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Utilization of stored hydrogen for power production to overcome intermittency from wind power

ERLING ALME

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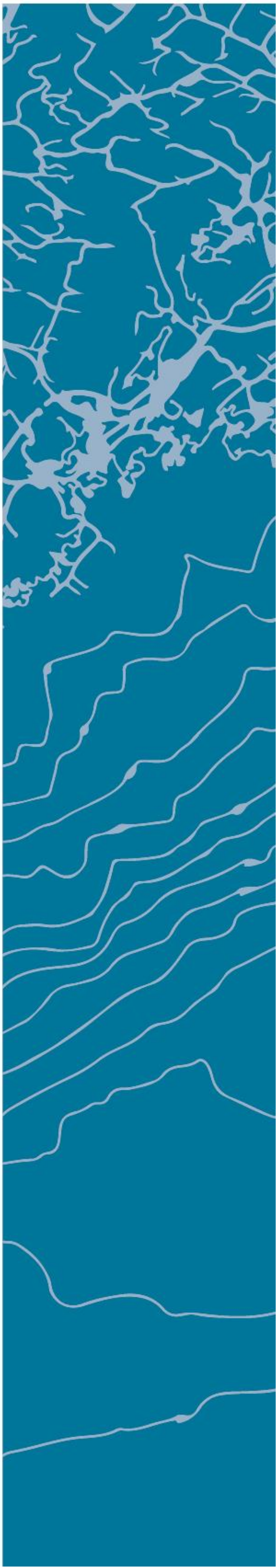

Abstract

The energy demand is increasing and due to the enormous amount of pollution that comes from fossil energy it is time to think alternatives. This thesis is about using hydrogen and energy storage to produce power. The system is designed based on an expanding of wind farm at Smøla of 50,13MW, but without doing anything with the grid, which is close to its maximum capacity. The power produced from the year 2015 is used to measure the different component size which is needed. The simulation of the system is used by Simulink with control to handle underproduction and overproduction from the wind farm. The optimal size calculated for the system is, fuel cell with capacity of 4,66MW, a hydrogen storage tank with 79,19 capacity and a alkaline electrolyser with capacity of 50MW . The average hourly increase in one year is 11,59MW where 1,56MW is from the fuel cell production. The average production has been increase from 45,7MW to 58,3MW. The change gave an increase of grid utilization from 29,5% to 37%. The average production has been increase from 45,7MW to 58,3MW which gave a total annual production of 502,202GWh. The utilization of the network capacity is increase by 11,592MWh. However, all of this increased power does not get produced by the fuel cell alone. At times when the wind turbine produces less power than the grid capacity of 155MW, there would not be need to use the system. The actual extra power that comes from fuel cell, electrolysis and hydrogen tank capacity is 1.5578MWh. The cost of the project gives a net loss of 966millionsNOK over a time period of 20years with use of the same power price as 2015. For the project to go out in plus it is necessary to get an power price over 0,899NOK/kWh.

Preface

Thanks to professor Mohan Lal Kolhe for guidance with the thesis.

Thanks to Pål Preede Revheim from NVES for all the information and data of Smøla wind park, and the conversation about use of hydrogen as an energy source.

Special thanks to my wife Mari Kristine for the support.

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Abbreviations

MW	Megawatt(10^6watt)
MWh	Megawatt hour(10^6 Watt hour)
M/S	Meter per seconds
M	Meter
Rev/min	Revolution per minute
V	Voltage
AC	Alternating current
DC	Direct current
PEM	Proton exchange membrane
Co_2	Carbon dioxide
H	Hydrogen
O	Oxygen
NVES	Nasjonalt Vindenergisenter (National Wind Energy Center AS)
e	Electron
E°	Cell potential in voltage
J/K	Joule/Kelvin
Kj	Kilo joule
Pa	Pascal
Mole	Unit of measurement
η_F	Cell efficiency (0,681 for electrolyzer and 0,94 for compressor)
I_{Cell}	current running through the cells
Z	number of electrons($H\ ^2$have 2)
F	Faradays constant 96485 C mol^2
MPP	Maximum power point
PWM	Pulse width modulation

Chapter 1 Introduction

Smøla wind park has a large power production and have been operative since 2002[1]. It has 68 wind turbines installed[1], 20 turbines with capacity of 2MW and 48 turbines with capacity of 2,3MW, which gives the maximum total production to be 150,4MW, as shown in equation 1.1 Between 2008 and 2015 the average yearly production was 333,18GWh[2]. This gives an average production of 39,0MW throughout the year. The maximum capacity of the grid is 155MW[29], and with this we can see that the average usage of the grid is 25,16%, as shown in equation1.2, and that the production from wind could be increased by an average of 116MW. The main issue with the grid capacity is that it has to be engineered to handle the maximum production from the wind at an instance production, and not the average throughout the year. There are several solutions for this. One way is to increase the capacity of the grid, but this has been found too costly to be realized.[3] Another solution for the issue is to store the energy in terms of hydrogen production, storage and then to either ship the hydrogen to another marked or to generate electric energy by fuel cells. The electric production by use of hydrogen is what this thesis is takin one closer look at.

Total power capacity from the wind park today.

$$20 * 2MW + 48 * 2{,}3MW = 150{,}4MW \qquad (1.1)$$

The average yearly grid capacity utilization,

$$\frac{39MW}{155MW} = 25{,}16\% \qquad (1.2)$$

Average power available that could be fed out on the grid.

$$155MW - 39MW = 116MW \qquad (1.3)$$

1.1 Motivation

The global Co2 emissions have been increasing annual for many years[4] and in 2015, many of the world leaders agreed to reduce the emissions[5]. One solution of reducing the Co2 emissions is to include more energy from renewable energy from sun, water and wind. The main issue with use of renewable energy is that the power needs to be generated and used instantly. This is when the sun is shining, the wind is blowing or the water is falling. This conflicts with the demand for power, since people like to use power when they need it and not necessary when it is produced. With water, it is possible to build a dam, which could hold energy depending on the size of the dam that could later be used for power generation. With power from sun, wind and tidal wave it is more difficult to store the energy. To store this energy it has to be implemented storage in form of electrochemical storage or electrolyzer. The electrolyzer would in addition need a storage tank for storing hydrogen and a fuel cell for power generation. To use hydrogen for energy storage and power production has been known for a long time, but since the cost of using hydrogen for power production relatively high compared to other sources, it has not got a big share of the total power marked.[30] In the past few year there has been more focus on clean energy. Several countries are pushing on to make renewable energy sources take a bigger chair of the total power marked. One example is the hydrogen car, which in Norway is sold with no tax. Measures like this could lead to a higher demand for hydrogen, and especially hydrogen produced from renewable energy like wind power.

1.2 Project Description

The objective of this thesis is to look for possible solutions for increasing the power generation from the wind turbines at Smøla. This thesis is about increasing the power generation by the use of hydrogen. Another solution for increasing the power generation capacity is to increase the grid capacity, and by this increase the maximum power capacity of 150,4MW. This solution have been evaluated by the grid owner, Statkraft, and found to be too costly to be realized.[3] If this had been realized, then a large distance of power cables had to be installed with transformer and control to implement it into the grid network.

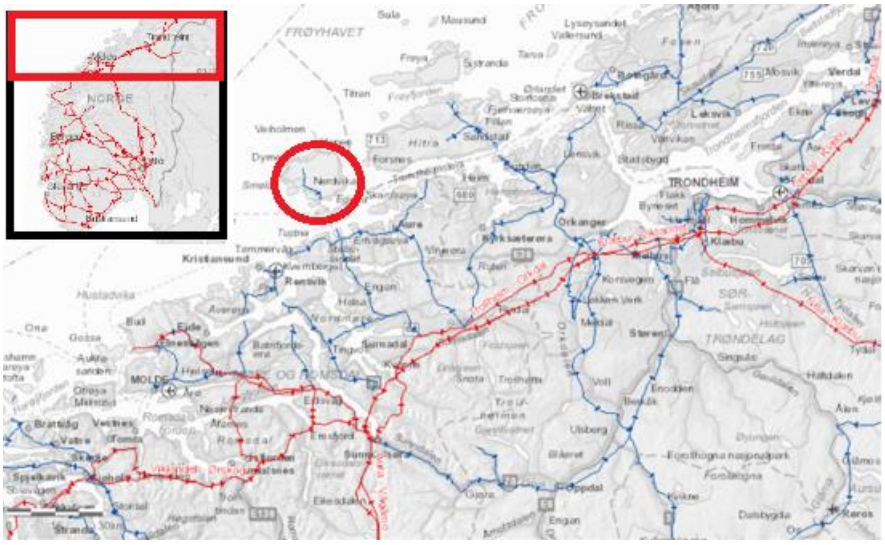


Figure 1 Grid network around Smøla]

1.3 Overview over how the system is today

1.3.1 Wind turbines installed

Today, there are two types of wind turbines installed. One type is from Bonus, which has a capacity of 2MW and the total installed turbines of this type is 20. The specification of this type is shown next to its figure.

Figure 2 Bonus wind turbine

Operational data

Rated power	2.000 / 400 kW
Rated wind speed	15,0 m/s
Cut-in wind speed	3,0 m/s
Cut-out wind speed	25,0 m/s
Diameter	76,0 m
Hub height	60,0 m
Swept area	4,536.46 m^2
Number of blades	3
Rotor speed	11 / 16 U/min

Generator

Type	asynchronous, pole-switchable
Speed	1000 / 1500 rev/min
Voltage	690 V
Grid connection	via thyristors
Grid frequency	50Hz

The second type, which it is installed 48 of at Smøla, is a Siemens with a capacity of 2,3MW as shown on Figure 3.

Figure 3 Siemens 2,1MW

Operational data

Cut-in wind speed	3-5 m/s
Nominal power at	13-14 m/s
Cut-out wind speed	25 m/s
Blade length	40 m
Tip chord	0.8 m
Root chord	3.1 m

Generator

Type	Asynchronous
Nominal Power	2,300 kW
Hub heights	80 m

1.2 Overview of planned system

The planned block diagram of the new system is shown on Figure 5. The existing system is shown in the middle with wind turbines connected to transformers and out to the consumer marked load. The new system have AC to DC diode connected to the wind turbine 3 phase 690VAC. This gives a voltage of $690AC * \sqrt{3} = 1195VDC$. This voltage is reduced by a buck converter to give the rated current and voltage of electrolyzer. This gives a electrolyzer with rated power of 50MW. The hydrogen and oxygen produced are then compressen and stored in storage tank, until it is used by the fuel cell. The fuel cell are activated when the produced energy from the wind are below 150,4MW. This is maintained by the fuel cell control and master control. The energy from the fuel cell are integrated to the grid trough a boost converter and inverter.

