoren i enderegionen i aksiell retning og tapene som oppstår her. Bakgrunnen for oppgaven er at Statkraft AS har hatt et problem med en av sine store synkrongeneratorer, der varmgang i enderegionen førte til havari. Dette er første og eneste gang Statkraft AS har hatt dette problemet, men har siden blitt mer interessert i dette området. Dette for å få en bedre forståelse av hvordan magnetfeltene blir påvirket av forskjellige lastsituasjoner.

Det ble i denne oppgaven brukt en 3D-modell som er basert på en av Statkraft AS sine synkrongeneratorer for å undersøke dette temaet. Programvaren som er brukt er ANSYS Electronics, det er et feltberegningsprogram som bruker elementmetoden. Det har blitt utført simuleringer og utregninger i tre ulike driftsituasjoner. Disse driftsituasjonene er tomgangsdrift, overmagnetisert drift og undermagnetisert drift.

Gjennom ulike målepunkter og målelinjer som har blitt satt på ulike områder på overflaten av enderegionene til statoren har det blitt hentet ut data i form av ulike plott. Det ble gjennom disse plottene funnet at det totale feltet Bz som treffer statoren i aksiell retning er høyest for undermagnetisert drift. Dette ble undersøkt nærmere og grunnen til dette er at vinkelen mellom feltet fra rotorviklingen og statorviklingen er så stor i overmagnetisert drift at de vil ha en demagnetiserende effekt på hverandre, noe som vil føre til at det totale feltet Bz blir svakere. Denne vinkelen er ikke like stor i undermagnetisert drift og dermed vil ikke denne effekten være tilstede i samme grad i denne driftsituasjonen. I noen tilfeller viste det seg at det totale feltet Bz i overmagnetisert drift var lavere enn for tomgangsdrift som bare hare bidrag fra rotorviklingen.

Det ble funnet gjennom plott av strømtettheten at denne er høyest langs sidene og kantene til statortennene. Dette betyr at de induserte virvelstrømmene er høyest her og følgelig vil også de høyeste virvelstrømstapene være her. Grunnen til dette er strømfortrengninsfenomenet.

Det ble også regnet ut virvelstrømstapene for 10 mm av det øverste laget til tre utvalgte statortenner i z-retning. Dette ble gjort for de tre driftsituasjonene. Det ble regnet ut at virvelstrømstapene er høyest for undermagnetisert drift. Gjennomsnittet av utregningene viste at virvelstrømstapene var 16,4 % høyere for undermagnetisert drift sammenlignet med overmagnetisert drift. Den mest ekstreme forskjellen var 21,4 %.

Impact of Large-Scale EV Integration and Fast Chargers in a Norwegian LV Grid

Student: **Martin Lillebo**
Supervisor: **Hossein Farahmand**
Co-supervisors: **Salman Zaferanlouei**
Antonio Zecchino

Given a renewable power supply, the replacement of conventional vehicles with electric alternatives has the potential to significantly reduce climate gas emissions from the transport sector. Norway has implemented economic incentives over several years to encourage a transition from conventional vehicles to electric cars (EVs), and has now the largest share of EVs per capita in the world. The power levels required to charge this fleet may constitute a significant strain on the existing power grid, especially at a low voltage level. The deployment of fast chargers may further aggravate this. More knowledge about the challenges ahead will be advantageous.

This thesis explores the effects of increasing EV penetration levels in a Norwegian distribution grid, by analysing real power measurements obtained from household smart meters and implementing them in load flow analyses. The implications of installing a fast charger in the grid has been assessed, an optimal location for it has been proposed, and the potential for reactive power injection to reduce the voltage deviations caused by it has been investigated.

After presenting the theoretical groundwork, data set and methodology, the model is presented in detail and the following results are described. Given the underlying charging profile, results show that the EV hosting capacity of the grid is good for a majority of the end-users, but that the weakest power cable would be overloaded at a 20 % EV penetration level. The network tolerated an EV penetration of 50 % with regards to the voltage levels at all end-users. Injecting reactive power at the location of an installed fast charger proved to reduce the voltage deviation otherwise imposed by the charger.

Harmonic Propagation and Production in Offshore Wind Farms

Student:	**Audun Matre Meinich**
Supervisor:	**Elisabetta Tedeschi, IEL**
Co-supervisor:	**Fernando Marafao, Univ Estadual Paulista**
	Lukasz Kocewiak, Ørsted
Collaboration with:	**São Paulo State University (UNESP), Campus of Sorocaba.**

Abstract

Modern wind farms are increasing in size and complexity. As a result, increased power injected from large offshore wind farms is having a significant impact on the stability and power quality of the grid. Harmonics are a fundamental aspect to be evaluated during power quality assess-ment. Therefore, a thorough understanding of their behavior is needed to successfully plan an offshore wind farm.

Modern wind farms are increasing in size and complexity. As a result, increased power injected from large offshore wind farms is having a significant impact on the stability and power quality of the grid. Harmonics are a fundamental aspect to be evaluated during power quality assess-ment. Therefore, a thorough understanding of their behavior is needed to successfully plan an offshore wind farm.

A Simulink model of an offshore wind farm is built using data from Anholt Offshore Wind Farm in Denmark. The wind turbine in this model is simulated as a voltage source converter with an LCL-filter. A $d-q$ reference frame is used in the control system of the converter, with a pulse width modulator to control the switches and a phase locked loop to synchronize the converter with the grid. The turbine itself is connected to a simplified offshore grid with trans-formers and subsea cables. Nine different scenarios (running the turbines at half power, grid harmonics and adding a switch-on delay among others) are simulated on this model, each de-signed to mimic factors present in real offshore wind farms. In addition, active filtering is im-plemented to limit specific harmonic frequencies.

Results from all nine scenarios show that harmonics vary greatly in the presence of each simulated factor. There are two kinds of current harmonics produced by the wind turbine; high-order switching harmonics and low-order harmonics produced by the phase locked loop. While most of the scenarios had a constant harmonic output from the switches, the harmonics created in the phase locked loop varied as much as 120%, depending on the conditions under which the turbine is running.

While it is documented that the phase locked loop can cause harmonics and instability in the system, this thesis investigates specifically what amplifies harmonics by investigating several practical scenarios in offshore wind farms.

Correlation Between Electroluminescence and Partial Discharges in Silicone Rubber Used for High Voltage AC Subsea Connectors

Student: **Øystein Midttveit**
Supervisor: **Frank Mauseth**
Contact: **Sverre Hvidsten**
Collaboration with: **SINTEF Energy Research**

Problem description

The demands towards future oil and gas production include increased recovery and long step-outs. Subsea processing is considered as one of the main issues in achieving these goals. To enable the next generation subsea boosting and processing facilities, high power electrical connectors are strongly needed and considered one of the most critical components. The project work is part of a four year research project on subsea connectors run by SINTEF Energy Research and NTNU in cooperation with national and foreign industry companies.

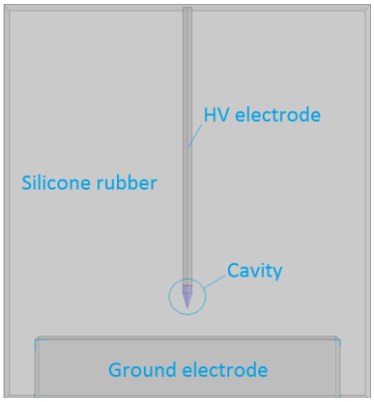
Compared to other known insulation materials as cross-linked polyethylene (XLPE) and polyethylene (PE), few studies has been performed on silicone rubber. In order for manufacturers of high voltage cables and accessories to meet the future requirements, more research must be done on the material.

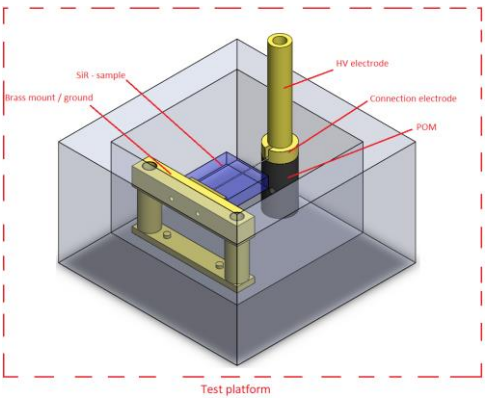
The task

Electrical tree growth is a precursor to electrical breakdown in high voltage insulation materials. The project work will mainly be experimental, where the main purpose is to test and use a new experimental set-up for studying the correlation between electroluminescence and partial discharge pattern in silicone rubber samples. This should be done by the use of a needle-plane gap. By extracting the needle partly, a needle-tip shaped void should be made in order to examine the partial discharges and electroluminescence occurring in air cavities. A proper molding and testing procedure should be made.

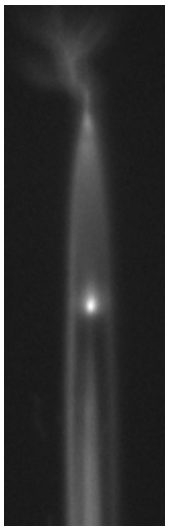
Model/ measurements

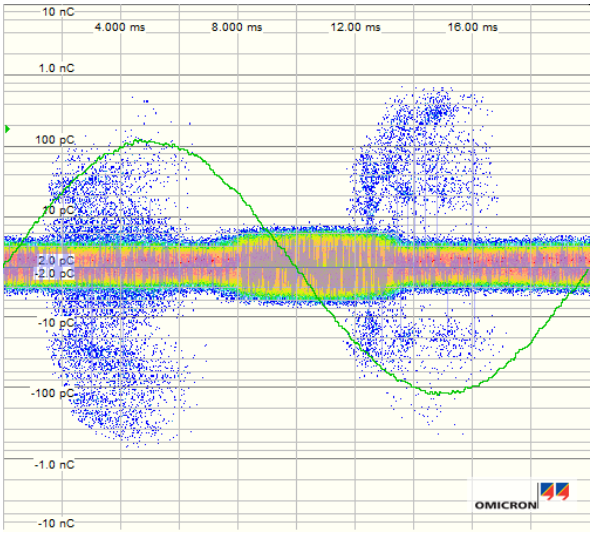
By the use of a needle-plane gap and a pre-made cavity, a correlation between electroluminescence and partial discharge patterns has been studied.





Calculation





Conclusion

In this theses a correlation between the partial discharge pattern occurring in a silicone rubber sample, both with and without a pre-made crack, and the light emitted has been examined.

Silicone rubber samples have successfully been molded, with and without a pre-made cavity. A molding procedure has been found for both types.

It has been found that partial discharges occurs almost instantaneously after switching on voltage. The intensity of the light is depending on the dissipated energy during partial discharges. Small magnitudes of partial discharges were often found to have the highest light intensity due to the high numbers of discharges. By examining the samples after testing it was found that the cavity surface tip was deteriorated; the samples containing a pre-made crack had electrical tree growth or electrical breakdown while the samples without a pre-made crack had visible deteriorating cavity tip. It is likely that electrical treeing soon would appear in these samples as well.

The impact of grid tariffs based on demand charges

Student: **Torleif Møretrø Moen**
Supervisor: **Gerard Doorman, IEL**

Abstract

In recent years, there has been an increase in power consumption for the consumers in the distribution grid. The consequence of this, combined with the consumers being inelastic, has forced the distribution system operators and transmission system operator to invest in the power grid system. To delay or scrap the investments, the Norwegian Water Resources and Energy Directorate (NVE) has proposed to change the current grid tariff, the energy tariff, to a new power based grid tariff named the subscription tariff.

In this thesis, an analysis of the subscription tariff is presented. Also, an analysis is conducted to find the ideal excess demand with the other parts of the subscription tariff given. Two alternatives for the subscription fee is then presented, and the excess demand fee is found for both of these. Further, an analysis is conducted on each alternative, and the ideal subscription fee is chosen to be 60 [NOK/kW/month] based on the analysis, and is used subsequently throughout the thesis. The ideal subscription tariff is then applied to move the consumption for each consumer. A reduction of 6.35% between the original and mov-ing scenario is obtained.

The reduction is then used for further analysis with the EMPS model. The firm power profile - "fastkraftprofilen"- is used to gain a similar decrease in general supply for the EMPS model. To achieve 6% reduction in peak load, the profile is flattened out with 40%. An analysis of the EMPS model is then performed, where two scenarios are presented, the original EMPS firm power profile and the 40% reduced firm power profile. The analysis concludes that the peak is reduced by 6%, which is the same as for the load data set. For the socio-economic perspective, the moving of the consumption gives a surplus for the whole system, while for Norway there is a loss. This is due to the producers losing more than the consumers are gaining. The thesis also follows the change in economic and de-mand for a consumer, where the reduction in grid tariff is -10% for all consumers when moving the consumption.

Investigation of Electrical Properties of a new low-GWP Insulation Gas

Student: **Ruben Mong**
Supervisor: **Frank Mauseth**

Problem description

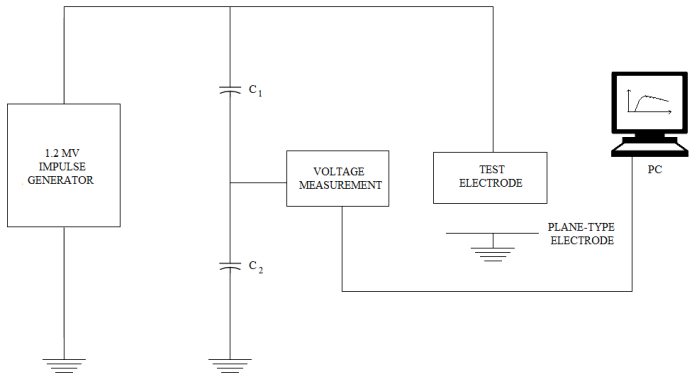
SF_6 is currently a commonly used gas in medium-voltage insulation equipment. Due to its high global warming potential (GWP), new gases with lower environmental impact are sought. This thesis investigates one possible insulation gas called AirPlus, a mixture of synthetic air and C_5 Perfluoroketone.

The task

AirPlus will be investigated using the up-and-down method for time efficient estimation of the 50% breakdown voltage for lightning impulses (LI) and the standard deviation. Parameters of interest are gas pressure, LI polarity, and electrode shape. The electrodes are chosen to represent a homogeneous field using a plane-plane configuration together with three rod-plane configurations resulting in inhomogeneous fields.

Model/ measurements

The electrodes are located within a gas sealed tank. The lightning impulses at the energised electrode are generated by a 1.2 MV impulse generator with a standard 1.2/50µs shape. With the circuit, the two most important values for further analysis, peak voltage and type of event (breakdown/withstand) can be found.



Circuit used for voltage testing and measurements

Gas tank containing the electrodes

Calculation

In homogeneous fields, the results for the plane-plane gap showed negligible impact of LI polarity for both synthetic air and AirPlus. For the three rod-plane gaps, the inhomogeneous field distribution confirmed that synthetic air is most dependent on positive polarity, resulting in higher values for $U_{50\%}$ compared with negative polarity. AirPlus on the other hand is most dependent on negative polarity, sharing the same property as SF_6, resulting in higher values for $U_{50\%}$ compared with positive polarity. The difference between negative polarity and positive polarity in AirPlus is generally 7-10 kV or higher.

The study of inhomogeneity and breakdown voltage revealed that AirPlus could be more sensitive to increased inhomogeneity than synthetic air. The critical flashover voltage is 50% larger for AirPlus compared with synthetic air in homogeneous fields, but for inhomogeneous

fields, the measured critical flashover voltage is only 30% larger in AirPlus compared with synthetic air.

Before changing a parameter, each test series was re-tested for the first gap length after performing the up-and-down method for all gap lengths. The re-testing resulted in an average increase of 10.6% for synthetic air and only 1.8% for AirPlus. The low impact of breakdowns is also reflected in the gas analysis of AirPlus which showed no indication of gas decomposition after 94 LI breakdowns at 1.50 bar.

Conclusion

For the scope of this project, AirPlus is an improvement from synthetic air and can be used for more compact protection designs. It is also beneficial that the critical flashover voltage in AirPlus is less affected by breakdowns than synthetic air. An important discovery is the potential reduced dielectric strength for increased field inhomogeneity caused by the shape of the electrodes, reducing the benefit of using AirPlus instead of synthetic air, from 50% to approximately 30%.

Performance of Stability Indicators based on Phasor Measurements

Student: **Pascal Muhirwa**
Supervisor: **Kjetil Uhlen**
Contact:
Collaboration with:

Abstract
The development of Wide Area Measurements (WAMS) is growing with the increasing usage of Phasor Measurements Units(PMU) in power systems. Its introduction gives power system operators greater observability, as PMUs can measure the voltage angle and magnitude in real time (up to 50/60 recordings per second), with the help of GPS technology. Given better situational awareness, system operators gain a higher chance of preventing unstable or insecure operation of the power system. The applications of PMU measurements are many, on the subject of power system stability the availability of using PMU measurements makes it possible to estimate system modal characteristics directly from the measurements. System identification and signal processing method has in the last decades been studied and customized for power system application, particularity to estimate modal properties in power systems.

The objective of this thesis is to assess the performance of two algorithms which are commonly used in the structure and civil engineering for modal estimation. The two methods investigated in this report, are the Natural Excitation Technique used in conjunction with Eigensystem Realization Algorithm (NExT-ERA) and Multivariate Auto-regressive model(MAR). The NexT-ERA is a twofold algorithm. The first algorithm, The Natural Excitation Technique, can estimate impulse responses of power systems by calculating cross-correlation functions between measurement. The second algorithm, Eigensystem Realization Algorithm, uses the impulse responses calculated with NExT to estimate a state-space model of the power system. From the state matrix, the eigenvalues which describes the dynamic of the system can thus be extracted. Multivariate Auto-regressive model is an extension of the Auto-regressive model which uses multiple signals to fit into the model. The modal properties can be calculated by the parameters of the MAR model by eigendecomposition.

This thesis shows that the methods can estimate the electromechanical modes, which correspond to low-frequency oscillations that are excited by continuously varying loads. The performance of the methods is investigated by comparing prior knowledge of the modal properties from a synthetic signal, simulation model and the Nordic power grid with estimated values. The evaluation of the performance of the methods is based on the consistency of the estimation for different window length and model order. The evaluated results are designated to give the reader input on how NExT-ERA and MAR perform as a stability indicator for power systems. Which may motivate the reader to implement and study the method further with the intent to create an application for real-time and off-line modal identification.

Modelling, Simulation, and On-line detection of Rotor Eccentricity in Hydro Generators

Student: **Andreas Blix Møller**
Supervisor: **Arne Nysveen**
Contact: **arne.nysveen@ntnu.no**
Co-Supervisor: **Mostafa Valavi**

Collaboration with: **Statkraft Energi AS**

Problem description

Hydro generators are a critical component of the hydropower power plant, and its failures can have a high associated cost and long downtime. To avoid excessive downtime and repair cost hydro generators are subjected to preventive maintenance. Preventive maintenance aim to reduce the repair cost, by repair or replacing faulty components before a critical failure occurs. To do this it needs to monitor the condition of the generator, this is done through inspections or on-line monitoring of fault related signals. On-line monitoring is normally preferred if it is cost-effective and accurate, because it can reduce downtime and increase safety by continuously giving the current condition of the generator. A new on-line, non-invasive detection method has been proposed for detection of rotor interturn short circuit faults. This method is based on the detection of fault induced sideband harmonics. Similar harmonics are induced by rotor eccentricity, and there was therefore an interest in investigating if the method can be used for detection of rotor eccentricity faults, and if it can differentiate between the two fault cases.

The task

Investigate if the method proposed for rotor interturn short circuit detection are capable of detecting the eccentricity condition of the generator. The methods capability of differentiating the two fault cases were also investigated.

Modelling

The fault response of the generator was simulated in Ansys Maxwell, a finite element software capable of doing transient simulations. Several models were simulated, one based on technical data for a real hydro generator, and three other models with slight modifications from the first one. All the models were made in 2D. Several models were simulated to investigate the impact of the generator topology on the induced sideband harmonics.

Result

Results of the simulation showed that dynamic and mixed eccentricity produce fault induced detectable sideband harmonics, shown for dynamic eccentricity in figure 1. The simulations on one of the other models did have elimination of these detectable fault induced harmonics shown in figure 2.

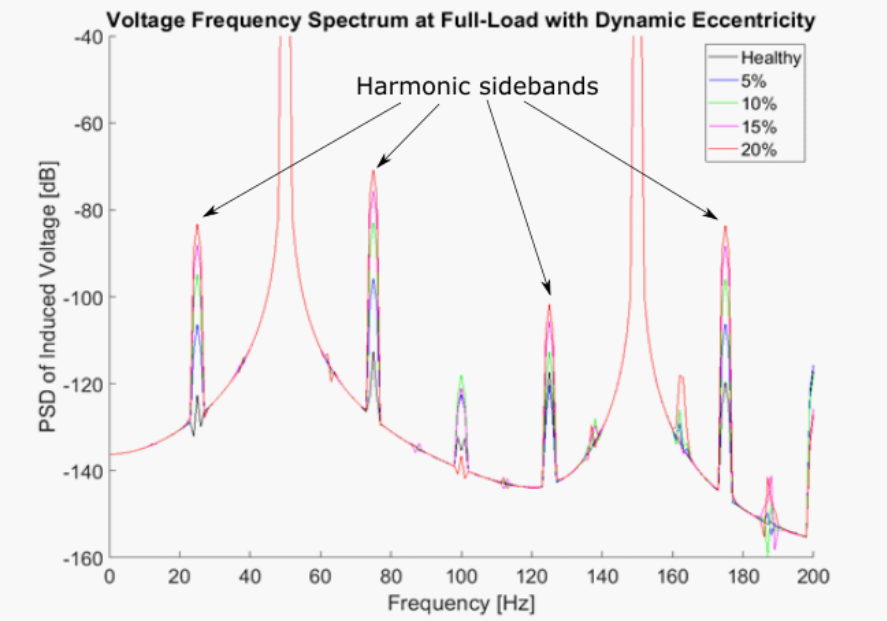


Figure 1: Power spectral density of the stator phase voltage for different degrees of dynamic eccentricity.

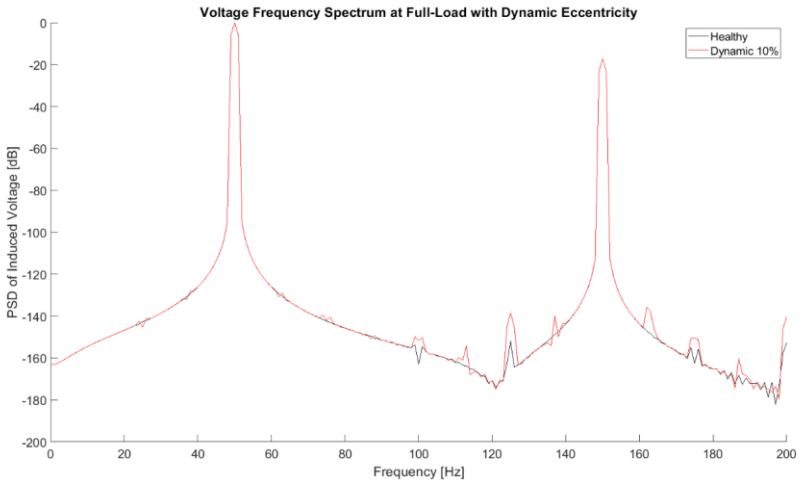


Figure 2: Power spectral density of the stator phase voltage for 10% dynamic eccentricity. No clear harmonic sidebands do occur.

Conclusion

The method ability to detect eccentricity and rotor interturn short circuit faults are highly topology dependent, some topologies can eliminate the harmonic sidebands used as fault indicators. For generators, which does not have this elimination, the method is capable of detecting pure dynamic eccentricity as it enters critical levels. The method is capable of detecting mixed eccentricity, but some low critical levels can go undetected. The method is unsuited for static eccentricity detection. The amplitude of the harmonic sidebands is dependent on fault severity, therefore the harmonics can be used to estimate the fault severity. Eccentricity with dynamic eccentricity component can be differentiated from the fault cases with rotor interturn fault short circuit by comparing the amplitude of two of the most prominent harmonic sidebands.

Sensorless Control of a 6-Phase Induction Motor

Student: **Emil Mørkved**
Supervisor: **Prof. Roy Nilsen**

Problem description
Sensorless control is now the standard control method in the industry for induction machines. However, the method experience some challenges. Especially the open integration in the voltage model will experience drifting and DC offset as a result of a wrongly estimated stator resistance and measurement errors in the current and voltage. The error caused from an erroneous estimation of the stator resistance becomes more dramatic in the low speed region. Hence a correction algorithm is necessary.

The task
In this thesis a model earlier developed shall be analyzed and possibly improved in the low speed region. The main focus in this thesis shall be:

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

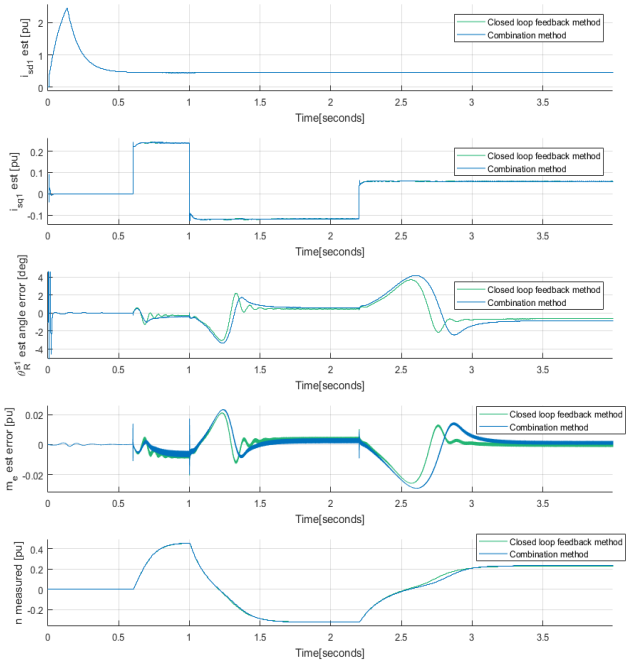
Model/ measurements

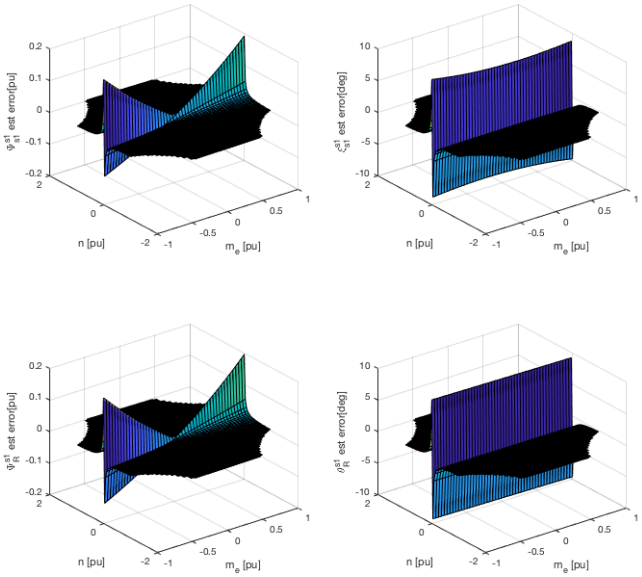
The voltage model:

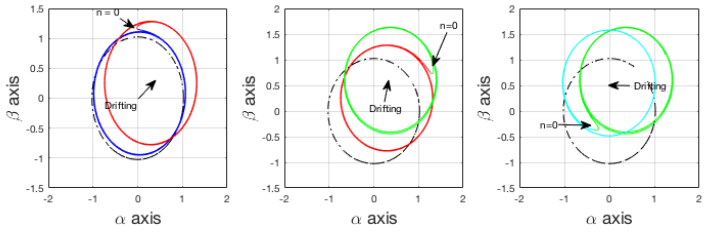
$$\hat{\psi}_{s1}[k] = \int_{k-1}^{k} u_{s1}[k] - \hat{r}_s i_{s1}[k]dt + \hat{\psi}_{s1}[k-1]$$

Early in the project the parameter sensitivity in steady state was analyzed using a script developed in MATLAB by the student. The analysis covered both the voltage model and the current model. Later parameter sensitivity of the voltage model during a dynamic state was investigated using a model in MATLAB Simulink that was developed before the project started. It was confirmed in both steady state and dynamic state that an error in the estimated stator resistance would be problematic in the voltage model. A correction algorithm was tested and in addition a new correction algorithm was developed using a combination of the voltage model and the current model and using the difference between the models as a correction feedback. The simulations done in this thesis is done in MATLAB Simulink with the ode23tb solver with maximum step time as 100 μs and the solver reset method is set to robust.

Calculations:







Conclusion

The parameter sensitivity analysis revealed the challenges with the low-speed operation when the stator resistance was estimated erroneous. Both stationary analysis and dynamical analysis that investigated the drifting phenomenon with extra attention. Two correction method was analysed. One developed by Niemelä in his doctoral thesis from 1999. (Niemelä, 1999) An alternative method based on a combination between the voltage model and the current model, developed by the author, showed interesting performance and was reliable in crossing zero speed.

(Niemelä, 1999)

Analyse av seksjoneringsmetodikker i høyspennings distribusjonsnett

Student: **Emil Hjelmseth Olsen**

Veileder: **Kjell Sand**

Utføres i samarbeid med: **Powel AS og BKK Nett**

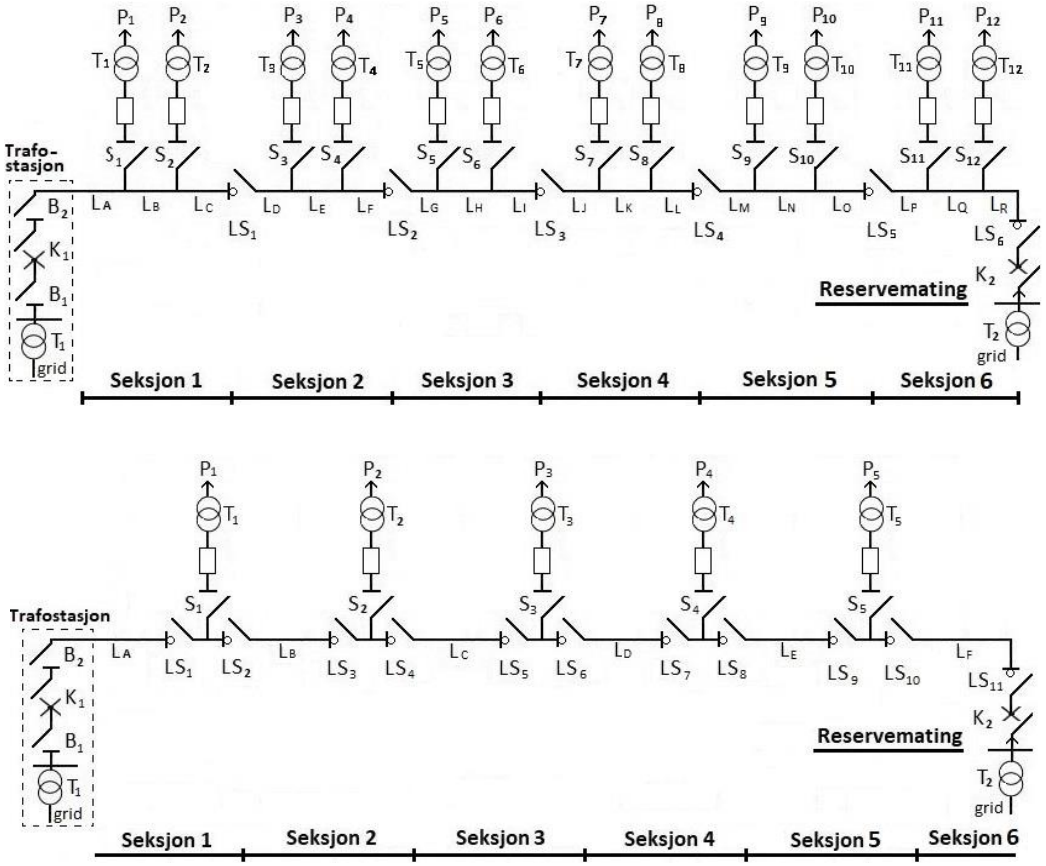
Problemstilling
Myndighetenes regulering av nettselskapers inntektsrammer stiller krav om opprettholdelse av høy leveringspålitelighet og kostnadseffektiv drift og utbygging av strømnettet. Et viktig element som inngår i nettselskapenes kostnadsgrunnlag er de kvalitetsjusterte inntektsrammene ved ikke levert energi, som representerer de totale samfunnsøkonomiske kostnadene som påføres sluttbrukerne ved avbrudd. Bruk av optimal seksjoneringsmetode og seksjoneringsmetodikk er en av mange måter å forbedre påliteligheten og redusere de årlige KILE-kostnadene.

Oppgaven
I feilsituasjoner seksjoneres distribusjonsnettet for lokalisering og isolering av feil, samt gjenoppretting av forsyning til friske deler av strømnettet. Seksjoneringsmetodikkene og kriteriene de baserer seg på varierer derimot fra nettselskap til nettselskap. Formålet med denne rapporten er å utvikle en metodikk for beregning av optimal seksjoneringsmetodikk i forenklede høyspennings luft- og kabelnett modeller.

Delaktiviteter som ønskes adressert:
- Utvikle metode for pålitelighetsanalyser av luft- og kabelnett-modell
- Identifisere relevante inputparametere og risiko- og kostnadsforbundet kriterier ved seksjonering
- Drøft fordeler og ulemper med seksjoneringsmetodene og de definerte kriteriene
- Identifiser optimal seksjoneringsmetodikk for nettmodeller

Modeller

Pålitelighetsanalysene er utført på to fiktive nettmodeller som representerer forenklede høyspennings luft- og kabelnett. Den øverste figuren illustrerer luftnett modellen, mens den nederste figuren kabelnett modellen.



Beregninger

Pålitelighetsberegningene baserer seg på bruk av RELRAD-metoden, og er utført i regneark i Excel. For å beskrive påliteligheten ved bruk av ulike seksjoneringsmetodikker er de forventede pålitelighetsindeksene KILE, ILE, SAIDI, ASAI og $P_{avbrutt}$ er beregnet, samt årlig antall innkoblinger mot varige feil. Det er i tillegg kalkulert forventningsverdier for avbrudds-varigheter i lastpunkter og antall innkoblinger mot varige feil.

De ulike seksjoneringsmetodikkene er detaljert beskrevet ved hjelp av flytskjema, og baserer seg på samtaler med veiledere, SINTEF Energi og driftspersonell i ulike nettselskaper.

Konklusjon

Det fremkommer av resultatene at analyser av seksjoneringsmetodikker er nødvendige da metodikkene som benyttes i virkeligheten ikke nødvendigvis gir best resultater. Pålitelighetsberegningene viser at enkelte seksjoneringsmetodikker gir langt bedre pålitelighet og lavere årlige forventede avbruddskostnader enn andre. Likevel er det ikke slik at metodikkene som gir lavest årlig avbruddskostnader nødvendigvis er optimale, da økonomiske innvirkninger tilknyttet manglede spenningskvalitet, aldring av komponenter og personsikkerhet grunnet innkoblinger mot varige feil også må tas i betraktning.

Reduksjon av effekttopper i kontorbygg

Student: **Marie Sveen Olsen**
Veileder: **Eilif Hugo Hansen**

Sammendrag

Den totale kraftetterspørselen i Norge er forventet å øke fra 133 TWh i 2016 til 146 TWh innen 2030. Lastene knyttet til nettet forventes også å bli mer effektkrevende. I tillegg forventes andelen enkelt regulerbar energi å synke fra 70 % til 58 % i løpet av den samme perioden. Kombinasjonen av dette vil gjøre det vanskelig for det norske strømnettet å håndtere de største effekttoppene.

Formålet med oppgaven er derfor å komme frem til en metode for å anbefale effektutjevnende tiltak i kontorbygg, samt beskrive fordelene ved en utjevning.

Dette blir gjort ved å først beskrive de samfunnsmessige og økonomiske fordelene ved en reduksjon av effekttopper, samt gjøre rede for ulike reduksjonsmetoder. Det er mindre utbygging av strømnettet sammen med en muliggjøring av større andel vind- og solkraft som er vurdert som de største fordelene.

Deretter blir lastprofilen til to kontorbygg analysert. Måleresultatene fra Geologibygget viser at det er oppvarming som er mest effektivt å begrense strømbruken til, dersom de høyeste effekttoppene skal reduseres. Det er mandag morgen mellom 07:30 og 08:30, samt etter strømbrudd at disse toppene opptrer. For Otto Nielsens veg 12E er det varmepumpe og kjølemaskin som står for 42 % av den høyeste effekttoppen, og jevnt over for 40 % av de 15 høyeste toppene. Toppene oppstår her mellom 11:00 og 12:00 på hverdager med mye aktivitet på kontoret.

Tiltakene som blir anbefalt for Geologibygget er et batteri, en maksimalvokter og å iverksette etterisoleringstiltak. For Otto Nielsens veg 12E er et termisk vannlager anbefalt, sammen med en maksimalvokter.

Lastprofilene og litteraturstudiet danner grunnlaget for en anbefalingsmetode for effektreduserende tiltak i kontorbygg, programmert med Excel VBA. Anbefalingsmetoden er basert på syv kriterier som viser seg avgjørende for hvilke effektreduserende tiltak som bør iverksettes.

Analysis and Optimization of Medium Voltage Line Voltage Regulators

Student: **Pankaj Raghav Partha Sarathy**
Supervisor: **Kjell Sand, IEL**
Co-supervisors: P**avol Bauer, Technical University of Delft**
Tobias Asshauer, ABB Brilon, Germany

Abstract

In recent years, distribution networks have been facing voltage quality issues due to the influx of renewable energy. Rural areas which are ideal for renewable energy development due to large vacant areas are faced with grid voltage variations due to long distribution lines. Because of the stringent conditions laid by the Distribu-tion System Operators (DSOs) on voltage variations, voltage regulation is becoming increasingly important in the distribution grid. A complete grid reinforcement by replacing the conductors can be very expensive for the DSOs. Active solutions such as shunt and series compensation provides an economical solution to address the voltage regulation issues in the distribution grids.

The initial part of this work focuses on quantitatively studying the impact of series and shunt compen-sation on increasing the grid capacity of a Medium Voltage(MV) line compared to a grid reinforcement with conductor upgradation. The analysis was done on a 20 kV, 10 MVA radial line with 5 loads distributed equally along the line, and a generator at the end of the line. An algorithm was developed in MATLAB/ Simulink to determine the allowable grid capacity to stay within the thermal and voltage limits for different voltage reg-ulation strategies. The study indicates that the series voltage regulation with Line Voltage Regulators(LVR) is an effective solution in increasing the grid capacity by actively regulating the voltage in the grid. The MV-LVR product offered by ABB consists of dry-type transformers and mechanical contactors for changing the tap position. However, dry-type transformers are bigger in size and more expensive than oil-type transform-ers. To reduce the cost and the size of the MV-LVR, the study is focused on the feasibility of a MV-LVR with oil-type transformers and On-Load Tap-Changers (OLTCs). The second part of the project work focuses on developing an economical LVR configuration with an oil-type transformer and a mechanical OLTC. ECOTAP VPD III 100 from Maschinenfabrik Reinhausen (MR) was selected as the mechanical OLTC to perform the tap changing operation in the LVR. ECOTAP OLTC enables low maintenance of transformers due to the use of vacuum switches for quenching the arc during tap-changes. 7 LVR configurations with single and two active parts are investigated. All the configurations are finally compared for their cost and range of operation. The final part of the work focuses on a feasibility study of a power electronics based OLTC for LVR applications as mechanical OLTCs require regular maintenance. Anti-parallel thyristors are used as the solid-state switches for the LVR application due to its low cost and losses. Commutation instants are defined for the complete power factor range for the thyristor based OLTC to have no/controlled short circuit during tap-changes.

The two active parts LVR configuration constructed with a center tapped feeder transformer and a booster transformer with the ECOTAP VPD III 100 OLTC is economical for a 20 kV, 10 MVA feeder line. A LVR rated at 20 kV, 10 MVA with ±6% voltage regulation using the selected configuration was simulated in MATLAB/Simulink. A 400 V, 5 kVA low voltage

setup was built with the ECOTAP VPD III 100 OLTC, and the LVR con-figuration was verified with experimental results. The feeder transformer model with two taps was simulated in MATLAB/Simulink for switching up and switching down operation with a thyristor based OLTC for capac-itive, inductive and resistive power factors. The complete LVR system with thyristor based OLTC placed in a MV distribution line was simulated to verify the control algorithm used for the commutation. The thyristor based OLTC successfully performs tap-changes for a LVR system with a low voltage stress on the thyristor, and low short circuit currents between the taps for certain power factor angles during the commutation process.

Teknisk-økonomisk planlegging av mikronett

Student: **Mari Andrea Pedersen**
Veileder: **Kjell Sand**
Medveileder: **Gøril Forbord**
Samarbeid med: **TrønderEnergi**

Masteroppgaven studerer hvordan rammevilkår påvirker planleggingen av mikronett i et teknisk-økonomisk perspektiv.

Et mikronett er et lokalt kraftnett med distribuerte energikilder og laster innenfor klare definerte elektriske grenser. Det kan driftes enten isolert fra andre kraftnett eller tilkoblet. Rammevilkårene i Norge baserer seg på de norske lovene. Det er spesielt energiloven som er relevant for anleggelse av mikronett.

Det ble laget en planleggingsmetodikk for mikronett. Metodikken består av fire faser. Første fase er å etablere forutsetningene og sette opp ulike systemgrenser som mikronettet kan ha. I den andre fasen skal energiressurser bestemmes og ulike driftsstrategier skal etableres. De ulike driftsstrategiene skal evalueres med tanke på energibalanse, kjøp, salg og struping av energi. I tredje fase skal det kontrolleres at de ulike alternativene funnet i de foregående fasene overholder tekniske krav, og tekniske analyser skal gjennomgås. Den fjerde fasen går gjennom alle vurderingskriteriene, og skal komme med en anbefaling for beste alternative løsning.