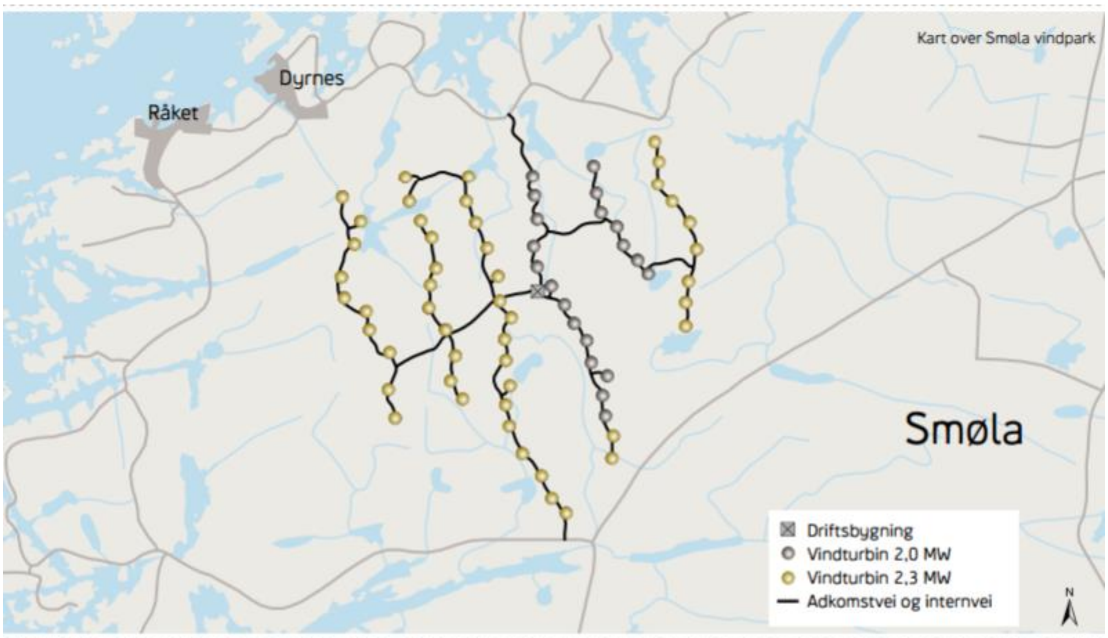


Figure 4 Overview of Smøla wind park[1]

Figure 4 Overview of Smøla wind park, shows how the system of Smøla looks today. This thesis is planning an increase of wind turbines which gives an increase in wind power installed capacity of 50,13MW. This would give an increase of approximately 22 wind turbines of 2,3MW each and then a total increase of power by 50,6MW, as shown in equation 1.4.

$$22 * 2{,}3MW = 50{,}6MW \qquad (1.4)$$

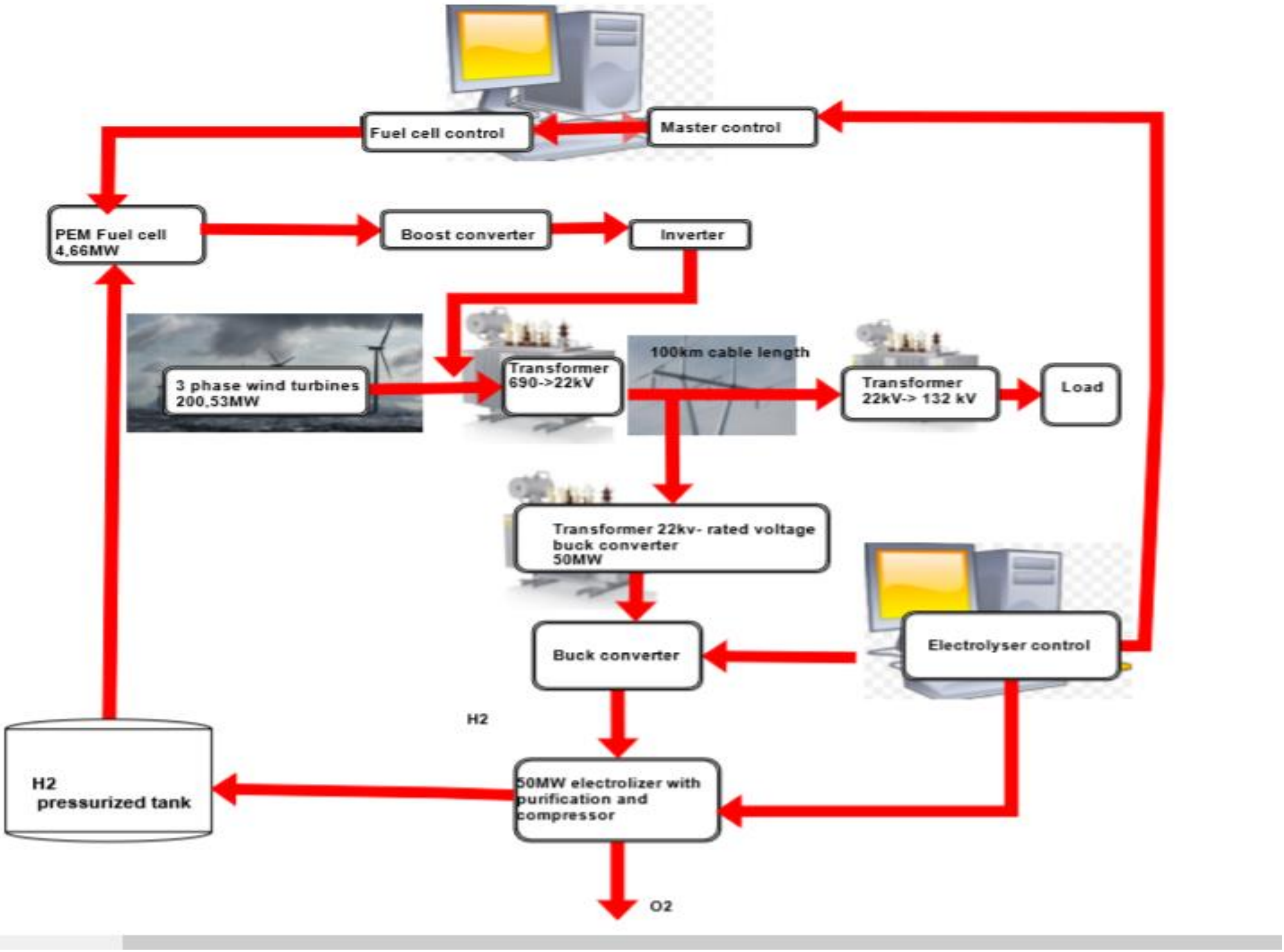


Figure 5 Overview of new system

1.3 Goals and Objectives

1. Design component size for hydrogen production and fuel cells utilization with an increase of 50MW installed capacity at Smøla wind park.
2. Make a model in Matlab Simulink to simulate
   - the hydrogen production and power consumption when the power from the wind turbine exceed the grid capacity
   - fuel cell power generation and hydrogen utilization when the grid has available capacity.
3. Make an economic overview over the total cost of the system over a period of expected life time.

1.3.1 Assumption

- When studying the problem it has not made any calculation of the layout on the wind park after the increase of 22 wind turbines. It is assumed that the power coefficient is similar to the existing turbines that is installed.
- The grid capacity is set to 155MW. This is based on 2 transformers at Smøla with a total capacity of 155MW, and the grid size after this point has not been considered.

- The power production data that is being used is from 2015, it is assumed that the newly production data will be the same as from 2015 multiplied with a factor of $\frac{4}{3}$.

1.4 Methodology

In this thesis, the main objective was to increase the power production of Smøla wind park with 50,13MW. Excel has been used for calculating the different size of component in the system, where the hourly production data from the year 2015 has been used.

When processing data in excel various formulas have been implemented so the whole set of data was processed when changing some of the parameter. This was necessary to be able to find the correct value needed for tank size and fuel cell size.

For simulation of system with integration to the grid, a model of the system in Matlab Simulink has been used. This set up in Simulink is as follows: PEM fuel cell of 5kW, DC-DC boost converter, alkaline electrolyzer 50kW and a back to back converter.

The model was scaled down so that it was easier processed when doing the simulation. Fuel cell was scaled down by a factor of 93,2, and the alkaline electrolyzer with a factor of 1000. The data has been scaled up and the correct size for the project is shown in the results. This is with a fuel cell of 4,66MW, and alkaline electrolyzer of 50MW. The fuel cell that was used is an implemented version in Simulink. The hydrogen flow rate was used for controlling the desired power production.

The alkaline electrolyzer has been made in Simulink based on formula and measurement of I – V curve from an alkaline electrolyzer cell[26]. The I-V curve was extracted to excel, which has the built in function for showing function of any graph. This function was used in Simulink, which showed the current level based on voltage level. Since the hydrogen production is based on current[26:414], it was possible to control the hydrogen production based on voltage level. The voltage level was controlled with a buck converter that had a closed loop. The system is controlled with logic for regulating the hydrogen supplied to the fuel cell and the hydrogen produced by the alkaline electrolyzer. This is for maintaining the grid of 150,4MW.

For the calculation of the economic value of the project, approximate values from manufactures have been used. NEL estimated that the cost of 50MW electrolyzer with compressor is between 200-300millions NOK[11], 0,5M€/T[30:37] for storage tank and 3000-4000€/kwh for PEM fuel cell[30:36]

1.5 Literature review

For information regarding fuel cell and electrolyzer and the energy needed for the chemical reaction, information from course "ENE401 Fuel cell" from professor Hugh Middleton have been used. This gave the information of the ideal performance of fuel cell and electrolyzer, which have been used for calculation of hydrogen and oxygen production. Also, the energy needed for operation of the fuel cell and electrolyzer have been gathered from lecture notes from the class "ENE401 Fuel cell"
A study has been done by Jagath Sri Lal Senanayaka with the topic "Power Dispatching of Active Generators using Droop Control in Grid connected Micro-grid" [23]. The paper described how to develop and implement simulation model of a back-to-back converter for a grid connected with a micro-grid operation which operates as a separate AC power system through a DC interconnect. In addition to this, the paper also describes how to analyse a grid connected with a micro-grid for achieving high penetration of renewable energy.
One paper written on photovoltaic "Simulation and comparison of perturb and observe and

incremental conductance MPPT algorithms for solar energy system connected to grid" by Sachin Vrajlal Rajani and Vivek Pandya is used as a base for extracting maximum power from fuel cell source in Simulink model.

A paper from New Energy World, "Fuel Cells And Hydrogen Joint Undertaking" has an overview of the market situation of fuel cell system and hydrogen storage and production today and expected situation in the future. This, together with information from Henning Langås from NEL Hydrogen, was used for calculating the cost of how the system.

The book "Fuel Cell Handbook" by EG&G Technical Services, Inc. The book shows the performance and building of a range of different fuel cells technology. It also shows how to optimize fuel cell systems based on temperature, pressure, utilization and heat recovery. In this thesis this information has been used to gain knowledge of fuel cell system and the different system available.

The book "Hydrogen Storage Technologies" by Godula-Jopek writes about different ways for storing and handling hydrogen. The book covers storage with pressure and with liquid and shows various compressor techniques. It this thesis it was used to tell how much energy was for compressing hydrogen to 8 bar for easier storage.

Power measurement given to me from Pål Preede Revheim from NVES. And this set of data showed the hourly power produced by the wind farm at Smøla. The data was used as a base for an extension of the wind park.

The publication" Hydrogen Production From Water Electrolysis": Current Status and Future Trends, Luis M. Gandia, Pablo Sanchis reviews water electrolysis technologies for hydrogen production. It had measurements of I - V characteristic from an alkaline electrolyse cell. The paper also had formulas of how much hydrogen that was possible to extract from the cell. These formulas from the curve and paper was used in the Simulation of the thesis.

Chapter 2 Hydrogen production and utilization

Hydrogen as an energy carrier has some chemical reactions that are necessary to look into when deciding size and losses for the system. This chapter shows the energy needed for producing hydrogen and energy that is possible to gain from the fuel cell when using the hydrogen.