Ved å se på Brattøra i Trondheim som et aktuelt område for mikronett ble det funnet 12 ulike systemgrenser. Området kan få fritak fra konsesjoner ved å bruke plusskundeløsning. I fase to ble det sett på ulike driftsstrategier med og uten batteri. I fase tre ble det funnet at de ulike alternativene sto likt med tanke på tekniske analyser. I fase fire ble de ulike løsningen vurdert. Forskjellen mellom alternativene var økonomisk lønnsomhet og energi brukt lokalt. Alternativene som inneholdt batteri hadde større investeringskostnader enn nytteverdi. Driftsstrategien som kom best ut var plusskunde med 100kW grense. Systemgrensen som inkluderer alle de fire bygningen har en inntekt på 3,5 millioner mer enn neste systemgrense. Det ble også funnet at denne løsningen gir god bruk av energien lokalt.

Ved å ha 500kW grense for plusskundeordningen kan eier av mikronettet tjene 2,7 millioner mer enn ved å ha 100 kW grense. I området for dette mikronettet er det ikke behov for ekstra oppgraderinger av kraftnettet ved å utvide plusskundegrensen. Ved å la systemgrensene inkludere flere bygninger minskes den totale forbrukseffekten for det området slik at kraftnettet kan dimensjoneres på et lavere nivå eller en kan unngå utbygging. Hvordan utbygging påvirker ovenforliggende nett er individuelt i hvert enkelt tilfelle, og det bør beregnes om mikronettet er en fordel eller ulempe for overforliggende nett.

Dielectric response and electrical conductivity of mass impregnated HVDC cable insulation

Student: **Lars Erik Pettersen**
Supervisor: **Erling Ildstad**
Contact:
Collaboration with:

Problem description
Mass-impregnated non-draining (MIND) paper insulation has been used since the 1950's and is still the choice for the longest high voltage direct current (HVDC) subsea cables. These cables consist of paper strips wrapped helically around a conductor and impregnated with high-viscous mineral oil. The paper strips are wrapped in such a way that gaps, called "butt gaps", are left between adjacent strips which allows bending of the cable. During the impregnation process, oil fills the fibrous structure in the paper and butt gaps. HVDC cables have long lifetimes but with an increasing demand for transfer of electrical energy their capacity may become insufficient. However, recent results of conductivity and electrical field distribution indicates a possibility of increasing the total capacity by increasing both maximum load current and DC voltage.

The task
The main purpose of the work in this thesis is to gather data which facilitates such capacity improvements. Conductivities of both paper and oil are of interest. Several samples with combinations of paper and oil are constructed for this purpose. The applicability of the Hamon approximation for each sample is also tested. Minor studies of the methodology development were also performed.

Methodology
Currents were gathered from samples of insulating paper using the method of "Polarization Depolarization Current" (PDC) in a laboratory setup. This method consisted of applying and removing a DC-voltage to a paper sample, which resulted in the flow of polarization current i_p and depolarization currents i_d, as shown in figure 1.

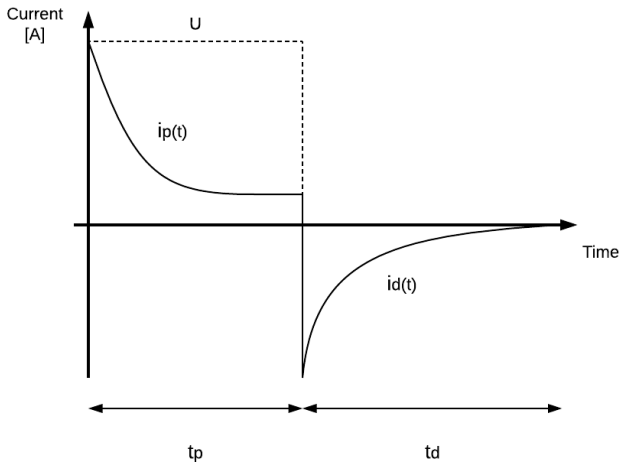


Figure 1 Typical curves of polarization current i_p and depolarization i_d current.

The region when the polarization current had reached a steady state (at the end of t_p) was used to obtain the conductivity of each sample.

Stacks containing several sheets of paper were made and impregnated in oil. Modified stacks containing oil pockets (called bulk oil stacks) and strips of paper to simulate butt gaps (called butt gap stacks) were also created, shown in figure 2, 3 and 4.

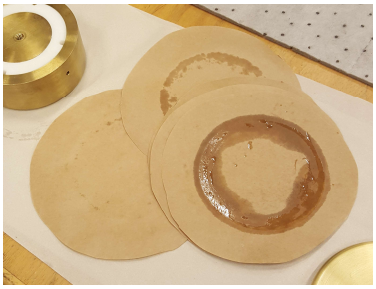


Figure 2 Paper stack

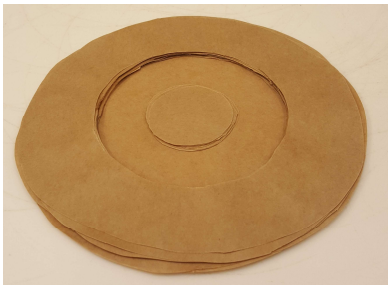


Figure 3 Bulk oil stack

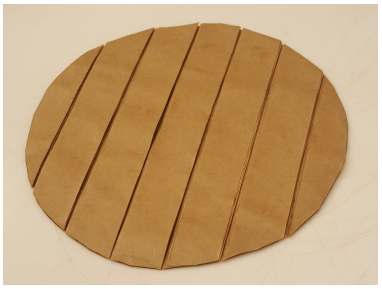


Figure 4 Butt gap stack

By creating paper stacks with no more than 5 sheets and combining these with bulk oil and butt gap stacks, which had various thicknesses, a flexible system was achieved. This system enabled many combinations of paper, bulk oil and butt gap stacks, which were combines to form samples. Using this system, the steady state current was studied in samples with paper in both series and parallel connections with oil. A sample of paper was stressed with several voltages and temperatures, while bulk oil and butt gap samples were only stressed with several voltages.
A formula expressing the conductivity of paper was derived from stressing paper samples and compared with the literature. A formula expressing the conductivity of oil was derived from bulk oil samples utilizing the results from stressing paper samples. Lastly, an expression of the expected steady state current in butt gap samples were derived utilizing expressions of conductivity of both paper and oil. These calculations were compared with measured steady state currents.

Conclusion
From the main study:

- A paper sample was stressed with electric fields in the range E = 10 – 40 kV/mm and temperatures of T = 23 – 83 °C, where the results were in accordance with the literature.
- Bulk oil samples showed an exponential dependency of voltage, but this curve became linear with increasing bulk oil volume. The voltage across the bulk oil differed significantly from zero, which opposes previous assumptions. The conductivity of oil was in the same range as for paper and showed an exponential dependency of voltage.
- Calculated currents in a butt gap sample compared with measured values showed equal magnitudes at low voltage but with different rate of rises. A sensitivity analysis revealed that the parameters in conductivity of paper were by far the most sensitive in this calculation.
- Paper samples were applicable for the Hamon approximation but neither bulk oil samples nor butt gap samples were applicable.

From the methodology development:

- PDC was an efficient method for monitoring the impregnation process. Steady state current in impregnated paper was lower by a factor of 10 compared to dried paper.
- Insufficient polarization duration t_p significantly affected the steady state current at low voltages. The depolarization currents were more affected by short durations than polarization but the magnitudes were only regarded as noise.
- Delay of at least one day was required after switching samples.
- At least 5 sheets in a paper sample was sufficient for PDC measurements.

Optimal design of wind turbine converters using advanced power semiconductor materials

Student: **Namireddy Praveen Reddy**
Supervisor: **Dimosthenis Peftitsis, IEL**
Co-supervisor: **Danilo Iglesias Brandão, Universidade Federal De Minas Gerais**

Summary

The tremendous increase in the wind farm installations worldwide during the last two decades is associated with the massive penetration of power electronic converters suitable to perform high efficiency electrical energy conversions. There exist several design and performance challenges related to these power electronic converters. These are not only related to the electrical and thermal performance of the converters, but also to the physical size of the complete system. Many of these challenges can be addressed by studying the power semiconductor devices, which are the heart of power electronic converters. Considering modern silicon-based semiconductors have already reached their theoretical material limits, there is need to utilise the advantageous performance of the recently developed wide band gap semiconductors. Silicon carbide power diodes and transistors are among the successful wide band gap power devices.

An all DC series connected wind farm configuration has minimum number of conversion stages. Modular multilevel converter has many advantages over other multilevel converter topologies and is a promising topology for medium and high-power applications. As silicon has reached its physical limits, wide band gap semiconductors are emerging as promising alternatives. A combination of all three suggested has not been researched so far for multiple objective optimization. This research is an attempt to realize benefits and challenges of this combination. The scope of optimization is semiconductor power losses, total harmonic distortion and operating junction temperature.

The research work is focused on reviewing the state of the art literature regarding modular multilevel converter to understand the operating principles, control methods. A wind generator side converter using modular multilevel converter topology and silicon carbide MOSFET is developed in Simulink/MATLAB environment. Sixty-two number of simulations are carried by varying the number of sub modules per arm and the number of parallel connected semiconductor devices. In each simulation, semiconductor power losses and total harmonic distortion are measured.

The simulation results show that the silicon carbide MOSFET with lowest voltage rating is found suitable due to higher number of sub modules and voltage levels, better voltage waveform, reduced filter requirement, lower semiconductor losses, less cost. Furthermore, minimum number of sub modules and maximum number of parallel connected devices result in lower losses.

Battery Energy Storage Integration via DC/AC Converter in Grid Connected Wind Turbines

Student: **Kristin Rekdal**
Supervisor: **Dimosthenis Peftitsis**
Contact: **Kamran Sharifabadi**
Collaboration with: **Equinor ASA**

Problem description
Considering the continuously increasing power ratings of wind turbines and the introduction of more demanding grid codes for wind farm interconnection to utility, the natural intermittent of the wind resource may influence the stability of the traditional power system. Potential imbalances between the power generation and consumption can be efficiently compensated by introducing energy storage systems interconnected to the grid. In order to integrate energy storage systems into the grid, a proper power electronics interface, having an inherent bidirectional power flow capability, is required.

The scope of this project is to study the integration of battery energy storage into a 10 MW wind energy system. More specifically, the main task of the project is to investigate the performance of a selected power electronics converter both under regular operation and under various fault scenarios.

The M.Sc. thesis during spring 2018 will have a specific focus on:

- Detailed modelling of a DC/AC power electronics converter suitable to interface the energy storage to the AC grid using Matlab/Simulink. Proper control strategies will also be studied and modelled.
- Electrical performance investigation of the system under various fault scenarios and various fault locations.
- Based in the results, identify some fault handling strategies and the most critical fault

Abstract

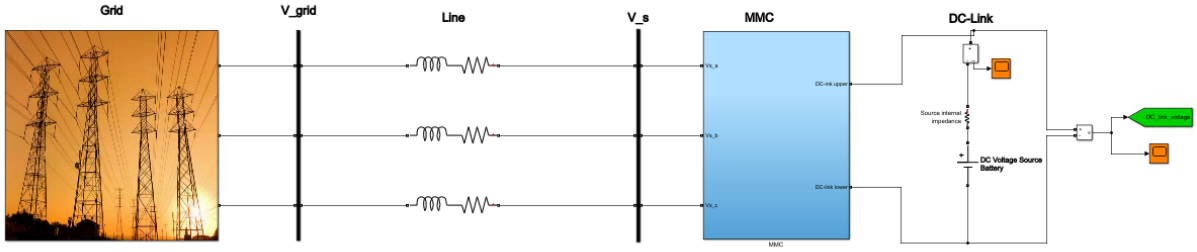
The growing need of battery energy storage to support the increase in renewable production in the electricity mix has brought the attention to the modular multilevel converter (MMC) for medium voltage applications. Modular multilevel converters have been verified as most promising battery interface as it has very high efficiency, excellent AC waveforms, scalable and modular structure and it allows for the use of low rating semiconductors. In addition, it provides redundancy due to the ability of distributing the batteries into each submodule. A drawback with the MMC, is that when half-bridge submodules are used, the converter cannot handle DC faults, hence it is necessary to understand the dynamics of the converter during various faults.

In this thesis, a MMC interfacing a 1 MW battery to the grid is built *Matwork's Matlab/Simulink*. Both the converter and control system are evaluated and designed to evaluate post-fault currents and voltages. The converter was designed with a DC voltage of 15 kV and five submodules in each arm. The degree of complexity chosen for this model is the submodule level switched model type, including IGBT, reverse diodes and SM capacitors. A

high carrier frequency and phase-shifted pulse-width modulation eliminate the need of submodule energy balancing. Five short circuit fault locations have been investigated, two inside the submodule, over one arm, on the DC-link and between two phases on the AC side of the converter. No fault handling strategies, AC- or DC breakers are implemented in the model.

The simulation of short circuit faults inside the submodules reviled that five submodules are not enough to ensure redundancy. The importance of developing fast responding DC breakers was demonstrated as the upper converter arm on phase *a* was short-circuited. As this fault only includes one phase, the first post fault zero-crossing appears too late to prevent damage on the converter. DC breakers are also necessary to prevent the extremely high discharge current from the battery to the fault during the short circuit fault on the DC-link. During the short circuit fault between two phases, all semiconductors will be damaged by the large current if no fault handling is applied, but on the other hand the zero-crossing appears fast enough to isolate the converter from the grid before the damage is done.

The most critical faults are the short circuit faults across one arm and across the DC link because they both requires DC circuit breakers, which is not yet commercialized.



El-sikkerhet for ladesystemer med jordfeil i elektriske kjøretøy

Student: **Jørgen Rendum**
Faglærer: **Eilif Hugo Hansen**
Veileder: **Eilif Hugo Hansen**

Sammendrag
På bakgrunn av økende bruk av elektriske kjøretøy, tar denne rapporten for seg flere aktuelle forhold ved jordfeil under lading av elektriske kjøretøy. Likestrøm kan flyte til jord dersom det er en jordfeil i den elektriske ombord-kretsen til elektriske kjøretøy under lading. Likestrøm kan påvirke jordfeilverns riktige drift, slik at det blir ufølsomt («blind») for ytterligere feilstrømmer og kan ikke garantere utkobling. Dette fenomenet kalles noen ganger for DC-blindhet.

For å opprettholde sikkerheten er det kommet nye nasjonale og internasjonale standarder. Flere forhold vedrørende jordfeil under lading av elektriske kjøretøy er under vurdering, som valg av jordfeilvern, antall faser og type nett-system kjøretøyet er tilkoblet. Rapporten gir innsikt i de ulike faktorene som er utslagsgivende ved valg av riktig jordfeilvern ved lading av elektriske kjøretøy.

Gjennom et laboratorieforsøk hvor ulike jordfeilvern type A er testet, er det konkludert med at jordfeilvern type A tåler likestrøm bedre enn hva som antas. Jordfeilvern type A med 30 mA merkeutløsestrøm kan opprettholde riktig drift ved påtrykket likestrøm fra opp under 60 mA til opp under 330 mA, avhengig av type vern og produsent. Samtidig er jordfeilverns evne til å koble ut avhengig av forholdet mellom AC- og DC-strømstyrken i jordfeilstrømmen. Likestrøm vil mest sannsynlig ikke føre til en betydelig økning i utkoblingstiden til jordfeilvern type A. Jordfeilvern type A fra anerkjente produsenter kan mest sannsynlig installeres oppstrøms jordfeilvern type B uten påvirkning av likestrøm, forutsatt at begge vern har en merkeutløsestrøm på 30 mA.

Gjennom en litteraturstudie er det konkludert med at det er størst sannsynlighet for DC-blindhet i et TN-nett på grunn av muligheten for trefaset lading som kan føre til jevn likestrøm til jord. I et IT-nett uten andre feil, vil en eventuell jordfeil i ombordladeren ved lading ikke føre til DC-blindhet av jordfeilvernet. Jordfeilstrømmen i lavspente fordelingsnett vil være avhengig av impedansen i feilkretsen, men totalt sett er jordfeilstrømmen hovedsakelig avhengig av det elektriske kjøretøyet.

Valg av riktig jordfeilvern ved lading av elektriske kjøretøy vil være avhengig av ombordladeren. Dersom ombordladere har høy isolasjonsresistans, forsterket isolasjon og galvanisk isolasjon er det liten sannsynlighet for at en jordfeil i ombordladeren vil forårsake DC-blindhet på forankoblede jordfeilvern type A. Dersom det kommer strengere sikkerhetskrav til ombordladere kan risikoen for likestrøm til jord kraftig reduseres, eventuelt elimineres.

Application of Optical Current Transformers in Digital Substations

Student: **Ingvill Urdal Rian**
Supervisor: **Hans Kristian Høidalen**
Collaboration with: **Statnett**

Problem description
Several transmission system operators (TSOs) have initiated the work to digitize their substations. This includes the Norwegian TSO, Statnett, which has implemented a small scale digital substation for testing purposes. Digital substations facilitate the integration of non-conventional instrument transformers (NCITs), such as optical current transformers (OCT). Such sensors are promised to bring significant improvements compared to conventional current transformers (CCTs).

Statnett has installed an OCT in their pilot digital substation in addition to a stand-alone merging unit (SAMU), which allow existing conventional instrument transformers (CITs) to be integrated into digital substations. It is thus of interest to gain a deeper understanding of OCTs to evaluate whether such sensors are suitable for application in digital substations in the transmission network. Since stand-alone merging units are likely to be applied in future digital substations, it is also relevant to perform experimental testing of such a device to investigate its performance and potential issues related to its application in digital substations.

The task
In this thesis OCTs are studied to evaluate whether such sensors are suitable for application in digital transmission substations. The analysis includes a discussion of benefits and drawbacks and an evaluation of performance, maturity and fulfillment of substation application requirements as well as the digital substation concept. Experimental testing of a SAMU is also performed with the objective of investigating its performance and comparing it to the performance of a conventional analog acquisition system. Potential impacts on the performance of transformer differential protection is also investigated.

Model/ measurements
A SAM600 SAMU was tested in the laboratory test setup which is shown in the figure. Two sets of three-phase currents were generated by the OMICRON CMC 356 test set and applied to the current inputs of the RET670 transformer protection relay and the SAM600-CT module, respectively. The disturbance recorder of the RET670 protection relay was used to record the currents from the SAMU and the analog acquisition system.

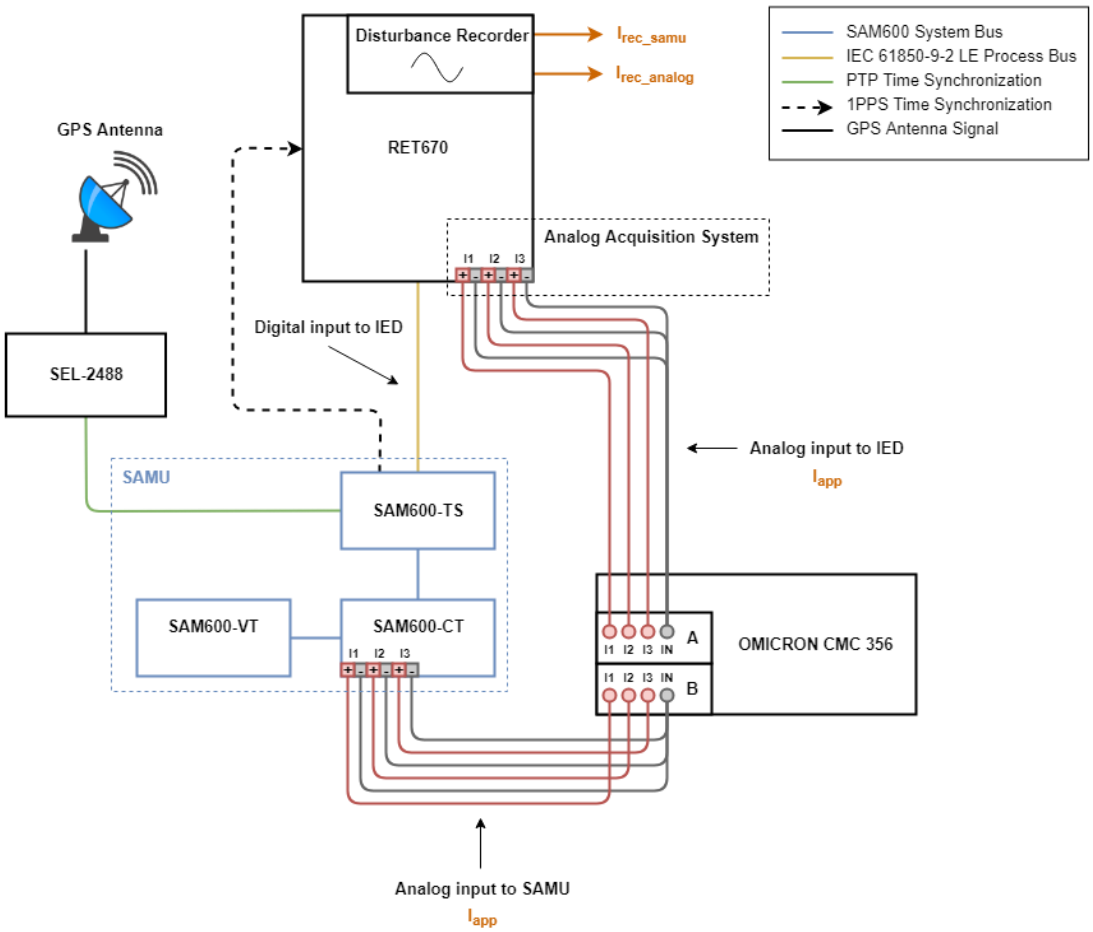
Calculation
The laboratory tests show that the SAMU has a steady state performance which is comparable to that of a conventional analog acquisition system and a significantly better transient performance. Because of the differing transient performances, fundamental frequency differential currents arise when these two technologies are combined in a hybrid mode configuration of a transformer differential protection. The resulting fundamental frequency differential currents are not big enough to affect the performance of the transformer differential protection in the tested cases.

Conclusion

OCTs transformers offer many benefits compared to conventional current transformers. Some of these are improved safety, reduced environmental impact, reduced need for maintenance and improvements in steady state and transient performance. The low weight facilitates integration with other primary equipment, which allows space to be saved in the substation yard. The combination of OCTs and a process bus makes the design of digital substations flexible and facilitates cost reductions.

The standards which apply to NCITs and digital substations often leave some room for interpretation. This may lead to lack of interoperability between devices from different vendors in a digital substation. Competence building will also be required, and digital substations may be expected to become more vulnerable than the present day conventional substations due to outdoor placement of electronics and stringent time synchronization requirements.

It is concluded that OCTs seem to be suitable for application in digital transmission substations. However, there are several signs that the products and solutions are not completely mature yet. There are several investigations to be made, questions to be answered and issues to be solved before a migration from the present day conventional substations with CCTs to digital substations with OCTs can take place.



A strategic investment model for multinational transmission expansion planning

Comparing competitive and centrally planned solutions for a North Sea Offshore Grid

Student: **Simon Indrøy Risanger**
Supervisor: **Magnus Korpås**
Martin Kristiansen

Abstract
Proper transmission expansion planning (TEP) is important to create an efficient electricity market that provide both economic and environmental benefits. However, if the expansion planner do not consider how the market agents act, situations may arise where market power can be exploited. To prevent this outcome, we propose a trilevel TEP problem where a market operator is in the lower level, multiple strategic countries trying to maximise their own welfare are in the intermediate and a benevolent system planner is in the upper level. Their actions will anticipate the behaviour of the other market participants.

When transforming the trilevel problem to a mixed-integer liner program (MILP), we use Karush– Kuhn–Tucker (KKT) conditions as optimality conditions for the lower level problem. The non-convex complementarity constraints are linearised into disjunctive constraints. To generate the intermediate problem optimality conditions, we again use KKT conditions, but exploit the relationship between the binary variables of the disjunctive constraints and the dual variables. We extend on current methodology which has to scan through multiple equilibria to find or guarantee the best solution, by providing a method of solving the trilevel TEP problem as a MILP directly to a global optimum.

The method is demonstrated on a case study consisting of Germany, Great Britain and Norway. Strategic countries are only trying to maximise their consumer surplus, because the non-convex bilinear expressions of producer surplus and congestion rents prevents necessity and sufficiency of KKT conditions. The minimisation of domestic prices is therefore the main objective of the strategic countries. Compared to a centrally planned expansion, which can be accomplished if the countries cooperate towards a supra-national regulator, the strategic framework deploy their generation assets less efficiently. The countries are focused on their individual goals and over-invest in domestic production. Consequently, there is less need for transmission expansion because the countries become more self-sufficient. As a result, the countries cannot diversify the risk of intermittent renewable production among each other, and are still dependent on more expensive fossil fuel generation. For the case study, a significant increase of five times the original generation investment cost was necessary for the countries to become sufficiently reluctant to invest for the transmission planner to deem it appropriate to invest in corridors. The centrally planned framework, on the other hand, invests in a lot of transmission capacity and little generation. She is able to use the system assets more efficiently and make a larger transition into renewable generation. Our case study show potential of decreasing total cost if a system moves from a strategic framework towards central planning. However, if strategic countries also try to maximise producer surplus and congestion rent they would gain an incentive to perform trade, which they lack when only consumer surplus is included.

Photovoltaic Power Prediction and Control Strategies of the Local Storage Unit at Campus Evenstad

Student: **Lene Marie Hope Rognan**
Supervisor: **Olav Bjarte Fosso**
Co-Supervisor: **Igor Sartori**

Summary
This thesis represents a building block for future model predictive control of a battery connected to a complex energy system consisting of a photovoltaic (PV) system and a combined heat and power (CHP) plant. The complex energy system at Campus Evenstad in Norway is used a case study in this thesis. The aim of this thesis is bipartite: (1) the performance of the PV system is to be predicted, and (2) various control strategies of the battery will be investigated to see the flexibility that the battery may provide for the end-user. Two models have hence been developed: a PV model and an optimization model of the battery. Both models have been developed in Python with the help of the PVLIB and the Pyomo libraries.

Two approaches to estimate the plane-of-array (POA) irradiance on the PV array were tested in the PV model: the dirindex and the erbs irradiance decomposition methods, which are both built-in functions in the PVLIB library. Results showed that the dirindex decomposition method gave the most accurate results. However, results for winter months are highly inaccurate, and hence the PV model should be improved to better predict the PV performance in such months. The model was also tested with various overall PV system efficiencies and surface types indicating how much reflected solar radiation that hits the receiver. An overall system efficiency of 74% and surface type *asphalt* resulted in the most accurate PV estimation.

The optimization model was solved with three different objectives: (1) minimization of total import of electricity, (2) minimization of spot energy costs, and (3) peak shaving. In addition to analyzing the charge and discharge of the battery, the total cost of import was calculated for each control strategy. When using the battery to minimize the total import from the grid, the battery is not frequently used. The only recharging of the battery that takes place is a result of low demand in times of high PV production. The minimization of the spot energy cost control strategy reduces the energy cost of the imported electricity, but low spot prices lead to an increase in the import peak and hence an increase in the grid tariff cost. The total import cost of this control strategy comes out higher than the total cost of the other two control strategies. The variation in spot prices results in a rapid charge and discharge of the battery. Optimizing the utilization of the battery with the objective of performing peak shaving, the grid tariff, which is determined by the highest import peak in the last 12 months, is reduced. The grid tariff makes up the highest share of the total cost of import, and hence does this control strategy result in the lowest total cost.

Flexibility from Batteries at End-User Level: Implications for Distribution Grids

Student: **Seijas, Andres Antonio**
Supervisor: **Farahmand, Hossein**
Contact: **Crespo del Granado, Pedro**
Rueda, Jose
S. Mohammadreza Emarati

Collaboration with: **TU Delft**

EU carbon emission targets related to climate change has set in motion a process of transition towards an environmentally clean and sustainable power system. A central focus on this process is the transition from fossil fuel based energy sources to clean Renewable Energy Sources (RES). However, the intermittency of RES (e.g. solar and wind) presents a formidable challenge to achieve a stable and reliable supply-demand balance in grid operations. To achieve high levels of RES deployment, increasing the power system flexibility will be central to accommodate large fluctuations in supply and to cope with peak demand. Prospects of electricity storage technologies have emerged as a potential key technology to manage high levels of RES in the power system.

Recent projections on the cost of electricity storage show a high decrease in the next five years ([1],[2], [3]). As the commercial maturity of batteries might become a reality within the next decade, many questions remain on the role of batteries in the power system, where batteries should be located? What capacity will be optimal? What kind of battery services are the most valuable? How do batteries contribute to the large deployment of distributed RES installations? Significant research has been done on estimating sizing and sitting of storage in power systems. Yet, most of this research treat storage capacity as continuous instead of discrete, i.e. allocating storage by percentages of a total allowed capacity, wherever necessary in the grid. Despite these previous studies have provided interesting contributions on the value of storage in the power system, many of them lack the modeling of power flows, technical limits, or voltage considerations.

This thesis focuses on battery flexibility in medium voltage grids. Specifically, how to define cost-effective strategies to deploy batteries in a medium voltage grid? What is the optimal battery location in a distribution grid? And how do the technical limits of the power grid influence the allocation of storage? To address these questions, an optimization model was developed to simulate half-hourly operational decisions for a distribution grid. The model is multi-period and includes: power flows, diverse technical consideration for different battery sizes, high RES penetration levels, time of use electricity prices (half-hour dynamic prices), load data of actual customers and battery costs. To decide on the battery location, the model employs binary variables to determine the investment and sitting of the battery in a distribution grid. That is, the model is a mixed integer linear program with multi-period features which provides an investment analysis for the cost-effective sitting of batteries in a time horizon of 10 years. The model is implemented to the IEEE 33 bus test system. Results show that in general battery location and size strategies are driven by multiple factors, which can be either fixed or dynamic, like thermal limits and power load consumption, respectively. Some relevant findings are: First, flexibility in terms of power arbitrage delivers costs reductions of around 4% when RES production is low, compared to a No-Batteries case. Moreover, when RES production is high, the reductions in total costs can ramp up to 12%

below the No-Batteries case. Also, this model decides to allocate batteries only if they are economically feasible for a 10-year time horizon. These results indicate a potential revenue up to 2.1 million pounds (GBP) based on the investment in batteries. And they are based on battery cost prices from 2008, together with several optimistic projections for the next decade. Furthermore, depending on battery size, RES penetration, RES generation and technical limits, batteries tend to be located for buses at the entrance of branches with high loads. Likewise, line limits and voltage limits proved to be decisive in the election of buses and the number of batteries placed.

On one hand, results show that optimal allocation strategies depend on grid topology features and technical limits, on the other hand, they also have a high dependency on time-varying and unsteady factors (e.g. power generation and loads). The optimal location strategies tend to change and adapt to the dynamics of the system. Moreover, with the exception of the slack bus, every bus in the system turned out to be an optimal location, at least once. These results indicate that batteries might be useful in every bus of the distribution grid, but only if each battery is operated in coordination and cooperation with one another. These insights support the idea of designing local electricity markets. Based on a reflection of this work, we recommend a market design that retrieves day-ahead and intraday DSO-reports of the battery operations and the flexibility that is available in the distribution grid. And also a subsequent structure of market incentives and penalties that maximizes the value of flexibility while keeping non-optimal operations to a minimum.

In short, this thesis contributes with a novel modeling approach that can shed some lights on the optimal battery allocation problem for distribution grids. Moreover, it provides insights on how location affects the value of storage, how optimal locations are affected by multiple technical factors. And finally, it also provides some reflections on the need to collectively, cooperatively and coordinately operate the storage resources in the grid by considering market-based solutions.

Selvhelende distribusjonsnett ved bruk av feilindikatorer og fjernstyrte brytere

Student:	**Pernille Berbu Seth**
Faglærer:	**Gerd Kjølle**
Veileder:	**Hanne Vefsnmo**
Utføres i samarbeid med:	**SINTEF Energi**

Problemstilling

Smartere distribusjonsnett vil inkludere nye konsepter basert på de intelligente sensorene i nettet og et effektivt kommunikasjonssystem mellom de nevnte sensorene og kontrollsentersystemet (driftssentralen). I sammenheng med dette er det blitt spesielt fokus på det man kaller *Selvhelende Nett*. Et selvhelende nett utnytter kommunikasjonsløsningene og sensorene til å automatisk utføre lokalisering og isolering av feil, samt automatisk gjenoppretting av forsyning til nettet. I denne forbindelse er det aktuelt å benytte fjernavleste feilindikatorer i kombinasjon med fjernstyrte brytere for å raskere gjenoppretting av forsyning etter feil i distribusjonsnettet som medfører avbrudd for sluttbrukere.

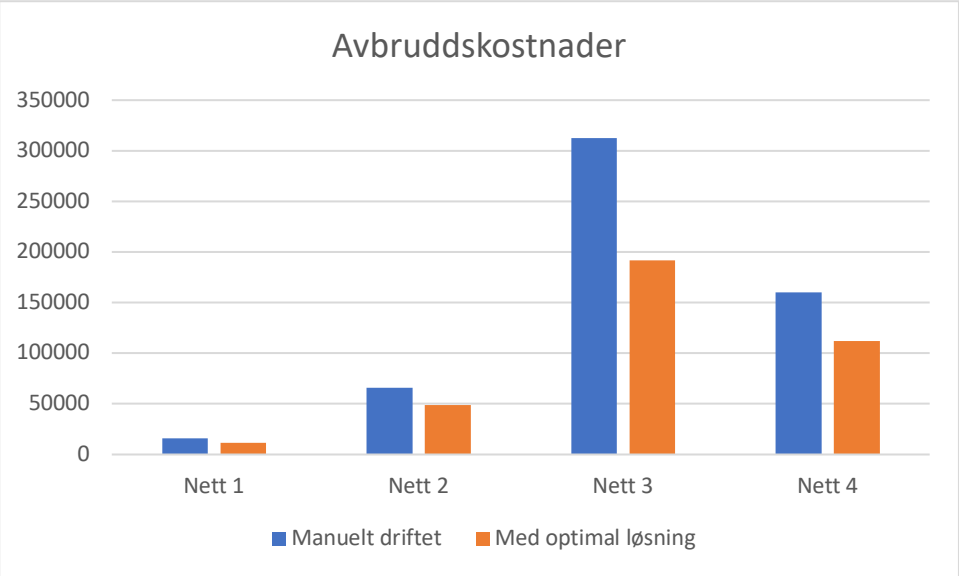
Oppgaven

Målet med masteroppgaven er å undersøke hvordan bruk av feilindikatorer, fjernstyrte brytere og selvhelende funksjonalitet kan utnyttes for å oppnå en raskere feil- og avbruddshåndtering. Det er først gjort prinsipielle studier i et eksempelnett for å vise hvordan innføring av slike komponenter vil påvirke leveringspåliteligheten i et nett. Deretter er en prototype utviklet av SINTEF Energi benyttet som beregningsverktøy til å utføre analyser av implementering av komponentene i fire ulike reelle nett. Ved hjelp av resultatene er det utviklet en foreslått metodikk som kan benyttes av nettselskapene til å lettere finne en «optimal» kombinasjon av antall komponenter, samt hvor i nettet de bør plasseres.

Resultat

Gjennom tester utført ved hjelp av prototypen ble det funnet at det er mulig å oppnå nesten 30-40% reduksjon i avbruddskostnadene, ved fornuftig bruk av fjernstyrte brytere og feilindikatorer. For tre av fire nett er en kombinasjon av tre fjernstyrte brytere og to feilindikatorer en hensiktsmessig løsning. I tilfeller hvor komponentene blir brukt samtidig vil flere feilindikatorer ikke bidra noe nevneverdig i å redusere avbruddskostnadene. En ytterligere økning kan oppnås ved implementering av flere fjernstyrte brytere, men for hver ytterligere komponent vil «gevinsten» man oppnår minke betraktelig, og nettselskapene bør gjøre vurderinger for hvor mange investeringer som vil lønne seg i sammenheng med total gevinst. For et nett ble det funnet at optimal løsning er tre fjernstyrte brytere i kombinasjon med én feilindikator, da flere feilindikatorer vil gi en liten økning i avbruddskostnadene sammenlignet med bruk av kun én feilindikator. Dette har årsak i sannsynligheten for at indikatorene indikerer i gal retning, hvor total feilsannsynlighet vil øke for hvert øket antall av benyttede feilindikator. Metoden som er utviklet går også spesifikt videre innpå hvordan de fjernstyrte bryterne og feilindikatorene bør plasseres i sammenheng med hverandre, og ulikheter i plassering alt etter om de er brukt alene i nettene eller i kombinasjon med hverandre.

Figur 1 viser hvordan avbruddskostnadene vil reduseres ved benyttelse av «optimalt» antall og «optimal» plassering av nevnte komponenter for hvert nett.



Figur 1 - Avbruddskostnader før og etter implementering av fjernstyrte brytere og feilindikatorer

Konklusjon

I uttestingen av implementering av fjernstyrte brytere og feilindikatorer i fire reelle nett ble det funnet ut hvor viktig det er med nøyaktige analyser av datagrunnlag og nett-struktur for de enkelte nettene. Det ble oppdaget flere fellestrekk i resultatene mellom de forskjellige nettene som gir grunnlag for felles, generelle kriterier som kan benyttes i valg av optimal plassering av komponenter. Det er vist at fornuftige mengder komponenter med hensiktsmessig plassering i nettet kan gi like stor, eller større, gevinst enn en overflødig bruk og lite gjennomtenkt plassering av brytere og indikatorer.

Harmonic analysis of collection grid in offshore wind installations

Student: **Chan Shan**
Supervisor: **Ole-Morten Midtgård, IEL**
Co-supervisor: **Salvatore D'Arco, SINTEF Energy**

Abstract

Wind power as a green and low-carbon renewable energy could effectively mitigate the energy crisis and reduce environmental pollution, including the rapid developing offshore wind power with its rich reserves, wind stability, high wind speed, less interference, noise and other advantages. The trend for development of offshore wind farms is towards a growing size of installed power. This together with higher distances from the shore leads in many cases to HVDC connection as a preferred choice for power export. Thus, the wind turbines are connected through a collection grid to an offshore platform. As the offshore wind farm contains a large number of power electronic devices and submarine cables, it will inevitably lead to the occurrence of harmonic resonance. Offshore wind farm harmonic and resonance will affect the power quality, while poses a huge challenge to the power grid and wind power.

In this thesis work, a comprehensive harmonic analysis in offshore wind farm was studied. Firstly, a detail configuration of the wind energy conversion system and harmonic analysis basics are described and interpreted. Next, a suitable model of one offshore wind farm is built and validated in Matlab/Simulink. The equivalent circuit is calculated for the components in the aggregated wind farm based on their harmonic model. And potential resonance problems are analyzed by frequency scan method to calculate the resonance impedance and frequency. Afterwards, based on the self-built system model, potential harmonic issues that arise in the system are investigated in time domain to interpret the THD at PCC between the collection grid and the onshore grid. As well, a few effective strategy for suppressing harmonics are simulated to evaluate the various influence on the harmonic issue. Both the designed C-type filter and active power filter performed a satisfying results on harmonics suppression. The main contents are as follows:

1)
Study on the basics of harmonics and discuss the potential sources and the mechanism of harmonic resonance in offshore wind farms. The simulation model of PMSG Wind Energy Generation System is established. Harmonic characteristics of machine-side converter, grid-side converter and line filter capacitor are analyzed. It could be deducted that machine-side converter current is mainly influenced by wind speed and mechanical control system. Grid-side current, which has a lower harmonic to the machine-side current, are mainly affected by PWM control system of converter. Thus, harmonic current injected from PMSG to grid is mainly determined by gird side converter and filter in wind turbine out port.

2)
System resonance problem of OWF was analyzed in equivalent circuit models.
And then the frequency scan method is applied to detect the influence components which potentially affect the harmonic resonance. From the simulation results, the main resonance points are similar at collection grid bus of wind farm in HVAC transmission system and

HVDC transmission system, which are around 7th order frequency. Resonance points are also influenced by length, inductance and capacitance of submarine cable, due to the high distributed capacitance of submarine cable.

3)
Study on the strategy for suppressing harmonics at an offshore wind farm. The harmonics distribution in cases with C-type filter or active power filter adopted are designed and analyzed in the simulation models. The C-type passive filter performed satisfying results on harmonics suppression.

AC and DC systems interaction-opportunities and challenges of exchanging system services

Student: **Mohammad Rashid Shokooh Far**
Supervisor: **Olav B Fosso, IEL**

Abstract

Today, the world is facing a situation where only having an energy source is not the fi-nal priority, but, also having a clean energy source is the final concern. Where clean energy generation is concerned, only renewable energy resources come into the picture rather than conventional power generation sources. The tendency towards renewable energy sources has grown incredibly in recent years. It can be stated that wind and solar energy sources have the highest share of renewable energy sources. Nowadays, wind farms are usually located far away from load centers. Therefore, strong power transmission systems are re-quired to transmit bulk power over long distances based on AC or DC solutions. Several detailed comparisons have been performed on High Voltage Alternating Current (HVAC) vs High Voltage Direct Current (HVDC) systems. It can be noted that the HVDC trans-mission system is the more feasible solution to transmit power in renewable energy power systems, especially collecting power from offshore power plants and distributing it among onshore consumers.