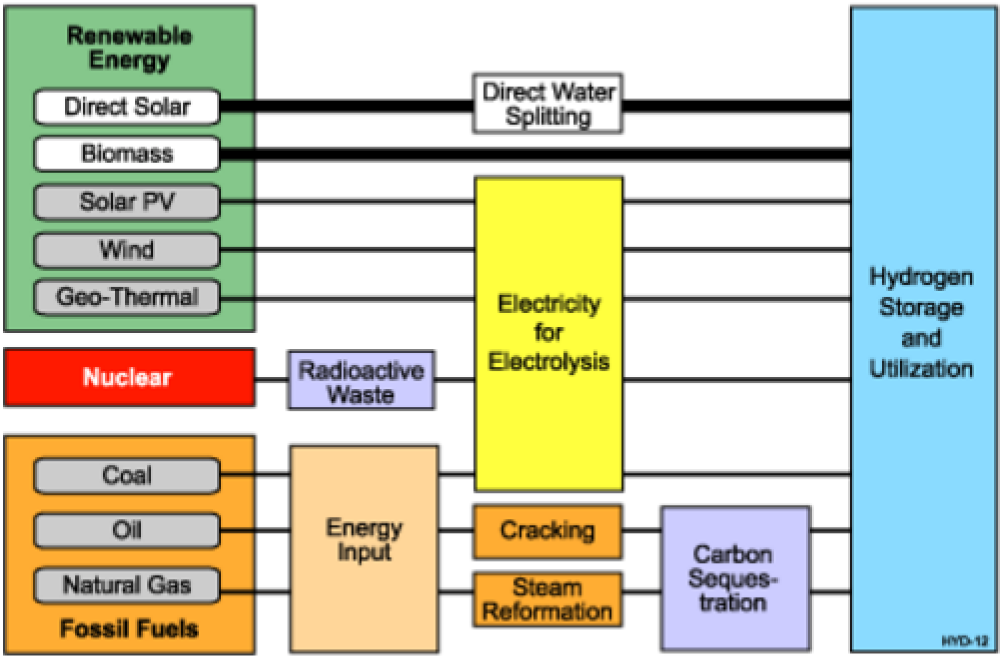


Figure 6 Different ways of producing hydrogen[19]

Figure 6 shows the two main sources for producing hydrogen, electricity for electrolysis and carbon sequestration. The green box are from renewable production and the orange is from fossil fuels. Fossil fuels is where the majority of the H_2 are being produced[8:17]. In this thesis the production of hydrogen will come from electricity and wind energy. For extracting hydrogen it is used water electrolyses. This reaction is shown in formulas 2.1, 2.2 and 2.3[9:23]

Anode (oxidation)

$$2H_2O \longrightarrow O_2 + 4H^+ + 4e^- \qquad E° = 1.23\ V \qquad (2.1)$$

Cathode (reduction)

$$4H_2O + 4e^- \longrightarrow 2H_2 + 4OH^- \qquad E° = -0.83\ V \qquad (2.2)$$

Overall cell reaction:

$$2H_2O \longrightarrow 2H_2 + O_2 \qquad E° = 2.06\ V \qquad (2.3)$$

2.1 Thermodynamic potentials water electrolyzer[18]

Quantity	$2H_2O$	$2H_2$	O_2	Change
Enthalpy	-571.66 kJ	0	0	ΔH = 571.66 kJ
Entropy	139.82 J/K	261.36 J/K	205.14 J/K	TΔS = 48.7 kJ

Figure 7 Table of thermodynamic potential

The work done by the system.

$$W = P\Delta V = (101.3\ x\ 103\ Pa)(1.5\ moles)(22.4\ x\ 10 - 3\ m3/mol)(298K/273K) = 3715\ J \qquad (2.4)$$

Since the enthalpy H= U+PV, the change in internal energy U is

$$\Delta U = \Delta H - P\Delta V = 285.83\ kJ - 3.72\ kJ = 282.1\ kJ \qquad (2.5)$$

This change in internal energy must be accompanied by the expansion of the gases produced, so the change in enthalpy represents the necessary energy to accomplish the electrolysis. However, it is not necessary to put in this whole amount in the form of electrical energy. Since the entropy increases in the process of dissociation, the amount TΔS can be provided from the environment at temperature T. The amount which must be supplied by the battery is actually the change in the Gibbs free energy:

$$\Delta G = \Delta H - T\Delta S = 285.83\ kJ - 48.7\ kJ = 237.1\ kJ \qquad (2.6)$$

Since the electrolysis process results in an increase in entropy, the environment "helps" the process by contributing the amount TΔS. The utility of the Gibbs free energy is that it tells you what amount of energy in other forms must be supplied to get the process to proceed.

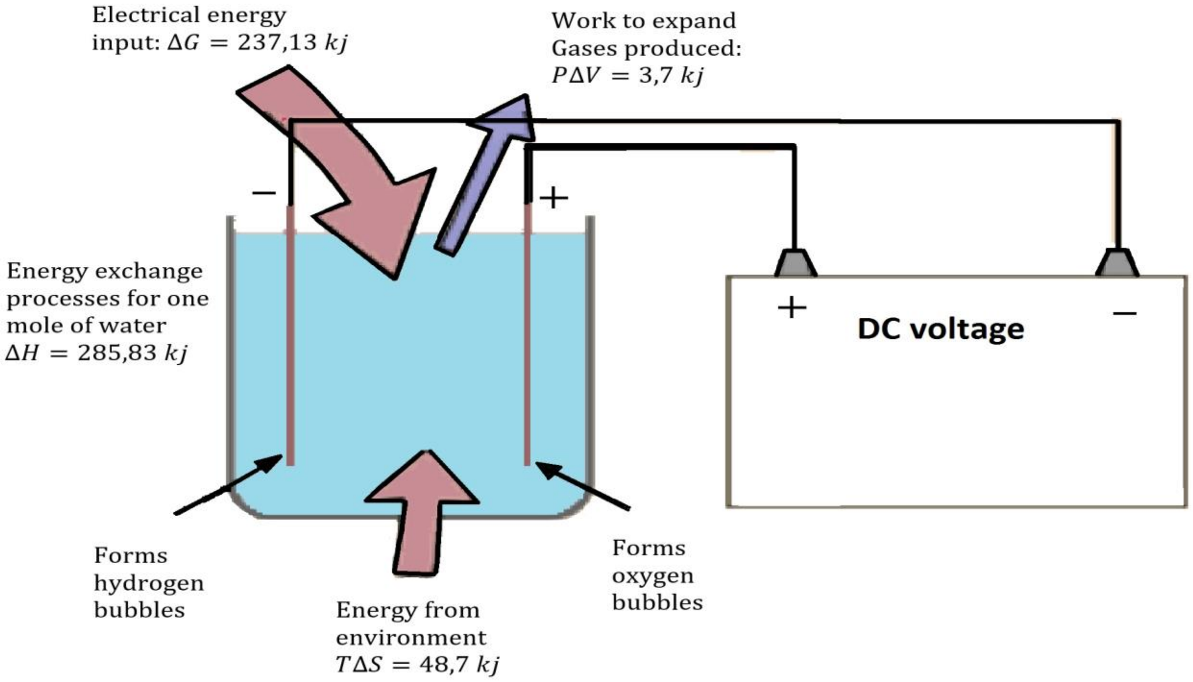


Figure 8 Water electrolyzer[18]

There are different methods for producing hydrogen by use of water electrolyzer. Since the cost of PEM types are more expensive than alkaline type mainly due to PEM uses noble metals(Pt, Ir, Ry), Alkiline type have been chosen in this study.[10:2]

2.2 Hydrogen production from alkaline electrolyzer

The theoretical maximum value of hydrogen production from electrolyses is calculated by the use of Gibson Free Energy. The free energy of combustion of hydrogen is the same as the free energy of formation of water. [9:28] This is shown in formula 2.7 and equation 2.8

$$2 * H_2O \rightarrow 2H_2 + O_2 \qquad (2.7)$$

$$\Delta \mathrm{Gf} = 2H_2O = -2 * 237.13 \text{ kJ mol}^{-1} \qquad (2.8)$$

The energy is calculated for two mole of water, which has two mole of H_2. The free energy for one mole of H_2 is -237.13 Kj mol^{-1} as shown in equation 2.9

$$\Delta Gf(H) = \frac{\Delta Gf(H20)}{2} = -237{,}13\ kJ \text{ mol}^{-1} \qquad (2.9)$$

The maximum energy that is going to be transferred into hydrogen is 50MW, where the definition for Watt is J/s [14:28] This would be a total energy production of 4,32*10^9Kj as shown in equation 2.2

$$Joule\ per\ day = 50 * 10^6 W * 24 * 60 * 60s = 4{,}32 * 10^{12} j = 4{,}32 * 10^9 Kj \qquad (2.2)$$

The production of $4{,}32 * 10^9 Kj$ per day gives the maximum capacity of H_2 moles per day of 31,6*10^6 moles as shown in equation 2.3. Since the chemical reaction only needs half of oxygen moles when producing the hydrogen as shown in equation 2.9, then the total moles of oxygen are $9{,}109 * 10^6$ moles as shown in equation 2.4.

$$\frac{4{,}32*10\text{^}9\text{Kj}}{237{,}13\ kJ\ mol{-}1} = 18{,}218 * 10^6 moles\ H_2 \qquad (2.3)$$

$$\frac{18{,}218*10^6}{2} = 9{,}109 * 10^6\ moles\ O_2 \qquad (2.4)$$

Hydrogen has a mole weight of 1,008[14:38]. Since there are two molecules per mole the total weight of hydrogen is 36727588 grams or 36,728Tons as shown in equation 2.6. Oxygen has a mole weight of 16,00[14:38], and one mole of O_2 has two molecules of oxygen. This causes the total day production of oxygen to be 291,5 tons as shown in equation 2.7.

$$\frac{1{,}008g}{mol} * 2 * 18{,}218 * 10^6 moles = 36727588\text{g} = 36{,}728 \text{ tons Hydrogen} \qquad (2.6)$$

$$2 * 9{,}109 * 10^6 \text{moles} * \frac{16{,}00\text{g}}{mole} = 291488000g = 291{,}488\ tons\ Oxygen \qquad (2.7$$

2.3 Size of alkaline electrolyzer

The size have been set to 50MW for the system. Since the power from the wind turbine at nominal speed would be larger than the grid can handle, then the size of the electrolyzer was set to handle maximum produced power from the turbines. This was set when defining the project since this size would make system to be able to use all of energy produced from the wind. The cost of the system if bought by NEL is around 300-400millions NOK and produce around 25tonn of hydrogen per day[11]. If this is compared with PEL the price for production would almost be twice as much[12:13]

2.4 Effectiveness of the alkaline electrolyzer

Since the production from NEL, the manufacture of alkaline electrolyzer is given to be 25 tons of hydrogen[11] this would give a production of $12{,}40 * 10^6$ mole hydrogen as shown in equation 2.7 and $6{,}2 * 10^6$ mole of oxygen as shown in equation 2.8

$$\frac{25*10^{6 gram} hydrogen}{2*\frac{1{,}008g}{mol}} = 12{,}40 * 10^6 mole\ H_2 \qquad (2.7)$$

$$\frac{12{,}40*10^6 mol}{2} = 6{,}2 * 10^6 mole\ O_2 \qquad (2.8)$$

The total production of 25Ton of hydrogen would give an effectiveness of the system of 68,1% if we compare it to the maximum theoretical production of hydrogen shown in equation2.9.

$$\frac{Actual\ hydrogen\ production}{Teoretical\ maximum\ production} = \frac{25\ tonn}{36{,}728 tonn} = 0{,}681 = 68{,}1\% \qquad (2.9)$$

2.5 Fuel cell

There are different sorts of fuel cells that will work under different temperature ranges, efficiency curves and with different material used. In this thesis, the calculation have been done with a PEM fuel cell. This has been done mainly since the technology is commonly used and since it has the lowest price per produced kWh compared to other fuel cells.[15]. The next sections shown how a PEM fuel cell is built up. It gives an overview of how it work and how it produce energy.