Line Commutated Converter (LCC) and Voltage Source Converter (VSC) are two available technologies in HVDC transmission systems. VSC (modern HVDC) technol-ogy with Pulse Width Modulation (PWM) has a number of advantages compared to the classical thyristor-based converters, such as the separate and fast-acting controls of ac-tive and reactive powers. Hence, VSC is the most suitable converter technology to make a multi-terminal DC (MTDC) power transmission system. It is desired that MTDC sys-tems be capable of interfacing with all types of AC systems since the dynamic of MTDC systems is very fast. The main objectives to construct and use MTDC systems are: the large-scale integration of renewable energy sources into the existing AC grids and the ex-pansion of international energy markets through super grids.

This thesis presents ancillary services from HVDC system and analysis power trans-mission systems based on VSC technology. The main focus of this thesis is to investigate interactions of AC and DC grids and sharing power between them. A network based on MTDC power transmission system is designed in MATLAB/Simulink by developing a Matlab example to demonstrate interactions between the four AC grids and the MTDC system. In the test model, two AC systems, which are located at two different areas, are transmitting power via two VSCs (rectifiers) to two VSCs (inverters), and the inverters are finally connected to two other AC systems. Dynamic performance of the VSC MTDC system is examined by simulating different conditions to illustrate the energy balance in multi-area grids. Detailed simulations results are presented for normal operation and two case studies with different control strategies, such as active power control and DC voltage droop control to illustrate the behavior of the entire system under different conditions.

Condition Assessment of Hydro Generator Insulation Using Partial Discharge Measurements

Student: **Regina Skattenborg**
Supervisor: **Erling Ildstad**
Co-supervisor: **Torstein Grav Aakre**

More than half of all hydro generator failures are caused by insulation breakdown. Insulation failures inflict serious damage on the generator and represent significant operating costs for utility companies. One of the main reasons for insulation breakdowns is the irreversible degradation caused by internal partial discharges (PD) resulting from voids in the insulation system. Therefore, it is crucial that methods for condition assessment of generator insulation can identify and analyze the partial discharge activity in these voids.

The main purpose of this thesis is to facilitate condition assessment of generator bar insulation by measuring partial discharges resulting from voids in insulating materials. The aim is to clarify how important PD parameters relate to the void size and the discharge mechanisms in the voids. A part of the work also involves comparing the experimental results with the theoretical model of internal partial discharges: the Abc Model. In addition, possibilities and limitations of partial discharge measurements as a diagnostic tool are examined.

The test samples consist of both real generator bar insulation and specially designed laboratory samples containing disk-shaped voids of different diameters. A thin layer of aluminum was applied by vacuum evaporation to the cavity surfaces of one sample group to investigate the effects of increased surface conductivity. Electrical detection of partial discharges was performed using a conventional measuring circuit, and the PD activity was analyzed in the form of inception voltage, as well as the discharge magnitude and discharge frequency at a voltage frequency of 50 Hz.

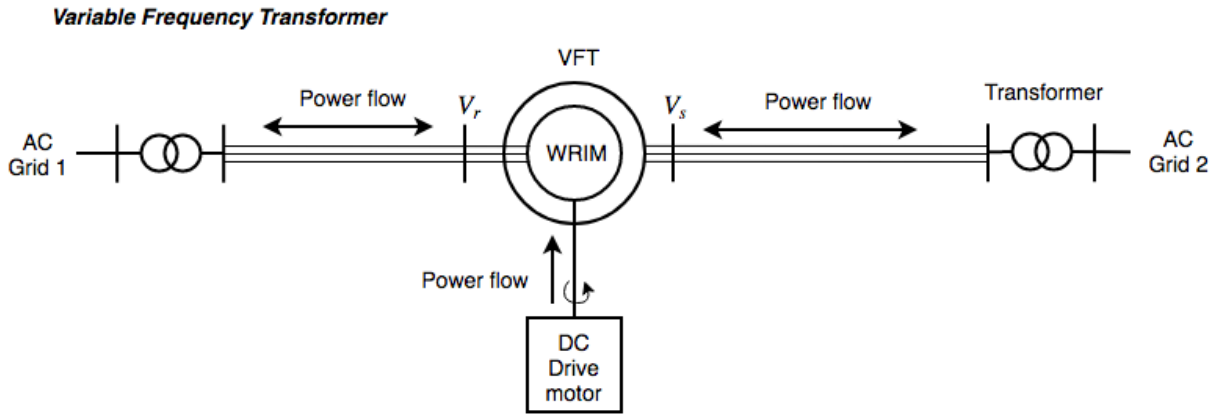
The inception voltage is found to decrease with increasing void diameter due to lower field enhancement in larger voids. In the case of the laboratory samples, the discharge magnitude is generally increasing with increasing diameter. The discharge magnitude is larger when the void surfaces are conducting since the discharge area then is equal to the void surface area. However, for samples made of aged generator insulation, the discharge magnitude is constant regardless of void diameter. More importantly, it was not possible to conclusively distinguish the PD activity in the voids from the PD activity inherent in the insulation. The discharge frequency tends to increase with increasing void size. This can be explained by the differences in the electric field strength in the different cavities at the specific voltage level, and the occurrence of parallel discharges. Higher void surface conductivity generally leads to lower discharge frequency.

In conclusion, the PD activity is seen to depend on the void size. The theoretical model is successful in describing the PD activity in voids with conducting surfaces, but fails to describe the PD activity in aged generator insulation. PD measurements performed on the laboratory samples can detect the voids and assess the relative void size. However, the voids in aged generator insulation cannot conclusively be detected using the chosen PD approach. This represents an important limitation to the PD method.

Study on the Reactive Power Behaviour of the Variable Frequency Transformer

Student: **Maren Skrunes**
Supervisor: **Olimpo Anaya-Lara**

The majority of the power system networks in the world today operate at a nominal frequency of either 50 or 60 Hz. Merging of adjacent power networks will expand the world's power supply system and thereby increase the possibility to utilize available power sources and deliver quality power. This Master's thesis investigates the Variable Frequency Transformer (VFT) concept, which has been proposed by General Electric as a solution for interconnecting two asynchronous networks whilst enabling controllable, bi-directional power flow between them. The mechanical design of the VFT is based on the well-known technologies of the hydro generator and the transformer. The core of the VFT is a rotary transformer, and it operates like a phase shifting transformer by adjusting the phase angle to transfer power between the two electrical networks. The principle of operation and fundamentals of the VFT are investigated with particular emphasis on understanding reactive power characteristics and requirements.



The VFT facilitates active power exchange between the two asynchronous networks and also provides a path for reactive power exchange which, however, is not fully controllable. A basic model of a 100 MW VFT interconnecting the two power networks is implemented in MATLAB/Simulink. A thorough study is conducted to understand the reactive power requirements for different operating conditions in terms of the power flow exchange between the two networks. Simulation results indicates substantial amounts of reactive power

requirements in the machine during active power exchange. Two solutions are investigated to provide reactive power compensation, namely electromechanical capacitor bank and power electronic based STATCOM. Reactive power compensation by means of passive capacitor banks was able to improve system capacity and bring grid voltage to its nominal value. An active compensation by a STATCOM was investigated and a voltage regulation control scheme was suggested for implementing the STATCOM and the VFT in a combined system.

Utvikling av algoritmer for automatisk effektkontroll i bolig

Student: **Hanna Tysseland Skulstad**
Veileder: **Eilif Hugo Hansen**
Utføres i samarbeid med: **Sikom**

Innen 2019 skal utrullingen av AMS-målere til norske hjem være ferdigstilt. De smarte målerene sender detaljert informasjon om husholdningenes energi- og effektforbruk til nettselskapene. Dette muliggjør innføringen av en nettleiemodell hvor også effekt prises. NVE har annonsert at en effektbasert nettleie vil innføres i starten av 2021. Den nye effekttariffen skal fungere som et insentiv til reduksjon av effekttopper på forbrukersiden.

Selskapet Sikom, en norsk leverandør av smarthusløsninger, ønsker å utvikle et system som reduserer effekttopper for å imøtekomme de nye tariffene. Som et bidrag til prosjektet er det i denne oppgaven utviklet en algoritme for automatisk effektkontroll i bolig. Effekttopper reduseres ved å skru av varmtvannsbereder og varmelaster i prioritert rekkefølge. Algoritmen har blitt implementert i kontrolleren LM4, som en del av et digitalt styringssystem, hovedsaklig basert på grensesnittene KNX og MBUS. Styringssystemet har blitt installert i smarthuslaboratoriet på NTNU Gløshaugen, som er utformet lik en leilighet med kjøkken/stue, gang og bad. Et fiktivt forbruksscenario er utviklet og brukt som basis for å teste algoritmens funksjonalitet. Hensikten har vært å vurdere nytteverdi for forbrukeren opp mot eventuell reduksjon i komfort.

Basert på simuleringer i smarthuslaboratoriet der ulike effektgrenser har blitt testet, kan følgende resultater trekkes frem:

- Reduksjonspotensialet for effekttoper er lik den totale effekten til de fleksible lastene, som i smarthuset førte til en reduksjon på 30 til 46 % for alle simuleringene.

- Algoritmen antas å ikke gi store konsekvenser for komforten så lenge effektgrensen ikke settes for lavt. Det er knyttet mye usikkerhet til resultatene, så testing hos pilotkunder bør gjennomføres for å få et større resultatgrunnlag med forskjellige effektprofiler, og tilbake- melding på opplevd komfort fra forbrukerene.

- Kortvarige topper algoritmen ikke klarer å kutte, som følge av høy ikke-fleksibel belast- ning, ser ikke ut til å gi merkbare utslag på nettleien.

- Tariffmodellen *abonnert effekt* førte til en reduksjon på over 30% for de testede effektgrensene. *Time-of-use* og dagens tariff ga liten endring i den beregnede nettleien.

Model of Single-Phase Synchronous Generator for Rotary Frequency Converter

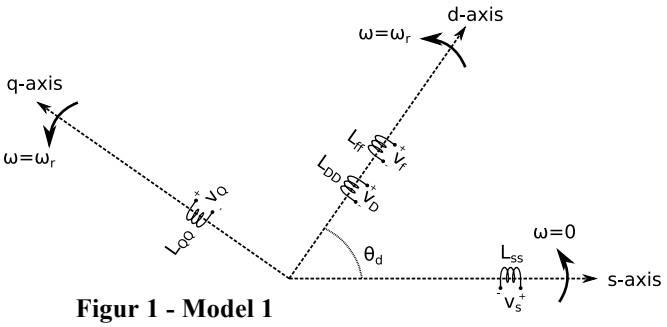
Student: **Gaute Molland Solberg**
Supervisor: **Trond Toftevaag**
Contact: **Steinar Danielsen**
Collaboration with: **Bane NOR SF**

Problem description

The standard for the Norwegian traction power system is single-phase AC voltage at 15 kV and 16 2/3 Hz. This single-phase system is fed from the three-phase public power grid through several converter stations. Most of these converter stations are made up of synchronous-synchronous rotary frequency converters. This Master's Thesis continues the work carried out fall 2017 and presented in the specialization project "Model of Single-Phase Synchronous Generators for Rotary Frequency Converters". The Master's Thesis will describe three different approaches for modeling single-phase synchronous generators for rotary frequency converters.

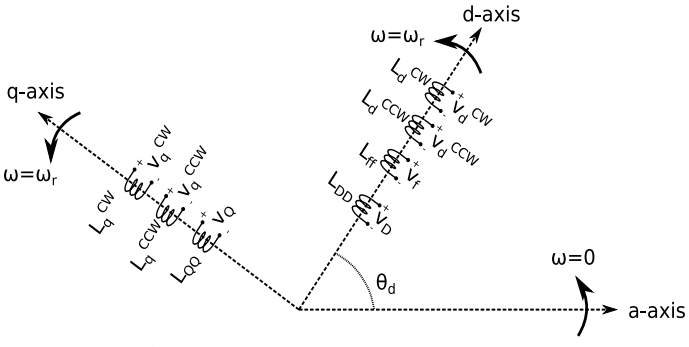
Instantaneous time-domain related models

Model 1 is developed by applying one armature winding combined with rotor windings identical to the three-phase machine's rotor configuration. The equations are used directly, and not transformed to a common reference frame. Test results obtained from the implemented model present a rotary converter model experiencing initial conditions that are destabilizing the converter.



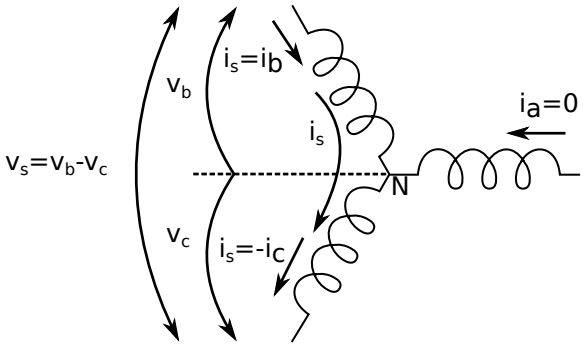
Figur 1 - Model 1

Model 2 views the behavior of the armature single-phase winding's pulsating MMF distribution as the result of two fictitious three-phase machines. Each machine induces a rotating MMF distribution. Equations are developed for each machine individually. They are decoupled from each other but interacts with their common rotor circuits. Successful model implementation has not been obtained, due to the simulation not converging to final solutions.



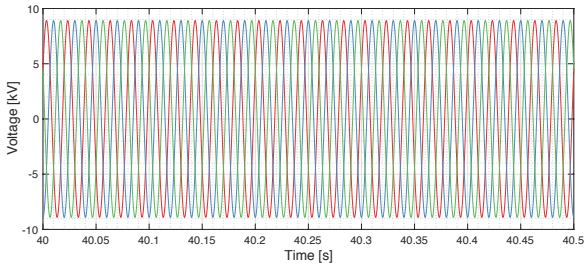
Figur 2 - Model 2

Model 3 applies a three-phase synchronous machine with one open-circuited phase and necessary parameter adjustments for obtaining the behavior of the single-phase machine. Test results present the converter model behaving as expected during the loaded steady-state performance. The rate of decay of symmetrical fault current is faster than for sets of parameter adjustments carried out in the literature.

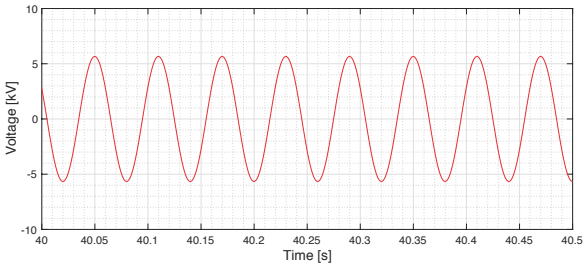


Figur 3 - Model 3

Results model 3

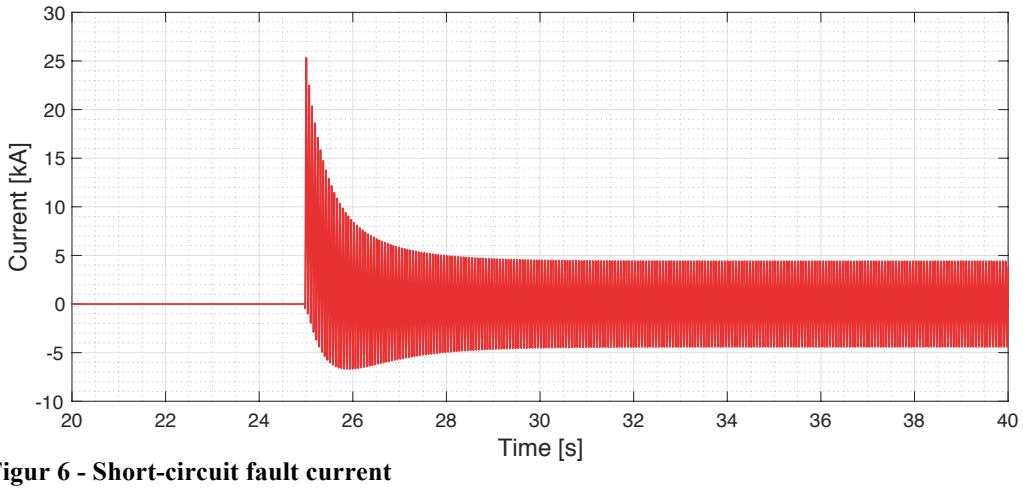


Figur 5 - Three-phase voltage



Figur 4 - Single-phase voltage

The instantaneous voltages for the three-phase- and single-phase terminals of the rotary frequency converter. Frequency conversion from 50 Hz to 16 2/3 Hz is observed.



Figur 6 - Short-circuit fault current

Fault current for short-circuited single-phase terminals using the obtained necessary parameter adjustments.

Dynamic Simulations of Simultaneous HVDC Contingencies in the Nordic Power System Considering System Integrity Protection Schemes

Student: **Espen Hafstad Solvang** (Times New Roman, 12 pkt, bold)
Supervisor: **Kjetil Uhlen** NTNU
Contact: **Iver Bakken Sperstad** SINTEF Energy Research
Collaboration with: **SINTEF Energy Research**

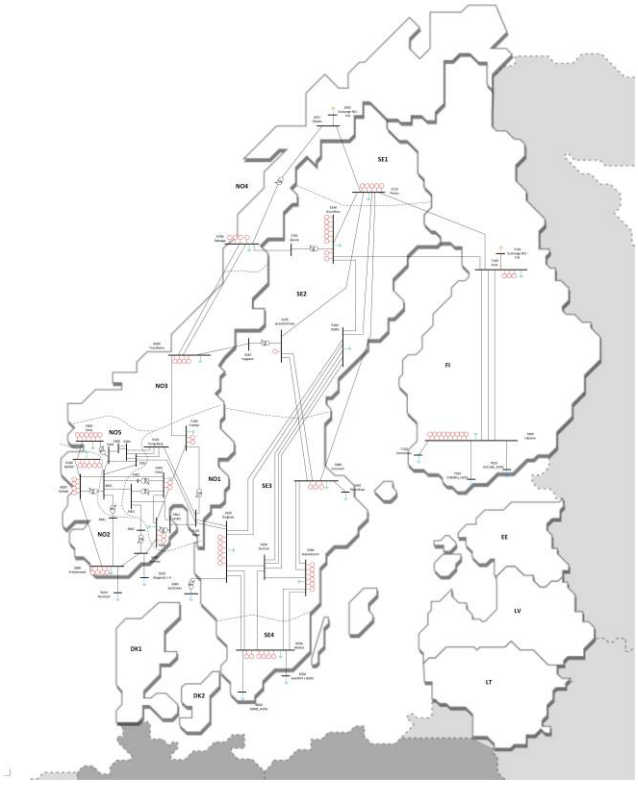
Problem description

HVDC links carrying gigawatts of power such as the under construction North Sea Link and NordLink introduces new challenges to the Nordic power system. The possibility of contingencies of one or several such links possibly represents a significant risk to the Nordic transmission system operators, especially if the extraordinary event of simultaneous HVDC link contingencies is considered. Such an outage may be of several gigawatts in size, far exceeding the dimensioning fault of 1450 MW of the Nordic power system.

The possible consequences, barriers and vulnerabilities of the power grid following large HVDC link outages must be identified. Specifically, the consequences at the transmission level for the Nordic power system if multiple outages occur simultaneously at HVDC links importing power should be illuminated. The sufficiency of existing barriers such as Under-Frequency Load Shedding, HVDC Emergency Power and generator primary response to hinder severe syst em states following such large HVDC link should be considered, along with the potential of the possible future barrier, Demand-Side Response, to improve the frequency response of the power grid. The extent to which the reduced inertia in the future power system affects the system's ability to withstand such HVDC contingencies should be quantified. Finally, vulnerabilities in the Nordic grid that limit the ability of the Nordic power system to withstand simultaneous HVDC contingencies should be identified.

Model/ measurements

The aggregated network model Nordic44 is used to simulate HVDC contingencies in the Nordic power system using PSS/E and the Python API Psspy



Calculation

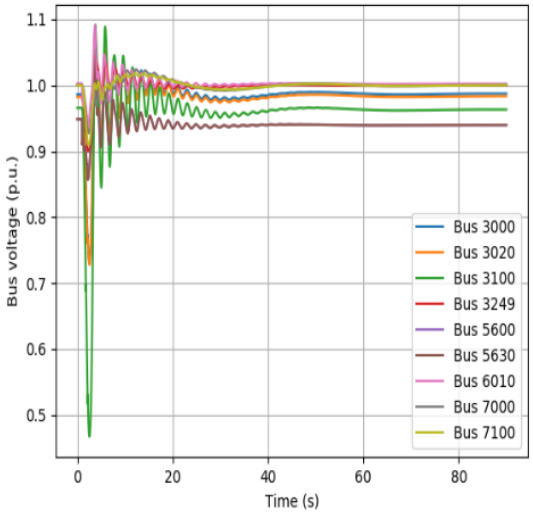
Import at each HVDC that experiences an outage is set to maximum import prior to running simulations. The dynamic response in terms of voltage, frequency, generator angles and more are then studied and compared between different cases, and results are analyzed to find weaknesses in the Nordic grid or the Nordic44 model.