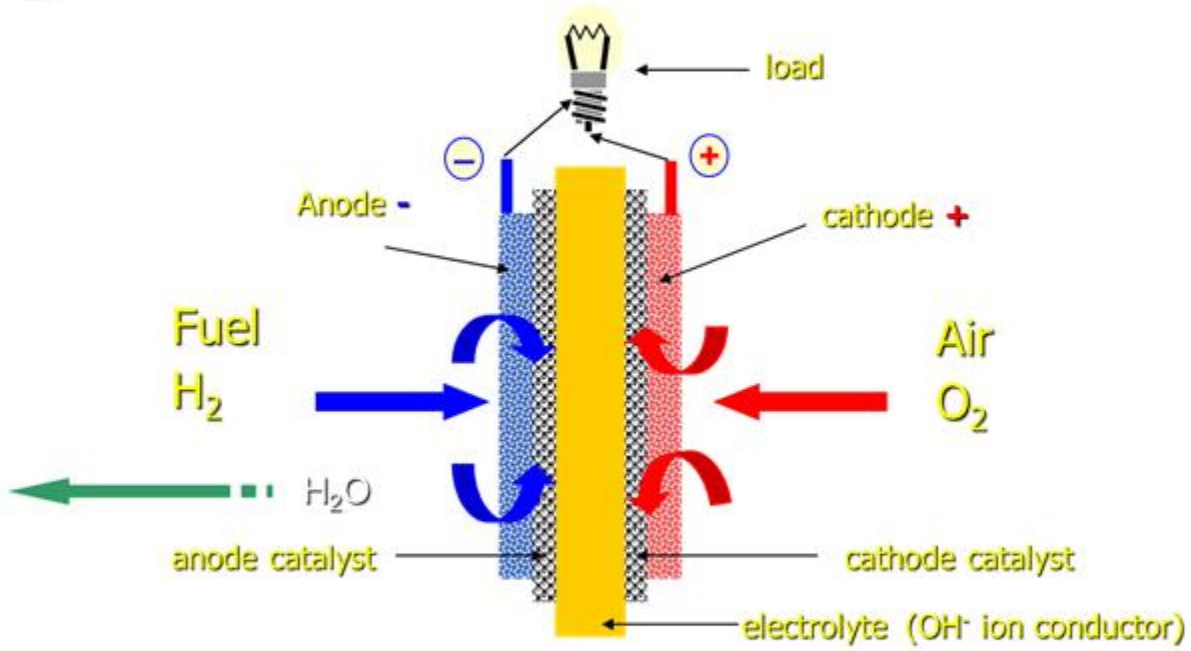


Figure 9 Overview over PEM fuel cell components

Figure 9 shows the schematic for alkaline fuel cell. The electrodes, anode and cathode contains of carbon in the form of porous graphite fibre and catalyst made from catalyst. Between the electrodes will it produce a voltage difference that could be used for electricity. The catalyst is made from very small particles of platinum supported on much larger particles of carbon. The electrolyte is made from polymer sheet made from fluorocarbon. This leads the proton trough the membrane but not the electron.

2.5.1 Ideal hydrogen-oxygen fuel cell operation[13]

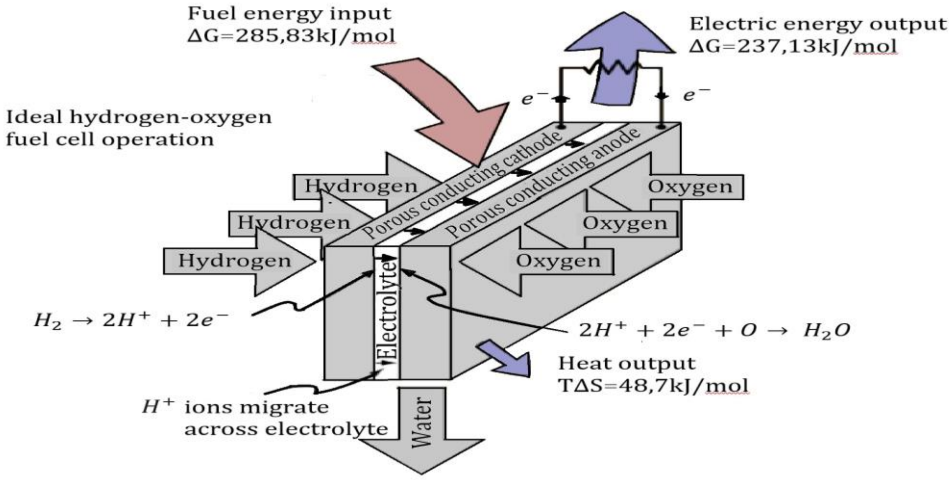


Figure 10 Ideal hydrogen-oxygen operated fuel cell[13]

Combining a mole of hydrogen gas and a half-mole of oxygen gas can be used to produce a mole of water. A detailed analysis of the process makes use of the thermodynamic potentials. This process is presumed to be at 298K and one atmosphere pressure, and the relevant values are taken from a table of thermodynamic properties.

Quantity	H_2	0.5 O_2	H_2O	Change
Enthalpy	0	0	-285.83 kJ	ΔH = -285.83 kJ
Entropy	130.68 J/K	0.5 x 205.14 J/K	69.91 J/K	TΔS = -48.7 kJ

Figure 11 Table of thermodynamic properties

As seen on Figure 11, the energy from the fuel cell is provided by combining the atoms and by decreaseing the volume of the gases. The table shows enthalpy and entropy information at 298K and one atmosphere pressure. The system work is shown in equation 2.10.

$$W = P\Delta V = (101.3\ x\ 103\ Pa)(1.5\ moles)(-22.4\ x\ 10-3\ m3/mol)(298K/273K) = -3715\ J \quad (2.10)$$

The enthalpy is $H = U + PV$. This change in internal energy U is shown in equation 2.11

$$\Delta U = \Delta H - P\Delta V = -285.83\ kJ - 3.72\ kJ = -282.1\ kJ \quad (2.11)$$

As shown in *Figure 11* the entropy of the gases is decreasd by 48.7 kJ. This is due to the chemical reaction in the fuel cell process, where making the water molecules is less than the number of hydrogen and oxygen molecules combinined. Since the total entropy will not decrease in the reaction, the excess entropy in the amount TΔS must be expelled to the environment as heat at temperature T. The amount of energy per mole of hydrogen, which can be provided as electrical energy, is the change in the Gibbs free energy shown in equation 2.12.

$$\Delta G = \Delta H - T\Delta S = -285.83\ kJ + 48.7\ kJ = -237.1\ kJ \qquad (2.12)$$

The maximum teoretical efficiency for a fuel cell, at temperature at 298K and pressure of 1 atmosphere, it is possible to reach an efficiency of 83% as shown in equation 2.13.

$$\frac{237{,}11}{285{,}8}\ x100\% = 83\% \qquad (2.13)$$

Chapter 3 System simulation

This chapter contains system simulation and calculation. The hourly production data from 2015 has been used for calculation the size of the components used. It has been optimized to make use of all the hydrogen produced throughout the year and for maximize the power production. These components were then used in simulation in a model in Simulink.

3.1 Yearly production calculation

To get an overview over the system on a yearly basis, a excel sheet has been made. This sheet use real value of power production from Smøla wind park. The real measurement of production data from Smøla wind park has been used. It has an hourly measurement throughout the year 2015. The values were multiplies with a factor of $\frac{4}{3}$ to get an estimate of the power production if the power was increased by 50,13MW from 150,4MW to 200,53MW, as shown in equation 3.1.

$$150{,}4MW * \frac{4}{3} = 200{,}53MW \qquad (3.1)$$

Figure 37 shows the power production from Smøla wind park in blue, where real data is used. The data that is used is from year 2015 where hourly measurements have been used and calculated the average for each month. The red line shows the estimated power production if the maximum capacity of the wind park is to be increased by 50,13MW to 200,53MW.

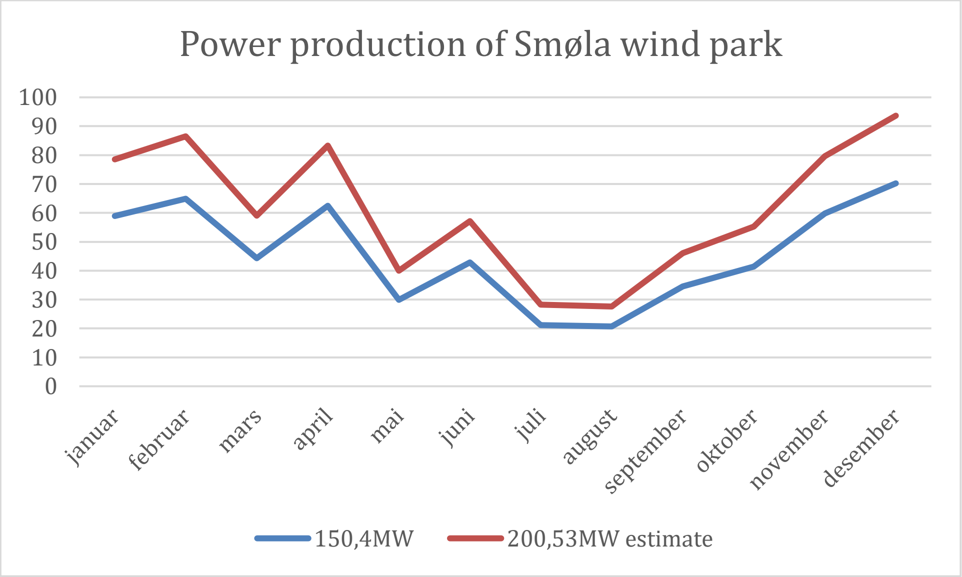


Figure 12 Power production of Smøla wind park

3.2 Fuel cell

The optimal fuel cell size based on the production year 2015 is 4,66MW[27]. After this point there is not any gain of having higher capacity of the fuel cell. This is shown in Figure 14. In this figure we can see that the percentage gain from fuel cell has a steep climb at lower fuel cell size from 1 to 5 MW, and then flattens out after 5MW. The size that has been chosen in this thesis is 4,66MW. This gave and average power from the fuel cell of 1,558MWh[27] throughout the year. On this production level, the hydrogen produced by the alkaline electrolyzer throughput the year is fully utilized. The production data that was used for this is at 31.12.15 at 19:00Figure 13 shows how the tank level decreases at the end of the year by choosing a higher fuel cell size.