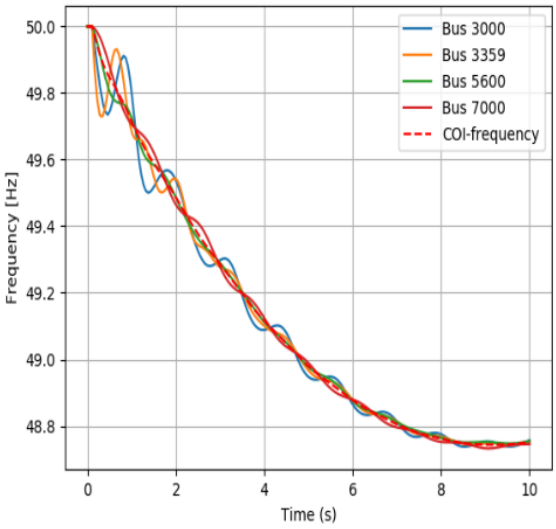
Conclusion

- Emphasize achieving low time-delay for DSR activation in response to frequency decline in future projects on development

and implementation of DSR in the Nordic system. DSR must be regarded as a tool in dynamic as well static analyses.

- Investments in voltage stabilizing equipment such as STATCOMs in southern Sweden to improve the ability of the Nordic system to withstand very large outages. Investments in voltage stabilizing measures should accompany investments in increased HVDC link capacity and interconnection with other synchronous systems.





Transient Temperatures of Underground XLPE Power Cables – Comparison of Results from Different Calculation Methods and Full-Scale Experiment

Student: **Aleksander Hertzberg Steen**
Supervisor: **Erling Ildstad**

Abstract

According to predictions made by the International Energy Agency, electricity demand worldwide is expected to grow faster than any other type of energy. As a consequence, investments in the form of power grid reinforcement are needed. By gaining an better understanding of the limiting thermal mechanisms of the various power system components, work can be performed to increase the grid transfer capability. Of these components the underground power cable plays an crucial role, and an increased knowledge of transient temperatures is therefore important.

The main problem definition of this master thesis was:
• How does results from calculation of transient temperatures of underground power cables by means of numerical modeling, as well as by method specified in IEC 60853, compare to measurements from a full-scale experiment?

In addition, the following problem definition was of interest to this study:
• How will a change in the thermal characteristics of cable sand, used as bedding and initial backfill, influence the transient and stationary temperature conditions of underground power cables?

The main problem definition was solved by developing numerical models in COMSOL Multiphysics, as well as MATLAB scripts for the IEC 60853 method. In which results from the two calculation methods were compared to data obtained from an full-scale test facility. Moreover, the problem definition related to change in the thermal characteristics of cable sand and the influence relative to transient and stationary conditions, were solved by means of employing an numerical approach. Where an realistic change in the thermal characteristics of the cable sand was obtained by compressing a sand sample, and experimentally determine the change in the characteristics.

When it comes to the main problem definition, the report can based on the results conclude that both calculation methods were in good accordance with measured values, excluding no-load periods beyond an duration of ~70 and ~10 hours for which the numerical and IEC 6083 method respectively gave discrepancies. When comparing the two methods, the numerical approach showed marginally better correlation with measurements than the IEC 60853 method. Moreover, the report can also conclude that the IEC 60853 method have two main shortcomings compared to an numerical approach. Where the first shortcoming is the lacking ability to account for non-homogeneous soils, and the second shortcoming being the representation of

ambient temperature in which is implemented instantaneously in the solution, thus large variations in ambient temperature cannot be accounted for in an suitable way.

With regard to the second problem definition, the report can based on the results conclude that the thermal conductivity of cable sand have an significant influence relative to stationary conditions. However, the added thermal resistance associated with cables in pipe will reduce the benefits compared to cables directly in ground. When it comes to the dynamic conditions, an neglectable reduction in temperature was obtained by an increased heat capacity, due to the small mass of the cable trench relative to the native soil. The dynamic conditions with regard to cable sand characteristics is thus mainly governed by the thermal conductivity.

Optimizing weekly hydropower scheduling in a future power system

Student: **Ada Elisabet Strand**
Supervisor: **Hossein Farahmand**
Contact:
Collaboration with:

Problem description
In a future power system with high penetration of intermittent renewable energy sources, it will be necessary to adapt to their changes quickly to ensure system stability. In the European system, the Nordic hydro region could provide some of the necessary flexibility. For this to be possible, models used for hydro scheduling must be adapted to model a system with such variability correctly.

The task
The object of this thesis is to continue the development of a deterministic short-term hydro-thermal scheduling model. The main contributions by the student are the implementation of; transmission ramping constraints, startup and shutdown costs of thermal units, and finally a receding horizon methodology for mixed integer linear programming (MILP).

Model/ measurements
The model is developed by applying the open-source Python based optimization package Pyomo, and is solved with Gurobi. The student's implantations are documented on BitBucket for future uses. The effects of the student's contributions were investigated under five case studies developed by the student.

Calculation
The student's implementations were found to provide added value to the model, through increased accuracy in system description. However, some implementations were found to be non-optimal, giving unrealistic results.

Conclusion

Under testing, shortcomings in the implementation have been identified, and methods for improvement and corrections are suggested. Suggestions for further development of the model are presented, based on a high-level literature survey as well as case studies completed within the thesis.

The Academic Vesion of a Fundamental Marked Model

Student: **Vegard Paulsen Særen**

Supervisor: **Hossein Farahmand**

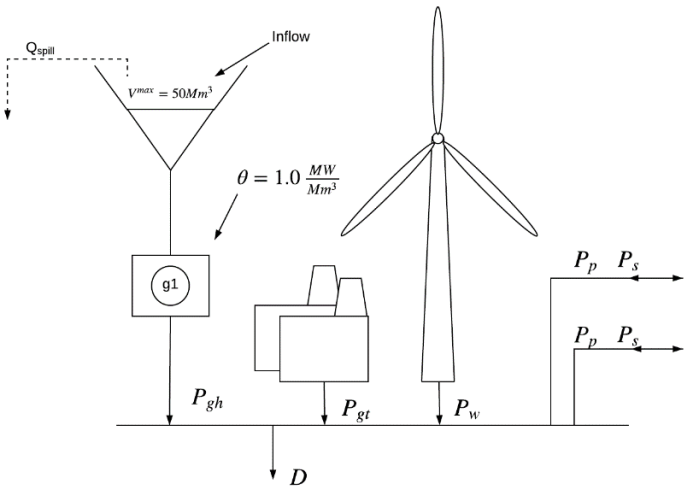
Co-Supervisor: **Martin N. Hjelmeland**

Summary

The Nordic market is at rapid change with new unregulated power being installed. Solar and wind energy is increasing as the EU commission demands 20 % increase of renewable energy by 2020. In 2015 a total of 27.3 GW installed power generated capacity were connected in the EU, and a total of 18.2 GW were decommissioned, resulting in 9.1 GW of new net capacity. Renewable energy sources accounted for 20.6 GW or 75.6% of all new power generation capacity. This increase in renewable energy sources decreases the balance and the reliability in the Nordic market. This will lead to more sales in capacity and in the balancing market, which are one of the topics in this thesis.

In this master thesis, the investigation of the Nordic market will take place in a smaller version. To analyze the market, four models have been constructed. The first model is a deterministic base model, which calculates the water values with fixed inputs. The second model is a one area aggregated stochastic model which calculates the water values with 15 price nodes and 5 inflow nodes. The third model is a two-area aggregated model which excludes the transmission losses. This has been done for the purpose of analysis. The fourth main model is the fundamental market model, including 3 areas that are interconnected with losses on the lines. The master thesis also contains a sensitivity analysis of including wind energy into the mix.

Since the market is in rapid change with decommission of thermal and fossil power, this has been included in the market models, where the model calculates the water values by minimizing the cost of thermal production. The bus system of each area has one hydropower station, one thermal power plant, one wind farm, a fixed demand and two interconnected lines with the option to sell and purchase energy.



To analyze the results, all the models have been tested and produced water values. The water values are further analyzed and have shown the difference in all the models. In this thesis, one can see the impact of including the option of buying and selling energy, and the impact of losses on the lines. Furthermore, the sensitivity analysis shows that wind energy can reduce the water values, and become a contributor for decommissioning thermal energy.

The conclusion of the thesis relay on the contribution of stochastic variables. The analysis shows that the accuracy of the calculations can be improved by increasing the reservoir levels and the price- and inflow nodes. This is because the model has simplifications and assumptions that makes the solution time lesser. By increasing the nodes and discrete reservoir levels one increases the solution time, but also the accuracy in the water values.

Strategies to Ensure Sufficient Inertia in the Norwegian Power System

Student: **Astrid Høst Sølna**
Supervisor: **Magnus Korpås, IEL**

Abstract

Having a stable system frequency is vital for safe operations of a power system. A small change in frequency is adjusted for by the system inertia. Inertia is the ability of the rotating masses of a synchronous machine to resist a change in frequency. The system inertia has the important ability that it helps maintain a stable frequency. The consequence of an unstable frequency can in the worst case be a blackout.

The Nordic power system is changing, and it is expected that these changes will lead to more occurrences of low inertia situations. Low inertia situations must be avoided as they lead to a more unstable frequency. To avoid low-inertia situations it is necessary to introduce measures to increase the inertia in the Nordic power system.

Three strategies to ensure suÿcient inertia in the Norwegian power system will be evaluated based on their socioeconomic costs and their e˙ectiveness in providing suÿcient inertia. The aim of the thesis was to find a cost-e˙ective strategy for the Norwegian power system. To analyze the e˙ect of the strategies, a market model of the Northern European power system was used.

Defining a minimum production level for the hydro generators proved an e˙ective strategy in ensuring suÿcient inertia. The socioeconomic costs related to this strategy were however, high. Extending the strategy to only apply on days with low inertia gave satisfying results: the inertia was increased on the days it was needed and the costs of the strategy were reduced. Reducing the capacity on an HVDC link gave lower socioeconomic costs. The strategy has a positive e˙ect on the system inertia, as long as there is import on the HVDC link when the capacity is reduced. The best economic outcome was estimated to come from load reduction by disconnecting the pumps for hydro storage. This strategy has however limited availability.

The results show that low inertia situations in the Norwegian power system can be avoided by taking necessary measures. Imposing a minimum production level on days with low inertia proved an e˙ective strategy to increase the system inertia. Looking at the cost-e˙ectiveness, load reduction by disconnecting the pumps for hydro storage or reducing the capacity of an HVDC-link are better options. However, the capability of these latter strategies to provide the inertia depend on external factors giving them a somewhat limited applicability.

Reliable Power Cable Ground Screen Connections

Student: **Peder Severin Søndenå**
Supervisor: **Frank Mauseth**
Co-supervisor: **Hans Lavoll Halvorson**
Collaboration with: **SINTEF Energy Research**

Problem description
The Norwegian power grid consists of an ever-increasing share of power cables. In Norway, the ground screen of the cable in distribution networks is usually grounded at each end of the cable length due to recommendations from the authorities. As a result, screen currents are allowed to flow through the ground screen due to the voltage induced in it by the current of the cable conductor and surrounding current carrying objects. The screen currents may vary from a few to several hundreds of amperes, depending on cable dimensions, load current and laying configurations. If this is not taken into consideration when designing the layout of the cable system, large screen currents may arise that can cause significant heating to occur in the cable screen and its connections.

Several breakdowns of power cables have occurred in the distribution grid, which are believed to be connected to the above mentioned topics. Because of this, a research project was initiated by REN AS with the goal of "establishing guidelines for testing and installation of ground screen connections to avoid future fault scenarios and to increase the reliability of the cable network" [1], and further use this knowledge as a basis to propose international standardization tests for ground screen connections.

Model/measurements
Two types of ground screen connection designs were obtained from Norwegian equipment vendors. A test setup was built allowing six ground screen connections of each type to be tested. The cable ground screens and the ground screen connections were heat cycled by a DC current source. In addition, the cable conductors were heated by inducing current from a ring transformer and a variable voltage source. 25 heat cycles were conducted with the ground screen connections installed as explained in the installation manuals, before the same number of heat cycles were performed with a known improper installation on the two designs, with stainless steel in series with the conductive copper components. The resistance of the ground screen connections was monitored with four-point resistance measurement before, during and between the heat cycle.

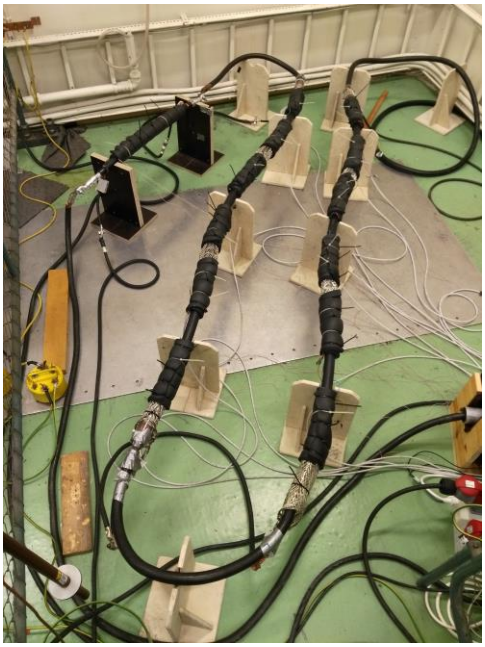


Figure 1: Picture of the test setup in the laboratory. The ground screen connections of type I to the left, type II to the right. Each ground screen connection is located underneath the black thermal insulation.

Conclusion

The results show that the improper installation of the ground screen connections increase the resistance drastically. With a screen current of 30 A, type I experienced a temperature increase close to that of the correct installation with 100 A. Type II saw an increased temperature with 30 A and improper installation compared to correct installation of the ground screen connection with 100 A.

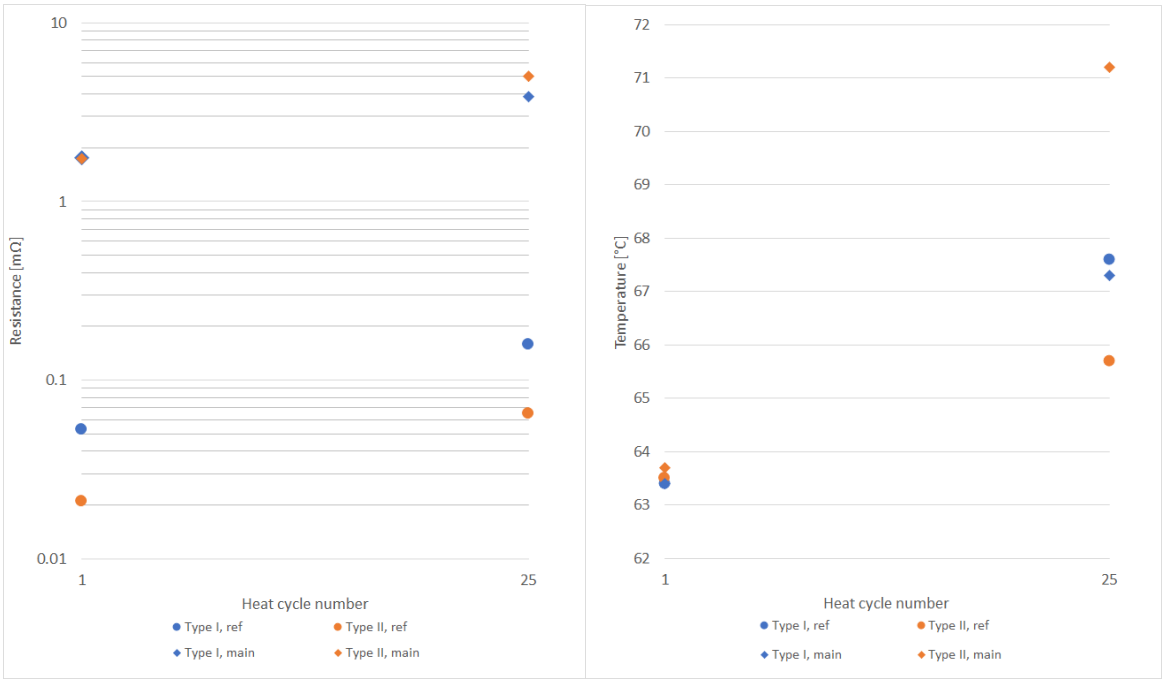


Figure 2: To the left: resistance development for the reference and main test. To the right: temperature development for the reference and main test.

[1]: https://www.forskningsradet.no/prosjektbanken/#/project/NFR/256261

Study of frequency dependent loss in magnetic steel by the Jiles-Atherton method

Student: **Magnus Erlend Tangen**
Supervisor: **Arne Nysveen**
Contact:
Collaboration with:

Problem description

Direct electrical heating system (DEHs) are used for safeguarding the well stream through pipelines to processing topside or shore. The heating source is conductive and hysteresis power losses in the pipeline due to electric current injected into the pipeline. For DEHs design, it is critical to predict the heating power as function of input current and frequency so that proper frequency and current can be selected correspondingly. This master thesis concerns using Jiles-Atherton modelling to simulate the induced loss in magnetic steel materials and verification with sample tests.

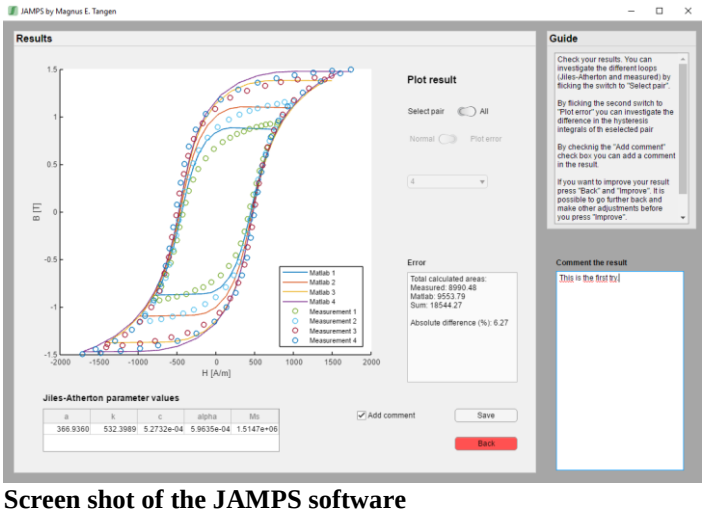
The task

1. Improve existing MATLAB script to be suitable for generic measured B-H Curves, creating five required parameters by Jiles-Atherton in Comsol.
2. FEM simulation to calculate the frequency dependent loss in a rod sample conducting AC currents.
3. Measuring AC loss of a rod samples with different frequencies and currents in Lab.

The work of this thesis comprises the development of a software that obtain Jiles-Atherton parameter values for new materials based on measured hysteresis loops. The Jiles-Atherton method should be implemented in a FEM model and verified in terms of comparison of simulated and measured AC losses.

Model

The generic software 'JAMPS' (Jiles-Atherton Parameter Search) was developed and used as the tool for obtaining the J-A parameter values. JAMPS was developed with a graphical user interface (GUI) to increase the usability of the software.



Screen shot of the JAMPS software

The verification of the J-A parameters was performed in the FEM software Comsol Multiphysics where a model was developed to simulate the measurement equipment used to measure the loss in the material samples. The operation principle of the measuring instrument is investigated and explained to obtain a comparable loss simulation in Comsol. The resulting FEM model is relatively efficient in terms of computation time and result resolution.

Calculation

The simulations and measurements were performed with the target flux densities 100, 200, 300 and 400mT at the frequencies 50, 100, 150 and 200Hz. The measured AC losses were used as a reference and compared with the simulated material losses from the FEM model:

- The difference between the simulated and measured total losses in material 1 is in the range -15% to 5%.
- The difference between the simulated and measured total losses in material 2 is in the range 0% to 37%.

16 simulations were performed per material, which constitutes 32 different simulations in total. 25 of these loss simulations are within a difference of ±10% compared to the corresponding measured loss.

The comparison of the measured and simulated eddy current and hysteresis losses in material 1 showed a significant difference between the measured and simulated losses:

- The difference between the measured and simulated eddy current losses is in the range 3% to 152%.
- The difference between the measured and simulated hysteresis losses is in the range -73.28% to -38.12%.

The comparison of the measured and simulated eddy current and hysteresis losses in material 2 showed a significant difference between the measured and simulated losses:

- The difference between the measured and simulated eddy current losses is in the range -12% to 32%.
- The difference between the measured and simulated hysteresis losses is in the range 3% to 73%.

Conclusion

In general, the simulation of the total losses was performed with a satisfactory low error and the implementation of the Jiles-Atherton method is regarded as a success. During the verification process it was discovered that the initial selection of B-H loops in JAMPS is corelated to the accuracy of the simulation of the total loss. There is a potential of improving the accuracy of the simulated total loss if a method is developed to determine which B-H loops that should be used as input in JAMPS.

An investigation of the separated losses was performed in terms of an attempt of expressing the measured eddy current and hysteresis losses analytically with commonly accepted theory. The separated losses were not satisfactory expressed analytically. This indicates that the difference between the measured and simulated eddy current and hysteresis losses may be due to the presence of anomalous loss. In further work it is recommended to investigate the relevance and possibility of including the anomalous loss in a FEM model.

Multi-Market Optimization of Energy Storage Taking Into Account Uncertainty

Student: **Kasper Emil Thorvaldsen**
Supervisor: **Magnus Korpås, Arild Helseth**
Contact: **kasperuss@hotmail.com, tlf: 90709578**

Collaboration with: **None**

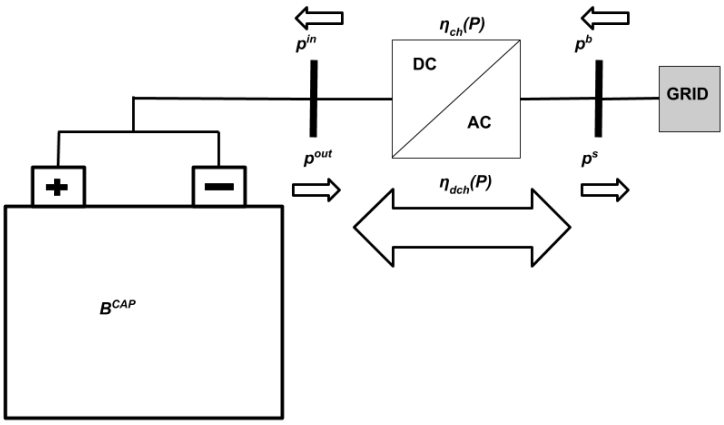
Problem description
Energy storage units implemented in small communities can have multiple purposes. Other than participating during peak consumption hours, which can prevent congestion problems on the grid, it can also contribute to balancing the grid with flexible production. As unregulated energy sources have low contribution in power flexibility, the need of potent balancing service will become more critical in the future, in both small and large scale applications. As an energy storage unit utilizes the variation in hourly energy prices to create profit, including participation in the balancing market will be another possibility to further increase profit.

The task
In this master thesis, the main focus has been to create an optimization model for an energy storage unit to consider the potential of storing energy for future use, when also operating in both the energy and balancing markets. The main goal was to successfully implement this model and study the potential of a storage unit maximizing profit within both markets, and how this affects the scheduling of the storage unit for varying storage capacity.

Model/ measurements
The optimization model that was created, simulates an energy storage unit with the possibility of operating in both the energy and balancing market, which extends the possible markets that storage units usually participate in. This has been done by including primary reserve sales in the balancing market. The model is considered a short-term scheduling model operating at a multi-stage, multi-scenario stochastic level. This model simulates sequential scheduling planning for a user-defined time horizon and time steps, and can therefore be both short-term and long-term depending on the scope and range.

The model is forecasting the future potential of stored energy by utilizing the same method as is typical for hydropower producers, through the implementation of water values describing the marginal cost for more storage for future use. This marginal cost has been described as the storage value in this report. As this is a method not commonly used for storage unit simulation, testing how the model functions with this implementation is part of the scope of this project.

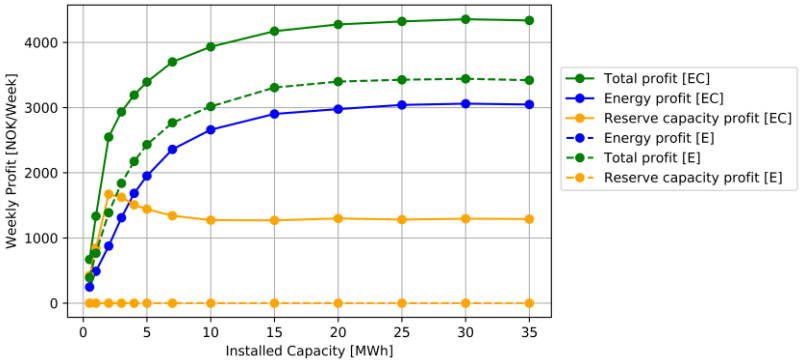
The model was compared the increased profitability when contributing in both markets versus contributing only in the energy market. This was done for February 2017 in the price location NO3 in Norway. Each day in each week of February was divided into stochastically possible scenarios that could occur for each day.



Calculation

The strategy phase managed to obtain convergence for various installed capacities with a deterministic setup, creating storage value curves that forecast potential future profit. However, this was found to be affected by the installed capacity, which struggled more when the capacity increased.

For all storage capacities, the storage unit had a higher total profit when reserve capacity sales were included. Due to the possibility of participating in both markets, the storage unit managed to optimize in both markets and give a higher total profit. However, for higher installed capacities, the increased profit became smaller because the storage unit struggled to fully utilizing the extra capacity.



Conclusion

The presented results from the simulation phase showed that the storage unit balanced participation in both markets when enabled to, while also taking into account the optimal end storage level based on the storage value curve provided. With different curves, the end storage level would change, promoting good accuracy in the strategy phase to have optimal performance.

The increased profitability reached 83 % at the highest, giving an increase from 766 to 1334 NOK per week for a 2 MWh storage unit. However, the increased profitability decreased for higher storage capacities. The study showed that for storage units above 15 MWh, this additional MWh gave almost no increase in profitability with a constant converter capacity at 1 MW for all storage capacities.

Balancing Market Integration in Northern Europe – a 2030 case study

Student: **Eirik Schjander Torhaug**
Supervisor: **Hossein Farahmand**

The future European power system is expected to incorporate a large share of renewable energy sources (RES). The intermittent nature of these sources will require a higher degree of flexible generation, thus increasing the need for reserve capacity providing balancing energy. In light of this the balancing market is predicted to play an increasingly important role in the future. European balancing markets are largely national markets, but because of the potential increase in system reliability and decrease in balancing costs associated with cross-border balancing, a fully integrated European balancing market is a target goal set out by the European Commission.

This thesis applies a flow-based Frequency Restoration Reserve (FRR) procurement model to a Northern European power system consisting of the Nordic countries, Germany, the Netherlands and Great Britain in a future 2030 scenario with a high share of renewables. The model clears a common day-ahead market, with FRR requirements as constraints. Transmission capacity is implicitly allocated with the same resolution as the clearing of the day-ahead market. A comparison between a non-integrated and fully integrated FRR procurement market focusing on the total system costs is conducted.

The results show that integration of FRR procurement markets leads to a decrease in total system costs of 4.8% compared to the non-integrated case. This cost reduction is due to two factors. First, integration leads to the procurement of cheaper FRR resources. The availability of the cheap hydro power resources of the Nordic countries is the main reason for the reduction in procurement costs. Second, the increased flexibility in generation capacity due to integration also leads to less load shedding and unprovided FRR in the system, reducing costs substantially. The insufficiency of FRR capacity observed in Great Britain in the non-integrated case, and the significant exchange of FRR from the Nordic region to Great Britain in the integrated case indicates that Nordic hydro power can play an important role in providing the British system with reserves in the future.

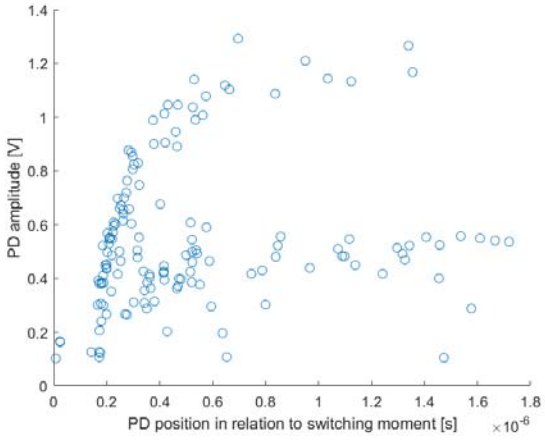
Partial Discharge Detection in Power Electronic Substrates Exposed to Pulse Voltage Waveforms

Student: **Morten Lund Torkildsen**
Supervisor: **Kaveh Niayesh, ELKRAFT**
Co-supervisor: **Lars Lundgaard, SINTEF Energy Research**

Summary
An increasing number of power electronic converters are integrated in power systems. The fundamental functionality of electronic converters is turning on and off semiconductor switches to form the wanted voltage shape. This causes fast repetitive voltage pulses which can have negative effects on the insulation systems. The increased degradation of the insulation systems is due to several mechanisms, but partial discharges (PD) is considered most harmful. The insulation of the electronic converter itself is also vulnerable to PD. Today, power electronic devices are tested for PD when the system voltage is above a certain level. They are not tested with the pulsed voltages they are exposed to, but rather using a conventional method applying a sinusoidal voltage. The conventional method for PD detection is unsuited for pulsed voltage conditions, and new detection methods must be developed.

The objective for this project has been to create a system for detection of PD in semiconductor substrate test objects at a fast-rising square voltage. The current through the test objects has been investigated using a frequency analyzer to identify the frequency content of the applied voltage and PD pulses. Three different interfaces for measuring the current through the test object has been made for direct, inductive and electromagnetic measurements respectively; resistive shunt, high frequency current transformer (HFCT) and antenna. Three different methods of suppressing the influence of the applied voltage has also been tested; filter, wavelet analysis and subtraction by average.

A functioning PD measuring system has been made utilizing a standard oscilloscope connected to a computer with Matlab for data collection. Current measurements were done using the resistive shunt. A Matlab script was made to suppress the influence of the applied voltage using the subtraction by average method. This script was also used to extract and plot the amplitude and location of the detected PD pulses. An example of results obtained using this PD detection system can be seen in the figure below. Optical detection with a photomultiplier was utilized as a method of confirming the electrical measurements.



Methods for Cost Allocation Among Prosumers and Consumers Using Cooperative Game Theory

Student: **Elise Tveita**
Supervisor: **Hossein Farahmand**
Co-Supervisor: **Markus Löschenbrand**

Summary

The decarbonization of the power sector is at the core of the transition to a sustainable energy future. In parallel with the growth in renewables, the costs of solar photovoltaic (PV) and electrical energy storage (EES) are decreasing, which facilitates installation of these devices at the residential level. With a higher penetration of distributed generation (DG) and electrical energy storage (EES), private end-users are taking a more active role in the power grid. Currently, independent operation of these devices is most common. With an increased amount of DG and EES available, opportunities for cooperation through power exchanges arise. In cooperative game theory, all players cooperate under joint benefits. Preliminary studies conducted by the author, show that such cooperation among prosumers and consumers yields reduced annual electricity cost compared to independent operation.

Focusing on cost allocation among end-users equipped with rooftop PV and batteries, the objective of this thesis is to analyze two possible solution concepts; the nucleolus and the Shapley value. An energy community consisting of private end-users is modeled as a cooperative game. By changing parameters that increase the value of the battery system in terms of reduced cost, this thesis aims to examine whether the deviation between the cost allocation methods increases as the value of the battery system is changed. The simulated energy community is based on data from private residences in Norway, provided by Trønderenergi Nett, the local distribution system operator (DSO).

Results show that both nucleolus and the Shapley value provide stable cost allocations under minor deviations, depending on the case. Results also show that the deviation between the methods increases, as the value of the battery system increases. The highest deviation between the methods is of 3 %. In this scenario, the value of the battery system is 8.84 %, which also represents the highest value of batteries within the considered scenarios.

Utilisation of Machine Learning in Power Transformer Asset Management

Student:	**Martine Ukkelberg**
Supervisor:	**Eivind Solvang**
Co-supervisors:	**Espen Eberg**
	Maren Istad
Collaboration with:	**SINTEF Energy Research and Statnett**

Problem description

This thesis involves examining potential opportunities obtained by better management of big data and utilisation of machine learning for power transformer asset management purposes. This is done in order to determine if machine learning is an alternative method to already existing models. It can optionally be one of several tools used. The motivation is to develop machine learning models to describe physical conditions based on big data. Using such models actively in decision-making will help developing safe and efficient operations of power transformers. The aim is that such a model can be able to use real-time data from power transformers in order to predict the temperature development of the given transformer in a more efficient way than already existing methods. This can further be used to estimate the condition and remaining lifetime of the transformer for asset management purposes. For this purpose, there exists a useful data base in addition to the correlations being relatively clear, making it possible to have a physical understanding of the relationships and results.

Abstract

Ageing assets in the power system increase the need for maintenance and reinvestments. There is currently a shortage of adequate data and analysis systems available for estimation of condition and remaining lifetime, to facilitate decision-making. It is a challenge to restructure asset management with regard to collecting relevant data and to introduce new systems for handling and analysing the data. There is a large potential for increased value creation through more online and automatic collection and analysis of condition values.

This thesis examines potential opportunities obtained by better management of big data and utilisation of machine learning for power transformer asset management purposes. Power transformers are expensive and important components of the power system, and an increasing volume of data concerning their condition is becoming available. Transformers also have the potential for longer lifetimes. The introduction of data analysis using machine learning and management of big data enables condition monitoring of components to a greater extent than was previously possible. As a result, power companies can potentially optimise maintenance, and postpone reinvestments by adding resources where needed.

After presenting the theoretical framework, two case studies are performed. A machine learning model was developed to predict transformer hot-spot temperature for a chosen transformer, using available data. Furthermore, predicted hot-spot temperatures were used to estimate winding insulation degradation for different scenarios, including increased load and increased and decreased ambient temperature. These estimates were further used to determine the associated remaining lifetimes. The emerged utility value is also presented.

The results show that machine learning models are able to predict transformer hot-spot temperature with satisfactory accuracy, compared to the hot-spot temperature measured by a fiber optic sensor. The models can also be used to determine the maximum acceptable loading. Change of hot-spot temperature has a large impact on the estimated remaining

lifetime, with higher hot-spot temperature leading to accelerated ageing. The predicted hot-spot temperature was also proved to correspond better with the measured hot-spot temperature than the ones obtained by the commonly used loading guide.

Better management of big data and utilisation of machine learning creates many new opportunities. Machine learning can be implemented in already existing activities to increase efficiency and accuracy, and to reduce uncertainty. New applications can also arise as the power system becomes more digital, with emerging use of sensors. Examples are normal behaviour models, sensor verification, and loading determination. Good ICT-structure and data of quality are necessary for these purposes. It is important to emphasise that predictions of condition and lifetime obtained using machine learning are estimates. This needs to be considered when making decisions involving maintenance and reinvestments.

Systematikk for planlegging av mikronett

Student: **Katrine Utvik**
Faglærer: **Kjell Sand**
Veileder: **Anne Hilde Nilsen**
Utføres i samarbeid med: **Haugaland Kraft Nett AS**

Sammendrag

Ved å sammenfatte de viktigste faktorene ved et litteraturstudie og systematikk utviklet i forberedende prosjektoppgave har det blitt presentert en revidert utgave av systematikk vedrørende planlegging av mikronett. Systematikken har hovedrøtter i RENs planleggingsbok for kraftnett og IECs retningslinjer for planlegging av mikronett, og presenteres som en iterativ struktur i et flytskjema med elleve prosesser.

Masteroppgaven foreslår en modifisert utgave av systematikken ved effektiviserende tiltak for hurtig utfasing av alternativer som ikke er gunstige. For effektiv planlegging foreslås algoritmer som kan implementeres i digitale hjelpemidler i de ulike trinnene i planleggingsprosessen.

Haugaland Kraft Nett har tildelt planlegging av mikronett for Utsira kommune som case for mulighetsanalyse og eksemplifisering av systematikken i et reelt tilfelle for mikronett. Hovedformålet med prosjektet er å minimere kostnader for samfunnsøkonomisk nettforvaltning, der fokus på miljø verdsettes med mål om å bli nullutslippskommune innen år 2020.

Forutsetninger med nye effektkrevende aktører i området danner behov for ny informasjonsinnhenting. Tekniske og økonomiske analyser resulterer i anbefalinger for videre undersøkelse av følgende løsninger for energiforsyning på Utsira:

1. Tilknyttet mikronett med totalt 3 MW vindkraft installert.
2. Tradisjonell nettoppgradering.
3. Tilknyttet mikronett med totalt 5 MW vindkraft installert.

Alle alternativene inkluderer oppgradering av sjøkabel på 2,5 MW for tilgang til overliggende kraftnett med rimelig, miljøvennlig energi samt å åpne for salg av energi for inntekt og derav dekning av deler av investeringskostnadene. Løsningene for mikronett forutsetter installasjon av aggregat på 1,3 MW og lasthåndteringssystem. Gjennomgang av systematikken belyser fire dimensjonerende aspekter ved planlegging av et mikronett:

• Riktige inngangsdata
• Spenningskvalitet
• Investeringskostnader
• Energibehov i området

Modeling and operation of hybrid ferry with gas engine, synchronous machine and battery

Student: **Martin Skaar Vadset**
Supervisor: **Trond Toftevaag**
Collaboration with: **Vard Electro**

In this master's thesis, a direct current (DC) hybrid energy system for a liquified natural gas (LNG) ferry is developed and studied. The system is constructed in Matlab and Simulink and consists of two generator sets with gas engines and synchronous generators, six-pulse diode rectifiers, battery storage, bi-directional DC/DC converter and a load. A control structure for the gas engine, excitation system of the generators and battery converter is developed. The gas engine is modelled with the GAST model and a speed governor, while the excitation system is modelled with the AC1A excitation model and droop control with respect to the DC link voltage. Two control methods are developed for the control of the converter, droop and peak shaving. The performance of the controllers and system is tested for generator sets with droop control, generator sets and battery with droop control and peak shaving with generator sets and battery. The specific energy consumption (SEC) of the gas engines is then calculated for fixed and variable speed during stationary operation with respect to the engine speed and engine load. The SEC values are compared for the cases and with respect to variable and fixed speed.

Variable speed resulted in lower SEC for all cases presented, and the highest difference was for the case with the peak shaving method. For the droop control configuration between the generator sets and the battery, the SoC limits of 80-65 % was violated with a δ_{Bat} equal 0.05. Then, the options for the system were to increase δ_{Ba} and reduce the contribution from the battery or install a larger battery that is able to contribute the load power without violating the SoC limits. With the peak shaving method, stored power was available in the battery since the SoC was in the range of 80-76 %. With the discharge and charging power (±1800 kW) delivered from the battery, a smaller battery with a capacity of 720 kWh could obtain the same operation. An opportunity to reduce the SEC of the operation is to develop a control system for connecting and disconnecting generators sets, which makes the generator sets operate at a more optimal loading rate.

Maximum step out of AC cables to offshore installations

Student: **Per Tore Vatn**
Supervisor: **Hans Kristian Høidalen**
Contact: **Nicola Chiesa, Equinor ASA**

Problem description
Investigation of passive and active compensation at both ends of an AC subsea cable. Both the case of supplying an offshore load and performing a DOL motor start up with background load will be investigated. How the system handles load rejection with different compensation configurations is explored. The compensation includes series, shunt and STATCOM devices. Several compensation technologies and the challenges related to compensation is presented. The problem of subsynchronous resonance and possible mitigation of this will also be discussed. The simulation and development of the system will be done through EMTP simulations and discussions with Equinor regarding practical challenges and system parameters.

Summary
The task of supplying an offshore installation with power is one that can be solved in several different ways. This thesis suggests a compensated AC subsea cable as the power from shore solution. At a length of 200km, the cable is stretched to its limits in order to provide sufficient power offshore. The simulation was carried out using ATPDraw, a graphical preprocessor to the ATP version of the Electromagnetic Transients Program (EMTP).

Using a fixed series and shunt compensation, it was possible to meet the demands of a 50MW offshore load. Even accounting for load rejection, the compensation meant the system was able to run within its operating limits. The need for both onshore and offshore compensation became apparent during no load conditions. At a transmission voltage of nearly 100kV, the voltage drop across the cable was no more than 7\%. The transmission losses across the whole system amounted to 11\%. There does however seem to be little encouragement for even longer cable lengths.

As the compensation of the system was realised, the problem of SSR came to the fore. Using a frequency scan, one could observe that the introduction of fixed series compensation in to the system introduced resonant SSR frequencies. This could partially be solved by using the premise of a very simplified STATCOM device connected to the system.

Illustrations
Figure 1 shows the voltage level at the offshore load bus after load rejection. This was the most critical point in the system during load rejection. Voltage levels had to be within +-20% of steady state voltage. Figure 2 shows a frequency scan done while series compensation is installed. One can clearly see the sub synchronous resonance introduced by the series compensation.