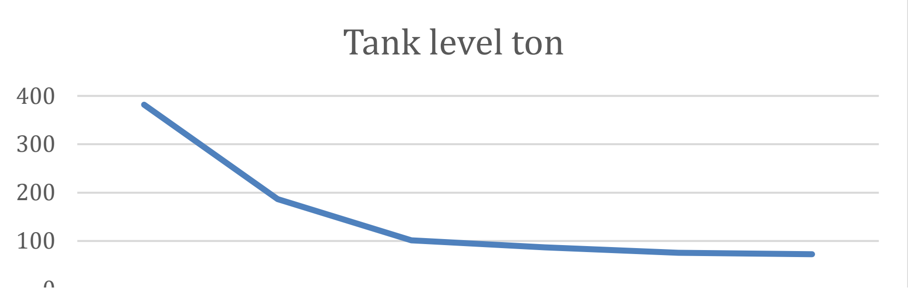


Figure 13 Tank level (ton)

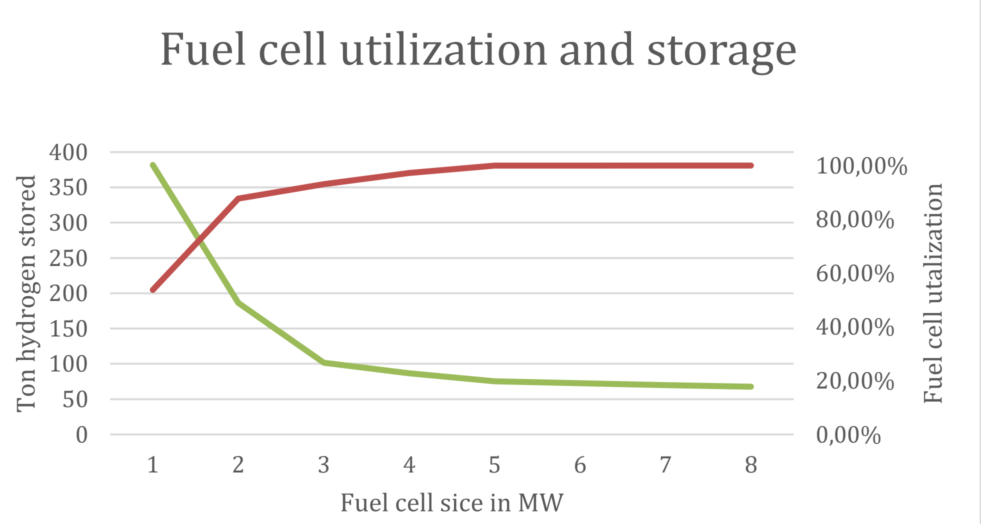


Figure 14 Fuel cell utilization and storage

3.3 Compressor

In order to get the desired pressure for the hydrogen gas, it is necessary to install a compressor. The pressure that has been used in this thesis is 8bar[28]. When increasing the pressure of hydrogen the need of storage tank size is reduced, but it will in addition also lower the overall efficiency of the system. The compressor efficacy is calculated based on formula which give the total work done for compressing the gas from 0,02 bar into 8 bar. 0,02 bar is the pressure from hydrogen gas from the alkaline electrolyzer.

$$W = nRTln\frac{p1}{p2}[25:100] \tag{3.2}$$

$$36659662{,}71 * 8{,}3145 * 353 * ln\frac{8}{0{,}02}Mjoule = 6{,}4466\text{E} + 11 \text{ Mjoule} = 179\text{MWh} \tag{3.3}$$

$$\frac{179MWh}{50MW*24h*3{,}17} = 0{,}047 \tag{3.4}$$

The alkaline electrolyzer use 3,17 days with maximum production of 50MW to fill up the tank. This has been used for calculating the efficiency of the compressor. The compressor uses 179087kWh for compressing all the gas from 0,02bar to 8 bar. When dividing that with the power usage from the electrolyzer it shows a loss of 4,71% in the compression process. Tis gives a factor for the calculation of 0,95.

3.4 Tank size

When increasing the power production by 50,13MW then there is time period when there is grid is fully utilized. The hydrogen tank is designed to store all of the excess energy into hydrogen. The tank is taken into account that there is loss in electrolyzer and compressor. The effectiveness of the electrolyzer has been calculated to 68,1%, as shown in equation 2.9, and the compressor to 95%, as shown in section 3.3. The tank level also takes into account that the fuel cell effectiveness is at 55%[15]. This means that it will use 1,818 more hydrogen to produce the desired power as shown in equation 3.5. The need for tank size is varying between the year, this is shown in figure 39, where the average need for tank size is illustrated. The size that has been used in this thesis is calculated based on the maximum need for storage which is 79,19ton of hydrogen. This date happened on 20.02.15. Figure 15 shows the average level each month.

$$\frac{1}{0{,}55} = 1{,}818 \tag{3.5}$$

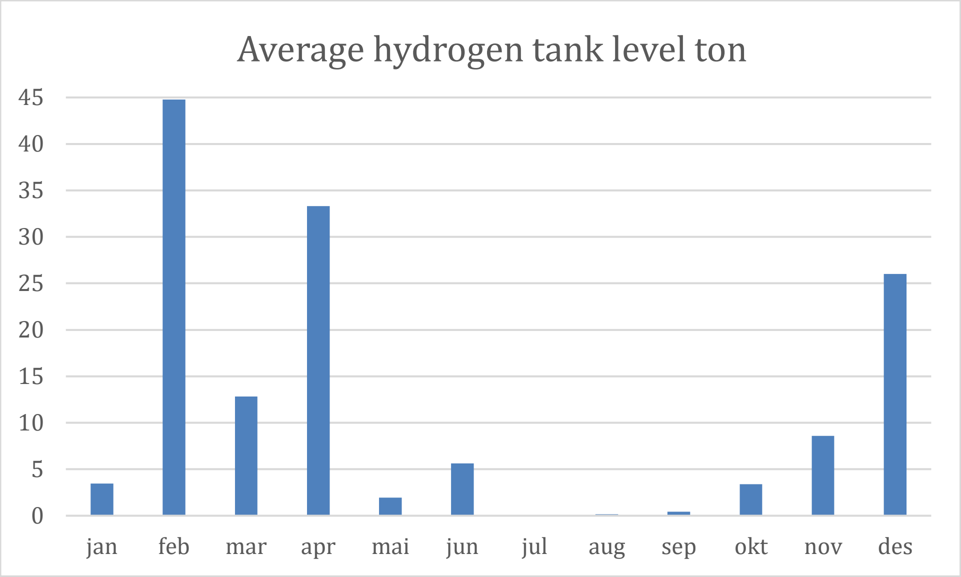


Figure 15 Average hydrogen tank level (ton)

3.5 Energy loss in electrolyzer and compressor

The choices of the different sizes of the components used in the system is based on the condition that the peak power generation will at time reach 50MW over the grid capacity, and that the average power generation over one year is 60,98MW. In order to store the extra capacity when wind speed is nominal, the electrolyzer has been set to be 50MW size. This would make the system able to store this energy into hydrogen. Since the effectiveness of is 68,1% then the electrolyzer the maximum energy that could be converted into hydrogen would be 30,61MW for every 50MW supplied. For the compressor the effectiveness is 95%. This leaves 32,35MW left that would be converted to hydrogen for each 50MW supplied, after going through the alkaline electrolyzer and the compressor. This is shown in equation 3.6 and 3.7.

$$0{,}681 * 50MW = 34{,}05MW \qquad (3.6)$$

$$0{,}95 * 34{,}05MW = 32{,}35MW \qquad (3.7)$$

3.6 Fuel cell hydrogen usage

The optimum hydrogen usage for the fuel cell is 3,42 ton H_2per day, as shown in equation 3.10. This is calculated based on energy produced from a fuel cell size of 4,66MW, with one full day production. This is shown in equation 3.8. The energy supplied by the fuel cell is calculated by use of Gibbs free energy of 237,13Kj/mole H_2 [13], as shown in equation 3.9. Since the PEM fuel cell used in the Simulink simulation is set to 54% effectiveness the total H_2 needed for the system to produce the desired power of 4,66MW is 6,634ton H_2 as shown in equation 3.10 and 3.11.

$$4{,}66MW * \frac{10^6}{M} * 24h * \frac{60min}{h} * \frac{60s}{min} = 4{,}026 + 11Ws = 4{,}026 + 11Joule[14{:}\,1] \qquad (3.8)$$

$$\frac{4{,}026+8KJ}{237{,}13Kj/moleH2} = 1697802{,}89Mole\ H2 \qquad (3.9)$$

The mole weight if one hydrogen is 1,008gram[14:288], so the weight of 2 hydrogen mole are 2,016gram per H_2.

$$1697802{,}89 Mole\ H2 * \frac{2{,}016 gram}{mole\ H2} = 3422770 gH2 = 3{,}42 tonH2 \tag{3.10}$$

$$\frac{3{,}43 tonH2}{0{,}54} = 6{,}634 tonH2 \tag{3.11}$$

Since the fuel cell would use excess hydrogen to produce heat instead of electric power, the system has implemented saturation block to prevent this. The combined gas law has been used to calculate the needed hydrogen usage for the PEM fuel cell.
The optimum energy that the fuel cell can producing is 237,13kj per mole of H_2, The total energy input from H_2 is 285,83kj per mole and the extra 48,7 Kj will produce heat in the fuel cell as shown in Figure 10. The flow rate has been restricted to 85,24lpm, and with hydrogen density of 0,08375g/l[14], this gives an daily usage of H_2 with 100% production of 6,29ton per day, as shown in equation 3.11.

The fuel cell is calculated to be 55008,29,22 litre per min as shown in equation3.13. Since the flow rate in the simulation file is scaled down by a factor of 93,2, the flow rate that is used for simulation 590,22 litres H_2 per min as shown in equation 3.16.

$$V_2 = \frac{P_1 * V_1 * T_2}{P_2 * T_1} = \frac{100kPa}{800kPa} * \frac{(273+60)7K}{273K} \tag{3.12}$$

$$\frac{6{,}634 TonH2}{Day} * \frac{1000kg}{1\ ton} * \frac{1000 gram}{kg} * \frac{1 day}{24*60 min} * \frac{1 liter}{0{,}08375 g\ H2} = 55008{,}29\ liter\ per\ minute\ H2 \tag{3.13}$$

$$\frac{55008{,}29\ liter\ per\ minute\ H2}{93{,}2} = 590{,}22\ liter\ per\ minute \tag{3.14}$$

The combined gas law[30:157], shown in formula 3.15, is used for calculate the volume change when adjusting the pressure to 8 bar and temperature to 50°C in the fuel cell. This formula was used for converting the flowrate, depending on the density. The calculation is based on that the fuel cell working temperature is 60°C. Since the flow rate from equation 3.13 is based on hydrogen density at 0 bar and 0°C, then formula 3.15 was used for correcting the flow rate. Since the volume is varying with the temperature and pressure the actual flowrate has been calculated to 87,29 as shown in equation 3.16. This flowrate has been used as restriction in simulation.

$$\frac{P_1 * V_1}{T_1} = \frac{P_2 * V_2}{T_2} \tag{3.15}$$

$$590{,}22\ liter\ per\ minute * \frac{100kPa}{800kPa} * \frac{(273+60)K}{273K} = 87{,}29\ liter\ per\ minute \tag{3.16}$$

3.7 Simulink model

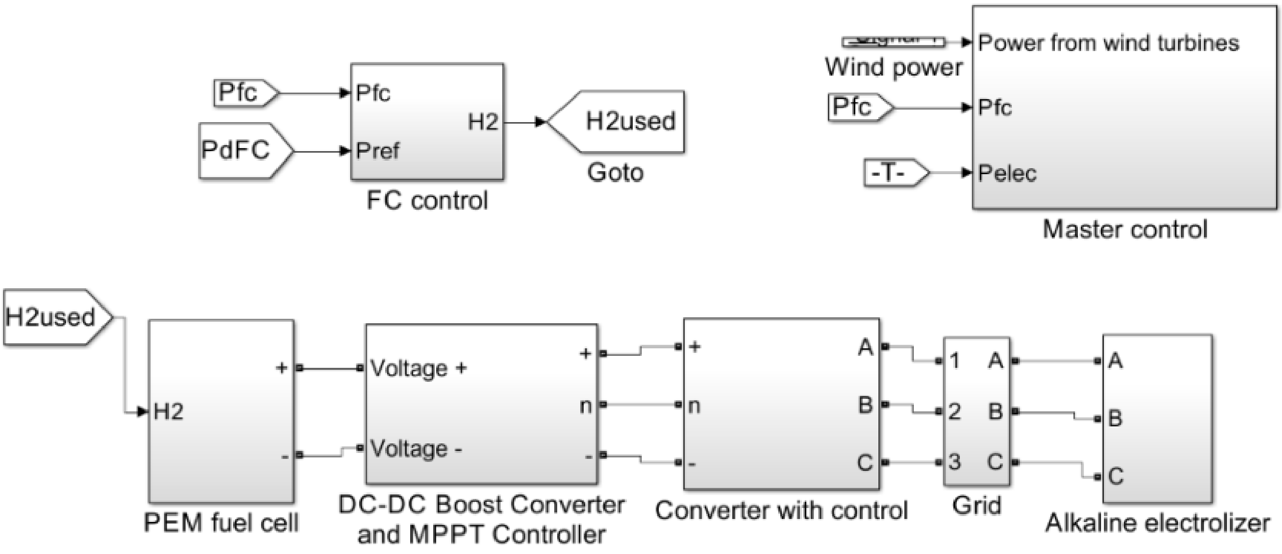


Figure 16 Overview of Simulink system

Figure 16 shows the overview of the Simulink model. It has the new system implemented with the existing grid. The model works like this. The "master control" process the power which is extracted from the wind. If the power measurement are lower than the grid capacity then this activates the PEM fuel cell. It then regulates power output from the fuel cell by changing the hydrogen flow. The power production is activated as long as there is available grid capacity. The fuel cell uses DC-DC boost converter for controlling voltage level and to maximize the power production. For integration to the grid power it uses a 3 phase converter with control. If the power production is higher than the grid capacity then the "master controller" activated the alkaline electrolyzer. The alkaline electrolyzer is activated as long as the power production from the wind turbine excess the grid capacity.