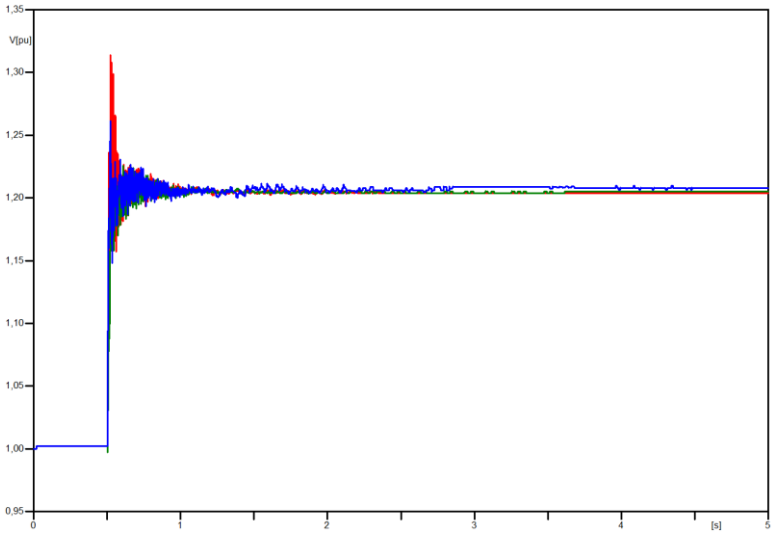


Figure 1: Voltage level after load rejection

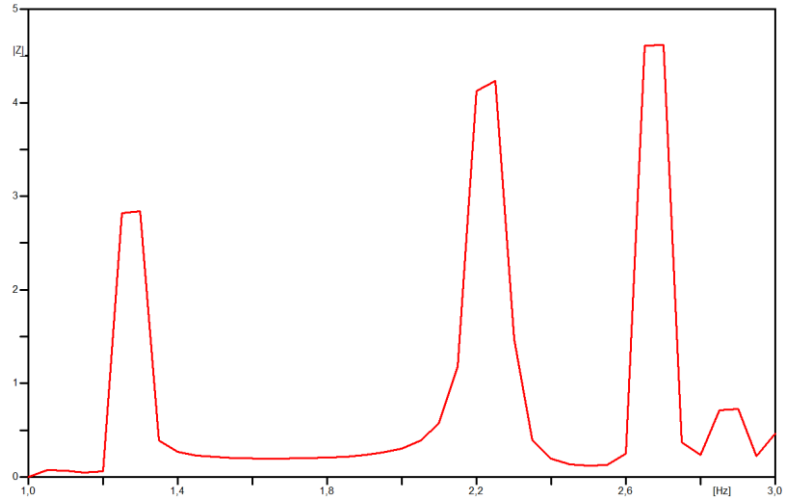


Figure 2: SSR with series compensation

Loss analysis in laminated iron cores using COMSOL Multiphysics and LiveLink for Matlab

Student: **Sondre Hamarheim Westad**
Supervisor: **Robert Nilssen**
Contact: **Astrid Røkke**
Collaboration with: **Rolls Royce**

Problem description

This thesis is an introduction to iron loss analysis for laminated ferromagnetic materials used in electrical machines. The existing methods for calculating iron core losses are struggling to produce correct results, so this thesis will be a fundament in trying to improve this. The loss analysis uses the Finite Element Method (FEM) program COMSOL to calculate the field distribution in a model, and Bertottis equation to calculate the losses. The challenge lies in the modelling the iron cores in the FEM software and to calculate the variables needed for the Bertotti equation in the post processing, which is the frequency and the peak flux density for every element in the model.

The task

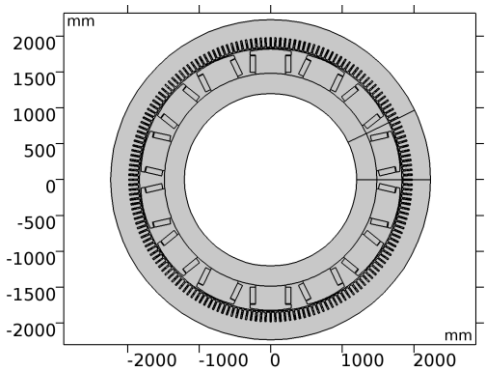
The task to be able to produce the variables needed for the Bertotti equation,

$$\overline{P_v} = k_h f \hat{B}^2 + k_c f^2 \hat{B}^2 + k_e f^{1.5} \hat{B}^{1.5}$$

which gives the loss density for every discrete element in the COMSOL model. The goal will be to study different aspects of the loss analysis. The first is the modelling of the ferromagnetic materials, especially the relationship between the H- and B-field. The next goal is to be able to export the solution to Matlab through LiveLink, and treating every element individually. The next goal is to discuss two different methods of extracting the flux density of the elements. A method for calculating the frequency of the flux density needs to be explored.

Model/ measurements

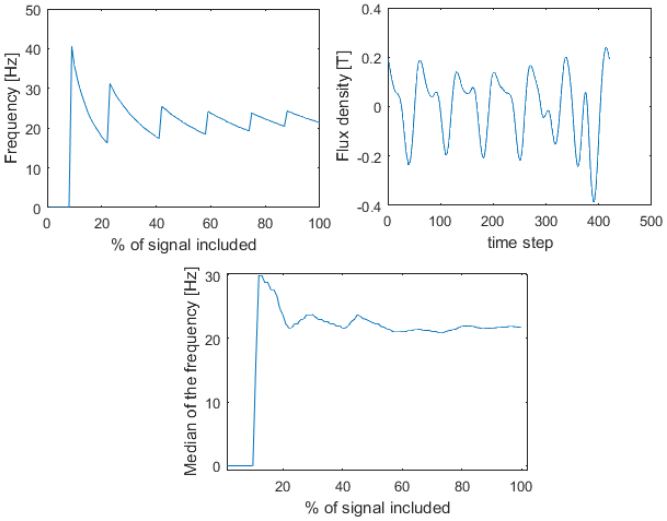
The method used to calculate the iron losses in this thesis exports the results from the FEM program COMSOL Multiphysics to Matlab through LiveLink. The model can be post processed in Matlab to find the losses in the iron core in the model. The Bertotti equation uses experimental material data from the IEC standard 60404-8-4:2013 to calculate the constants through the least squares method. The variables are the peak of the flux density, B, and the frequency, f. These variables are unique for each single element in the FEM model and must be treated individually. The peak of the flux density is found by taking the maximum of the flux density signal for one element, when the DC offset is removed. The frequency is the median of multiple Fast Fourier Transforms (FFT) of different parts of the signal. The method is tested on a 105 MVA hydro generator. The geometry is shown in the figure to the right.



Calculation

The 105 MVA hydro generator was simulated in COMSOL, using a parametric sweep in the time domain. The constants of the Bertotti equation was calculated by using curve fitting of the loss data of the M300-35A ferromagnetic material. The losses in the generator was found in the table to the right, for two different methods; one using the FFT analysis to find the frequency of each element, the other by assuming 50 Hz in the entire model. The losses using the FFT method are 57.2 % higher than the losses calculated by Engevik. The frequency analysis of the rotor is in the figure to the right, where the upper right figure is the flux density signal. The upper left part is the FFT analysis for different percentages, starting from zero, of the signal. The lower part of the figure is the median of the last half of the values presented in the upper right figure, when different parts of the flux density signal are included. It is shown that the frequency converges towards a value when using this method.

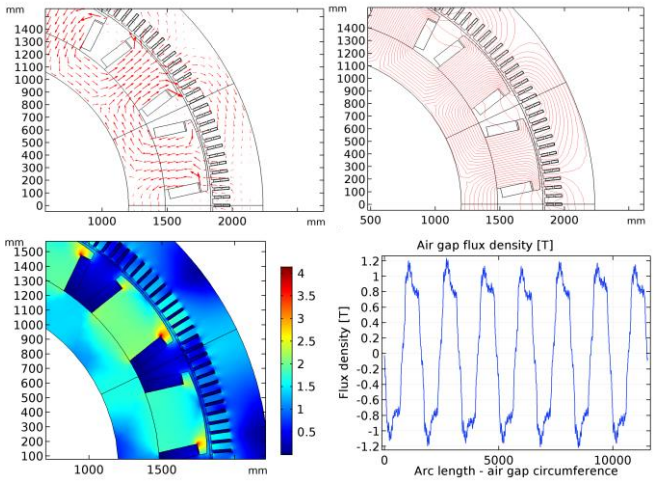
	Total losses using FFT [kW]	Total losses assuming 50 Hz [kW]
1/14th of stator	18.56	17.37
13/14th of stator	265.32	262.71
Rotor	29.74	96.52
Stator + Rotor	313.62	376.60



The methods for finding the typical flux density for an element is also discussed. The mphinterp function was much slower and did not work properly for rotating machinery. The method of using the average of the flux density of the corners of every element is much faster and works for rotating machinery.

Conclusion

The results obtained in the COMSOL simulation was successfully exported to Matlab through LiveLink, and the data needed for the Bertotti equation was found by using Matlab. The best way of modelling the relationship between the H- and B-field is the BH curve. The method was able to calculate the losses in the 105 MVA generator. The best method for extracting the flux density in an element is to use the average of the flux density in every corner of the element. The frequency analysis method is working and giving a more accurate frequency in all parts of the machine, especially the rotor. The full Fourier transform, or other frequency transformations could be applied to the method to increase the accuracy of the frequency calculation.



Implementering av logisk styrt automatikk i 22kV Distribusjonsnett

Student:	**Tor Helge Økland**
Faglærer:	**Hans Kristian Høidalen**
Medveiledere:	**Bernhard Bolsøy og Rune Paulsen (NTE)**
Utføres i samarbeid med:	**NTE Nett AS**

Innledning/Problemstilling

I dagens høyspente distribusjonsnett er forsyningssikkerhet og minimering av KILE-kostnader viktige tema. Nettselskap har via KILE-ordningen sterke incentiver til å jobbe for at antall feil, varighet og konsekvens av feil er så lav som mulig. I den tradisjonelle driften av nettet benyttes effektbrytere på 22kV samleskinne og manuelt betjente brytere ute på avgangen. Manuell betjening medfører ofte lange avbrudd med flere gjentakende prøvekoblinger før feilen lokaliseres, isoleres og resterende sluttbrukere kan forsynes. Ny teknologi gir mulighet for større grad av sensorikk og automatikk i nettet som medfører at feilen kan lokaliseres og isoleres raskt. Oppgaven vil fremstille aktuelle komponenter og teknologi for å automatisere deler av feilrettingsprosessen, samt beregne nytteverdier og lønnsomhet for ulike system-løsninger for å bestemme optimalt antall og plassering.

Metode

For å betrakte implementeringen er det tatt utgangspunkt i en aktuell avgang fra NTE Nett AS sitt konsesjonsområde. Gjennom litteraturstudie og kontakt med leverandører er komponenter og teknologien for å oppnå logisk styrt automatikk fremlagt. Dataverktøyet Powel NetBas benyttes i oppgaven til blant annet å simulere avbrudd på den aktuelle avgangen for ulike systemløsninger. Gjennom nåverdimetoden blir lønnsomheten beregnet for hver systemløsning basert på de reduserte KILE-kostnadene og investerings-kostnad. Optimale løsninger basert på teknologi, plassering og antall bestemmes ut fra resultatene. Det avgjøres også hvilke forutsetninger som avgjør potensialet for implementering av logisk styrt automatikk på andre avganger.

De analyserte systemløsningene er:	
Ingen automatikk:	Bruk av distribuerte effektbrytere
Desentral selv-heling:	Bruk av lastbrytere hvor logikk utføres av kontrollenhet i transformatorstasjon
Lokal selv-heling:	Bruk av gjeninnkoblere hvor logikk utføres av hvert enkelt bryter-anlegg
Sensorer:	Kommuniserer med driftssentralen ved feil

Resultater

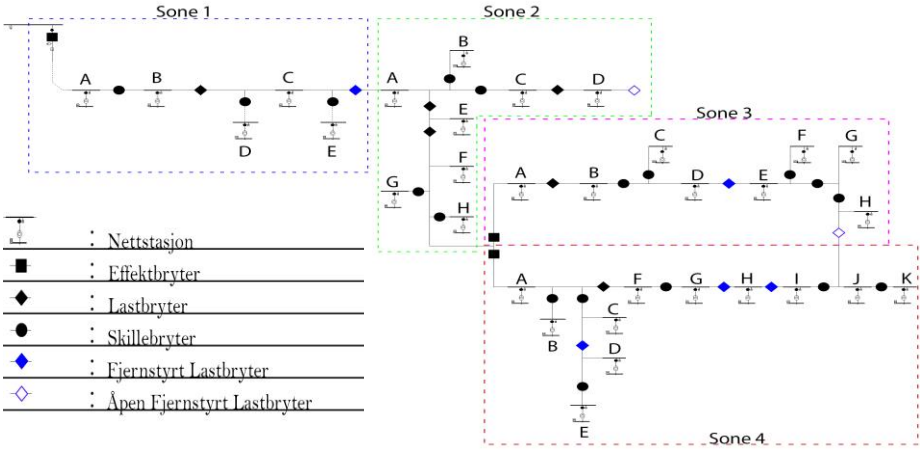
De optimale plasseringene for de ulike systemløsningene og medfølgende resultater:

- For effektbryter uten automatikk er optimal plassering en bryter i sone 1 og to i sone 2, og reduserer de årlige KILE-kostnadene med 195 077 kr som tilsvarer bortimot en halvering. Resultatet gir en lønnsomhet på 1 159 038 kr i løpet av analyseperioden.

- Desentral selv-heling har samme optimale plassering og antall som for effektbrytere, men gir et lavere potensial til reduksjon av årlige KILE-kostnader, beregnet til 159 230 kr, og fører til en lønnsomhet på 606 638 kr.

- Lokal selv-heling medbringer høyest investeringskostnad som fører til at ekstra bryter i sone 1 ikke gir optimal løsning. Den optimale løsningen er implementering av to brytere i sone 2, og gir en reduksjon av årlige KILE-kostnader, beregnet til 186 334 kr. Lønnsomheten over analyseperioden er beregnet til 1 004 034 kr.

- Optimal plassering ved implementering av sensorikk er i sone 2 med 5 sensorer og gir en lønnsomhet på 650 627 kr. Lønnsomheten øker med antall sensorer på grunn av behov for færre koblinger.



Figur 1: Forenklet en-linjeskjema av den aktuelle avgangen

Resultatene fra simulering og beregning av lønnsomhet indikerer at sone 3 og 4 ikke har tilstrekkelige kostnader forbundet med avbrudd til å gi lønnsomhet, da ingen av system-løsningene gir lønnsomhet ved referanseverdiene. Plassering i sone 2, som da også påvirker avbruddstiden i sone 1, gir de største KILE-besparelsene.

Konklusjon

Hvilke bryterplasseringer som er optimal er i større grad avhengig av avgangens sluttbruker-sammensetningen en feilhyppighet. Det er følgelig en sammenheng mellom hvor ofte avbrudd forekommer og hvor stor gevinst en oppnår av et automatisk koblingsprogram, men i betraktning av besparelse av årlige KILE-kostnader er det viktigere å redusere avbruddstiden i områder hvor kostnaden per uteliggende nettstasjon er stor. Dette er spesielt fremtredende på den aktuelle avgangen hvor sonene lenger ut på avgangen er utsatt for et betydelig antall årlige avbrudd, men består hovedsakelig av sluttbrukere med lavt forbruk og hvor en høy andel inngår i kundegrupper forbundet med lave KILE-satser.

Analysen antyder at implementering av logisk styrt automatikk vil føre til lønnsomhet. Leverandører har tilgjengelige komponenter for implementering, men mangler reelle driftserfaringer. Den lokaliserte løsningen gir best lønnsomhet av de automatiske systemene da løsningen benytter effektbrytere. Lønnsomheten er lavere enn ved bruk av distribuerte effektbrytere uten automatikk. Hovedårsakene er økt investeringskostnaden, men tyder også på at avgangens nettutforming er mindre gunstig for implementering av automatikk. Dette fordi de optimale plasseringene er tidlig på avgangen hvor nettutformingen gir begrenset muligheter for rask gjeninnkobling av forsyning som gjør at gevinsten av automatikken kontra uten ikke er like store som de potensielt kunne ha vært. Beslutningen avhenger derfor også av nettselskapets betalings-vilje og budsjett, hvor den redusert lønnsomhet må vurderes opp mot verdien av økt kunnskap og omdømme.

Forbrukerfleksibilitet som en ressurs i fremtidens kraftsystem

Student: **Thea Ulrikke Øverli**
Faglærer: **Magnus Korpås**
Medveileder: **Hanne Sæle**
Utføres i samarbeid med: **SINTEF Energi**

Med en økning i energieffektive men effektkrevende apparater, i tillegg til elektrifisering av bilparken, står det norske kraftsystemet ovenfor nye utfordringer. Disse utfordringene kan ikke lenger håndteres kun ved utbygging eller oppgradering av nett, da det vil være kostbart og lite samfunnsøkonomisk lønnsomt. Ny teknologi og digitalisering av kraftsystemet åpner for utnyttelse av fleksibilitet fra forbrukssiden fra lasttilbydere i mindre skala enn før. Forbrukerfleksibilitet kan redusere maksimalbelastningen i nettet, som gir reduserte tapskostnader og potensielt utsatte investeringer i nettet. Mindre investeringer i nettet betyr i det lange løp lavere nettleie til forbrukerne.

Fra 2019 vil alle norske målepunkt ha installert smarte målere, og kunden vil ikke lenger bare være et passivt uttak av strøm, men en aktiv deltager i et mer dynamisk kraftsystem. En aktiv forbruksside som responderer på prisendringer vil kunne bidra til en mer effektiv drift av nettet, med høyere forsyningssikkerhet, lavere prisvariasjoner og dempet markedsmakt.

Hovedformålet med oppgaven har vært å utforme modeller for styring av fleksibiliteten i varmtvannsberedere. Varmtvannsberedere er en last med gode egenskaper for fleksibilitet; den innehar god termisk treghet og en utkobling for en begrenset periode vil i liten grad påvirke forbrukerens komfort. I arbeidet med oppgaven ble det ble utviklet to modeller med fokus på flytting av vannoppvarmingen til timene på natten, hvor totalforbruket er lavere. De to modellene fikk navnene *forhåndsoppvarmingsmodellen* og *nattoppvarmingsmodellen*.

Forhåndsoppvarmingsmodellen benytter seg av varmelagringsevnen i varmtvannsberederen, og forhåndsoppvarmer varmtvannet til en høyere temperatur før morgenlasttoppen. Med en høyere temperatur i vannet vil det ta lenger tid før varmtvannsberederen må aktivere varmeelementet, og man får redusert effektbelastningen i morgentimene. Nattoppvarmingsmodellen utsetter oppvarmingen til natten ved å slå av strømmen til varmtvannsberederen ved et gitt tidspunkt. Den vil da være av helt frem til et gitt innkoblingstidspunkt på natten, eller til temperaturen på varmtvannet er under en kritisk grense.

De to modellene har blitt testet med to tariffer; spotpris og tidssonetariffen Time-of-Use. Resultatene viste at dersom det innføres ToU-tariff for alle forbrukere, vil de som ikke utnytter fleksibiliteten sin tape penger, mens de som utnytter den vil spare rundt 200 kr per år. Ved å gå fra spotpris til ToU med fleksibilitet vil forbrukeren spare litt over 100 kr per år. I tillegg til disse besparelsene kommer en eventuell langsiktig reduksjon i nettleie til kunden som resultat av utsatte nettinvesteringer for netteier.

Det ble utført stasjonære lastflytanalyser i analyse- og simuleringsprogrammet PSS®E for et lavspentnett fra NTE Nett, for å påvise nytteverdien av fleksibilitet for spenningsforbedringer. Det ble gjennomført tre caser, case 1 som basecase, og case 2 og 3 hvor motstanden i nettet var doblet for å simulere lengre linjer og et svakere nett. Dette førte til at to noder falt under spenningsgrensen på ±10%. I case 2 ble det brukt generell fleksibilitet fra varmtvannsberedere for å demonstrere nytteverdien av fleksibiliteten, og heve spenningen. En tunglasttime fra

NTE Nett ble brukt som referanseforbruk. Resultatet viste at i timer med høyt potensial for fleksibilitet kunne spenningen i kritiske noder bli hevet med over 8V. I kun en av de 13 timene som ble simulert klarte ikke fleksibiliteten å heve spenningen til en tilfredsstillende verdi, fordi timen hadde lavt potensial for fleksibilitet, og fleksibiliteten ble ikke utløst nært nok de utsatte nodene.

I case 3 ble påvirkningen fra de to modellene simulert i tre forskjellige timer hver; timen med høyest potensial for fleksibilitet, timen med høyest behov for fleksibilitet, samt timen med høyest innkobling fra de to modellene. Simuleringene ble gjort årets mest energikrevende dag. Case 3 viste at spenningen i nettet ikke tålte maksinnkoblingen av varmtvannsberederne i dette tilfellet. Selv om case 3 ikke ga ønskede resultater, ble det fortsatt vist at forbrukerfleksibilitet har en nytteverdi for både kapasitetsutnyttelse og spenningsforbedring. Modellene vil ha en bedre nytteverdi dersom formålet med de to modellene er kapasitetsreduksjon. Innkoblingen av varmtvannsberederne trenger ikke føre til kapasitetsproblemer i nettet, da modellen kan fordele innkoblingen jevnt for å unngå å overskride den opprinnelige forbrukstoppen. Komplikasjoner ved innkobling vil derfor stort sett forekomme i små nett med lokale spenningsproblemer.

Til slutt ble det gjort en grov kvantifisering for å vise potensialet for effektreduksjon ved innføring av de to presenterte modellene. Ved å anta at det er 2 millioner varmtvannsberedere i installert i Norge, og at halvparten styres av en av disse modellene, kan man estimere effektreduksjonen på nasjonalt nivå. I timen med størst potensial ga dette en reduksjon på 680 MW nasjonalt.