The model is scaled down by a factor of $\frac{1}{1000}$, so all calculated values are multiplied with 1000 to get the correct value for the system that is planned of Smøla.

3.7.1 Model factor correction

The system in Simulink uses a signal builder to simulate power from the wind. This is shown in Figure 17. The signal is simulating wind power, where 1 is 100% of possible power extracted from the wind, 0,4 is 40% and 0 is 0% extracted. The model is based on a factor of $\frac{1}{1000}$ and have to be multiplied with 1000 to get the correct value for the project of Smøla.

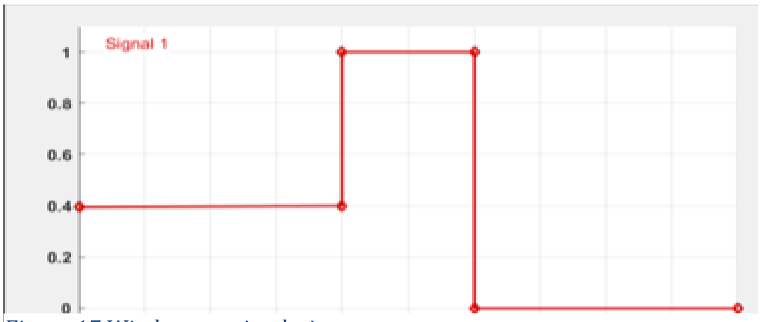


Figure 17 Wind power simulation

3.7.2 Master control in Simulink

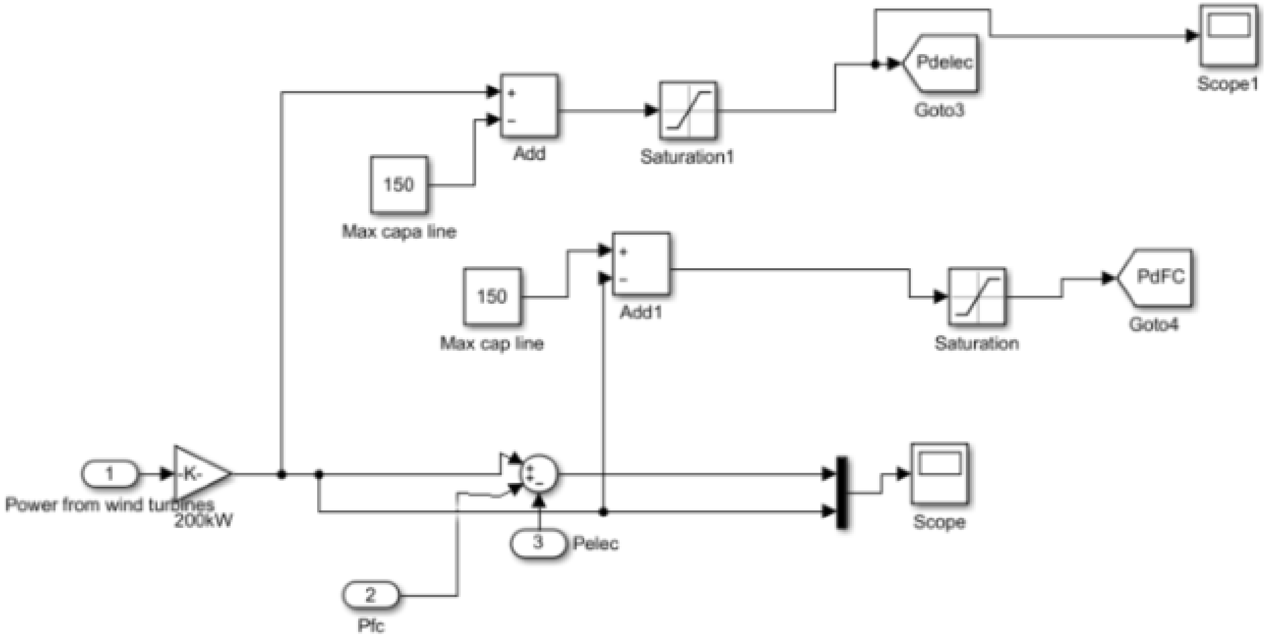


Figure 18 Master control Simulink

Figure 18 shows the master control in Simulink. It calculates how much energy that is needed to be produced by the fuel cell, or how much energy is needed to be used for hydrogen production by the electrolyzer. The system calculates the effect based on the maximum grid capacity of 150,4MW. If the produced energy from the wind are less than 150,4MW, then the PEM fuel cell kicks in and produces the remaining energy up to a maximum capacity of 50MW. If the energy from the wind is higher than 150MW, the electrolyzer kicks in and use the extra energy to produce hydrogen.

3.7.3 Alkaline electrolyzer in Simulink

There was not any integrated electrolyzer in Simulink, so this has been built up based on a publishment from Ursu ´a et al.: “Hydrogen Production From Water Electrolysis: Current Status and Future Trends”[26]. This shows the measurement of I – V curve for one alkaline electrolysis cell. The I-V curve was extracted to excel, which has the built in function for showing function of any graph. The function from the graph is shown in formula 3.18. This function is used in Simulink to calculate the current level based on voltage level. An overview over the electrolyzer is shown in Figure 19.

It is connected to the grid with a transformer. The electrolyzer has a resistor to simulate the resistance the cells has in the electrolyzer. The hydrogen production is based on current as shown in formula 3.19. This is implemented the simulation model as shown on Figure 20 The formula is used to calculate the amount of H_2 that is being produced by the alkaline electrolyzer

To regulate the voltage it uses a buck converter to reduce the DC voltage into desired value for hydrogen production. It uses a closed loop control for regulating the desired power consumption. This reference signal comes from the master controller, which regulated the consumption up to a maximum of 50,13kW. This is later scaled up to give the correct size of 50,13MW.

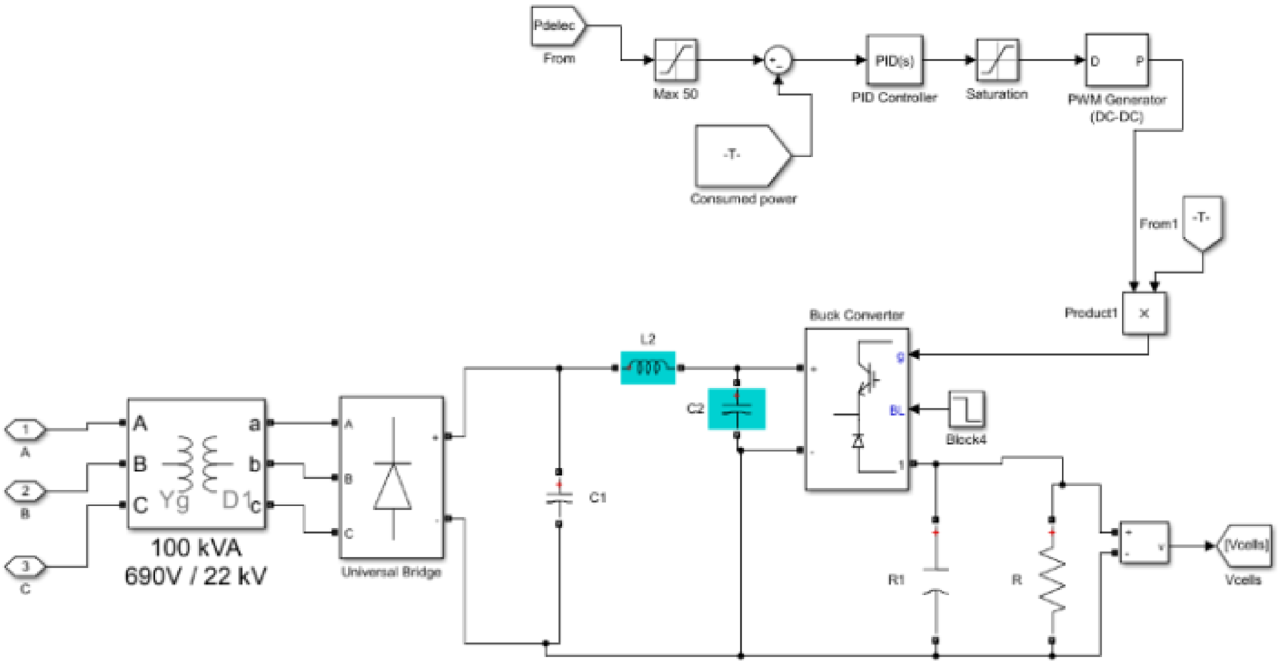


Figure 19 Alkaline electrolyzer in Simulink

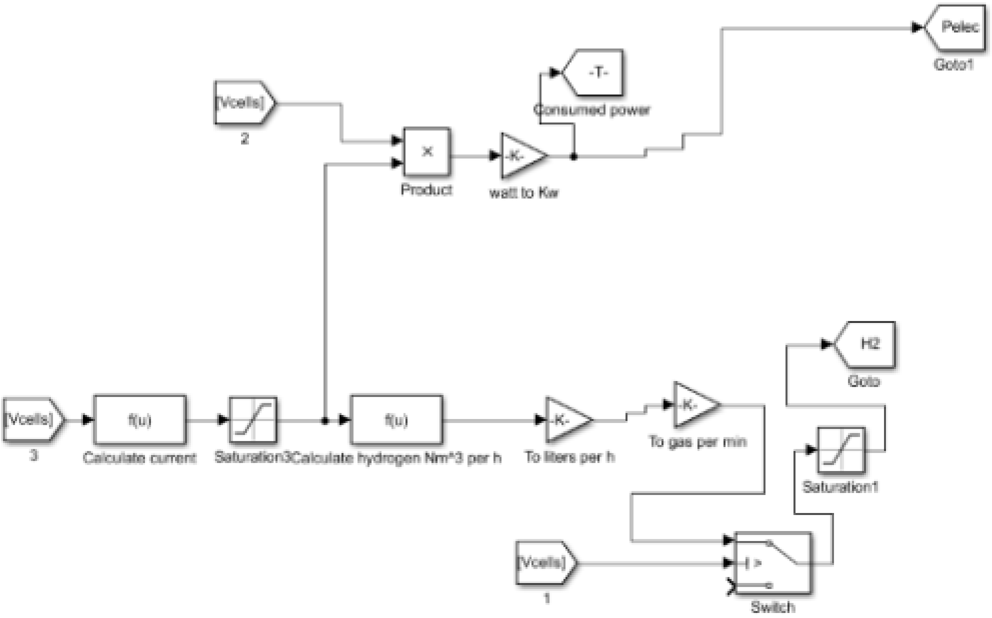


Figure 20 Alkaline electrolyzer hydrogen flow rate calculation

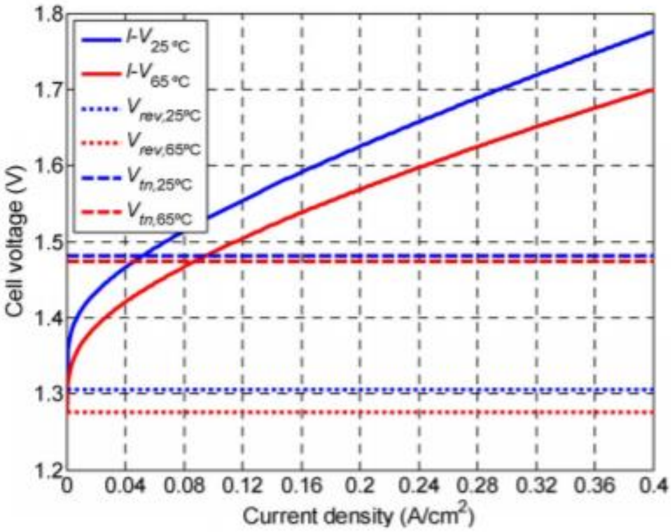


Figure 21 V/I curve alkaline electrolyzer [26:6]

Figure 21 shows current voltage characteristic of an alkaline electrolyse cell found in a different study[26]. The measurement from this study has been manually put into excel where the voltage and current levels have been adjusted to match a 50,13kW size electrolyzer. The total number of cells chosen is 900. The number of parallel cells is chosen to 450, so the voltage level is 450 times higher than for one cell shown in Figure 21. The number of series of cells has been chosen to be 450. The cell number is set to have the working area of the alkaline electrolyzer at 50kW after formula 3.1. The polynomic trendline from **Feil! Fant ikke referansekilden.** showing the relationship between current and voltage in the 50,13kW electrolyzer. The hydrogen production depends on the current flow in the electrolyzer cell as shown in formula 3.2. By adjusting the voltage level marked as X in Figure 22, the current flow and thereby the hydrogen flow is adjusted.

$$P = V * I \tag{3.17}$$

Formula 3.18 is used to calculate the current flowing through all of the cell.

$$0{,}0039 * \mathrm{Vdc}^2 - (4{,}4808 * \mathrm{Vdc}) + 1288{,}5 \tag{3.18}$$

Formula 3.19 is used to calculates the flow rate in Nm^3/h

$$f_{H2} = \eta_F \frac{N_{Cell} I_{Cell}}{zF} * \frac{22{,}41}{1000} * 3600 = 0{,}681 * 0{,}94 * \frac{900 * I_{cell}}{2 * 96485\ \mathrm{C}\ mol^2} * \frac{22{,}41}{1000} * 3600 \tag{3.19}$$

The flowrate is multiplied with factor shown in 3.20. This gives the output in Kg hydrogen per minutes.

$$1000\frac{liter}{m^3} * \frac{1h}{60min} * 1000(model\ factor) * 0{,}08999\frac{g}{liter} * \frac{1Kg}{1000g} \qquad (3.20)$$

3.7.4 The boost controller

The input voltage Vi and input current I_L are varying, it is important with control of the switching frequency of the IGBT for maintaining a stable voltage for DC-AC inverter.

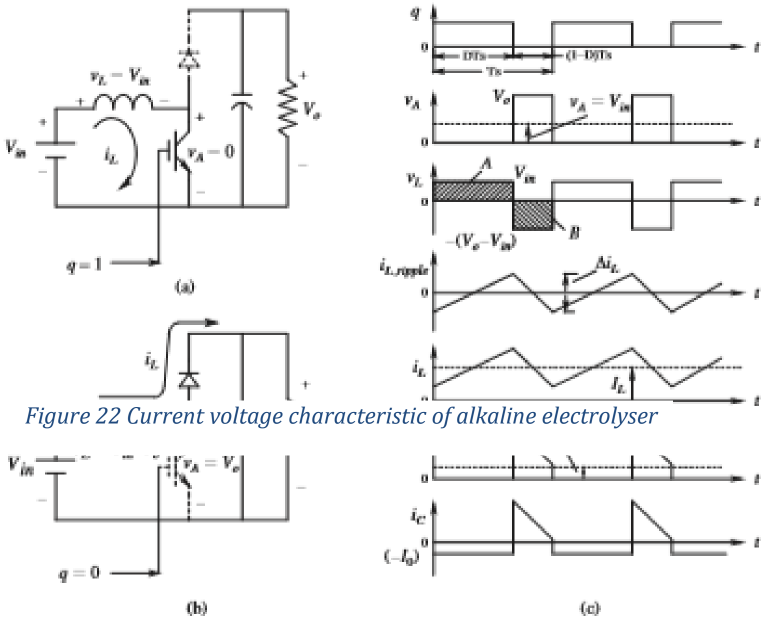
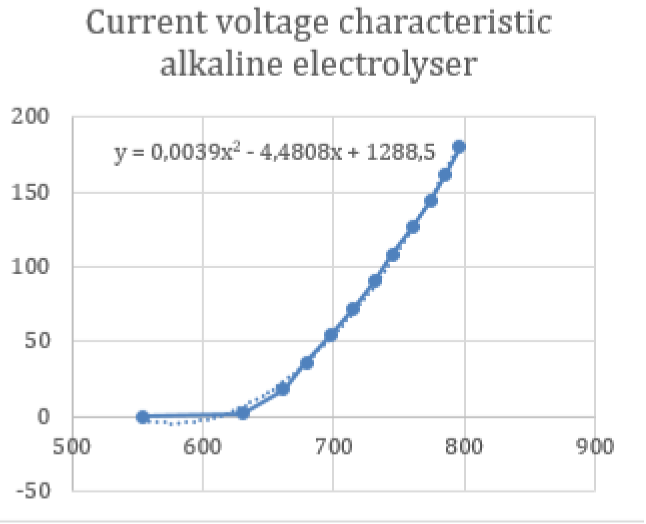


Figure 22 Current voltage characteristic of alkaline electrolyser

Figure 23 Boost converter, operation waveform under continues mode[20:47]

3.7.5 Maximum power point tracking

This is a technique that is used in wind turbines, photovoltaic solar system and fuel cells to maximize power generation with changing load condition.[24:20].



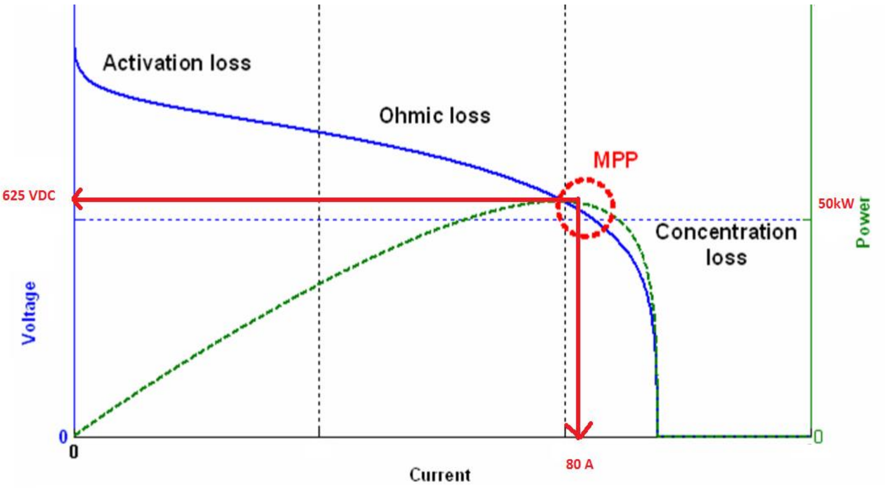


Figure 24 MPP fuel cell

Figure 24 shows that the maximum power from the graph is when current is 80A and voltage is 625Vdc, the total power output is 50kW. This only happens when the fuel cell system is under nominal condition shown on Figure 25. Since the power produced by the fuel cell are varies depending on how much power is extracted from the wind, then MPP point will change. By implementing the incremental conductance method described closed in the next chapter, the maximum power point is found. This is used by a closed loop system which monitors the voltage and current signal and calculate the point where the power extracted is on the maximum.

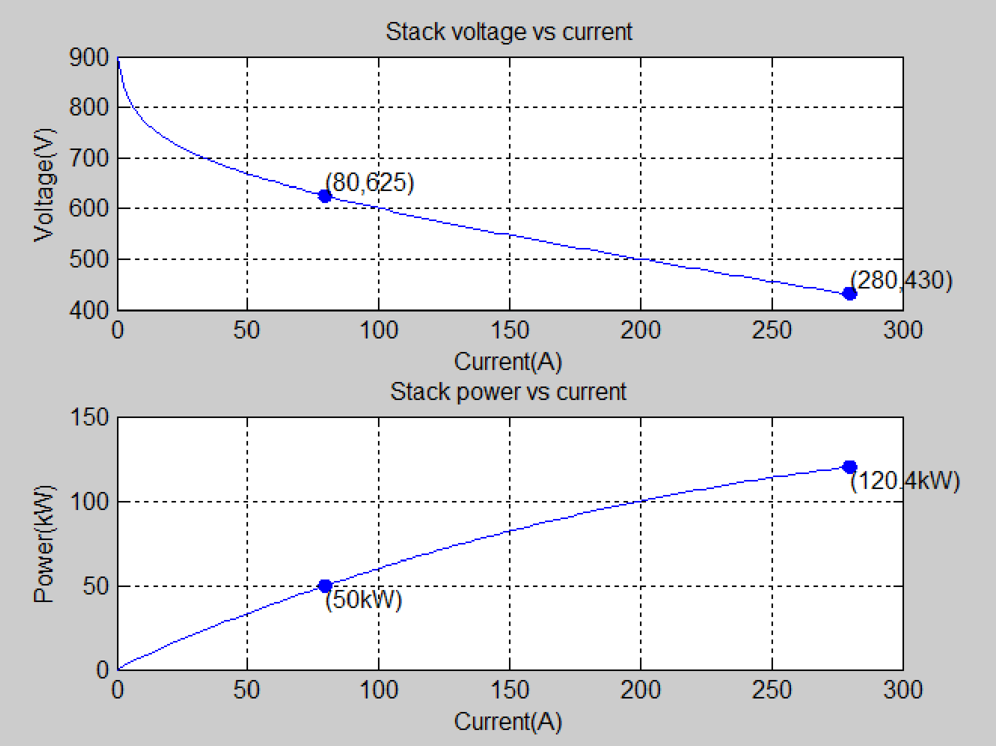


Figure 25 Stack voltage vs current

Figure 26 shows how the maximum power point, which is when the derivative of power divided by the derivative of the voltage, is equal to 0.

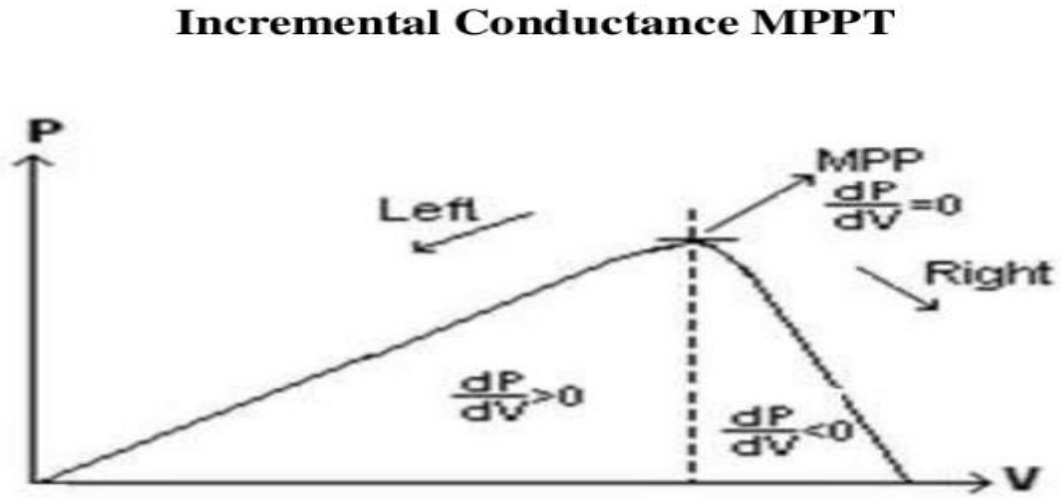


Figure 26 Incremental conductance MPPT

3.7.6 Incremental conductance method[21: 143-145]

For fuel cell array, power equation can be written as:

$$P = V * I \qquad (3.21)$$

Where P=stack power, V=stack voltage and I=stack current

By differential, with respect to V, and by using differential rule for product where:

$$y = uv \qquad (3.22)$$

This gives formula 3.23

$$y' = u'v + uv' \qquad (3.23)$$

By defining the following formulas.

$$v = V \qquad (3.24)$$

$$u = I \qquad (3.25)$$

$$y' = dP \qquad (3.26)$$

we get:

$$dP = dI * V + I * dv \qquad (3.27)$$

By dividing formula 3.10 on both side with dv we get:

$$\frac{dp}{dv} = \frac{dI * V}{dv} + I \qquad (3.28)$$

From Figure 26 it shows that the maximum power is when:

$$\frac{dp}{dv} = 0 \qquad (3.29)$$

By combining formula 3.11 and 3.12 we get the following formula.

$$\frac{dI}{dv} = -\frac{I}{V} \qquad (3.30)$$

3.7.7 Simulink boost controller

This block controls the voltage and pulses of the IGBT so that it would give the maximum power point tracking described in previous chapter.

Figure 27 Boost controller

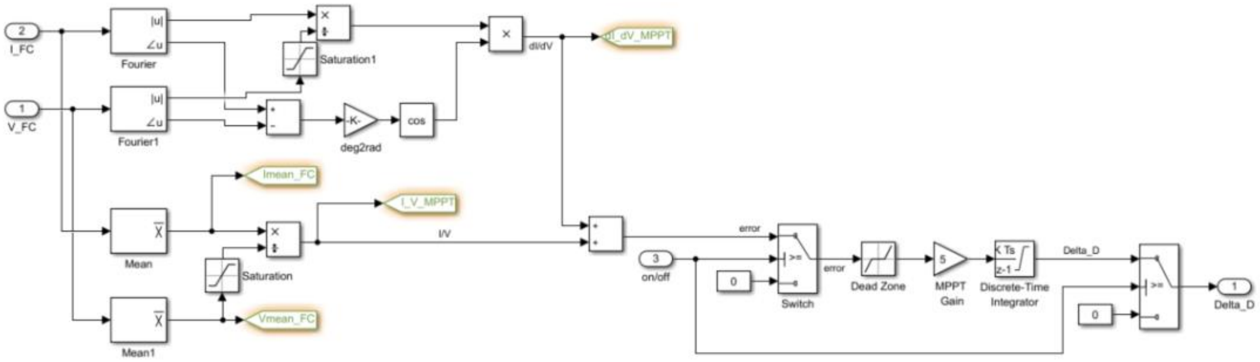


Figure 28 Inside boost controller

Figure 27 shows the input for controlling the boost converter with pulses, it uses the current and voltage from the fuel cell. Figure 28 shows further how the signals are processed. Both current and voltage are changed to magnitude and phase in Fourier block. This gives the output in the form[22]:

$$f(t) = \frac{a_0}{2} + \sum_{n=1}^{\infty} a_n cos(n\omega t) + b_n sin(n\omega t) \qquad (3.31)$$

n = 1 corresponds to the fundamental component.

$$|H| = \sqrt{}(a_n^2 + b_{n)}^2 \qquad (3.32)$$

$$< H_n = atan2 * (\frac{b_n}{a_n}) \qquad (3.33)$$

Where:

$$a_n = \frac{2}{T} \int_{T-t}^{t} f(t)\cos(n\omega t)dt \qquad (3.34)$$

$$b_n = \frac{2}{T} \int_{T-t}^{t} f(t)\sin(n\omega t)dt \qquad (3.35)$$

$$T = \frac{1}{ft} = \frac{1}{5000Hz} = 0{,}2ms \qquad (3.36)$$

Since we need the derivative of the function we use formula 3.34 and 3.35 as shown in Figure 29, we get;

$$a_n = 2 * [f(t)\cos(n\omega t)dt] \quad (3.37)$$

$$b_n = 2 * [f(t)\sin(n\omega t)dt] \quad (3.38)$$

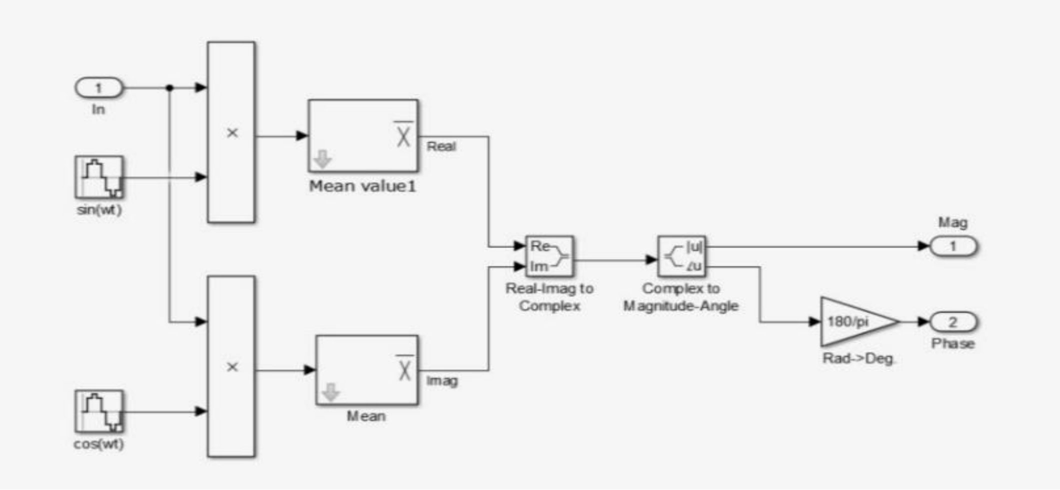


Figure 29 Fourier

By taking the different angle and multiplying by

$$\cos(\theta_{I\_PV} - \theta_{V\_PV}) \quad (3.39)$$

we get the real value of

$$\frac{dI}{dV} \quad (3.40)$$

The next part is to add:

$$\frac{I}{V} \quad (3.41)$$

As shown on Figure 30, which give out an error signal. This will make the regulator continues processing the measurement, until it gets to 0. At this point it has reached the maximum power production from the fuel cell.

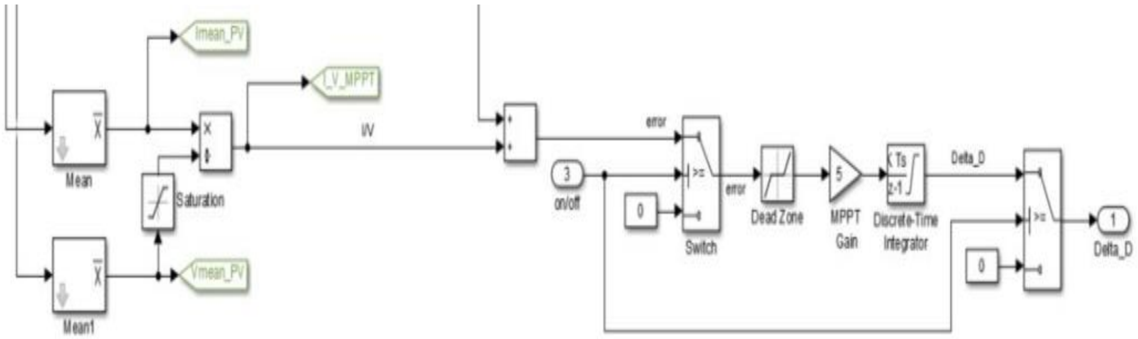


Figure 30 I/V and error signal

3.7.8 Power control with back to back converter[23:23-24]

Since the grid capacity from the wind farm is at its limit, it is important to implement a control which can adjust the power factor on the power produces. This can be done by controlling active and reactive power. For that it is necessary to get two control variables, one for reactive power and one for active power. By using $dQ0$ transformation we can get those two variables I_q and I_d, where I_d can be used for controlling active power and I_q for reactive power.

The Dqo transformation uses two transformation. This is Clark transformation and Perk transformation. When using this method it transfers 3 phase voltage or current sequence into 2 axis, rotating coordinate system, as shown in Figure 31. For a balanced symmetric three phase system, $dq0$ transformation can be simplified to dq transformation and zero component can be neglected. This lead to use of dq components instead of $dq0$ components.

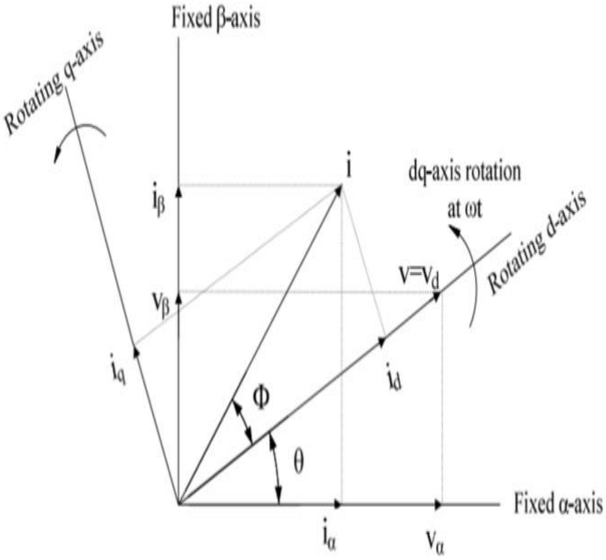


Figure 31 Clark and Park transformation

Clarke's transformation transforming 3 phase voltage or current sequence (V_{abc}or I_{abc}) to stationary voltage or current reference frame.(V_{α}, V_{β} or I_{α}, I_{β}). The mathematical equation is:

$$V_{abc}(t) = \sqrt{\tfrac{2}{3}}\begin{bmatrix} 1 & 0 & \frac{\sqrt{2}}{2} \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{\sqrt{2}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{\sqrt{2}}{2} \end{bmatrix} * \begin{bmatrix} V_{\alpha(t)} \\ V_{\beta}(t) \\ V_{\gamma}(t) \end{bmatrix} \qquad (3.42)$$

Since in a balanced system

$$V_a(t) + V_b(t) + V_c(t) = 0 \qquad (3.43)$$

and since

$$V_{\gamma}(t) = 0 \qquad (3.44)$$

This leads to a simplified tranformation shown in formula 3.45.

$$\begin{bmatrix} V_{\alpha} \\ V_{\beta} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} * \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \qquad (3.45)$$

3.7.9 Park transformation[23:24]

The transformations is for transforming stationary voltage or current reference frame (V_{α},V_{β} or $I_{\alpha\beta}$) to a rotating voltage or current reference frame(V_d,V_q or I_d,I_q). This can be shown as formula 3.46.

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} * \begin{bmatrix} V_{\alpha} \\ V_{\beta} \end{bmatrix} \qquad (3.46)$$

By considering symmetrical three phase system where:

$$V_a = Vcos\theta,\ V_b = Vcos(\theta - \tfrac{2\pi}{3})\ V_c = Vcos(\theta - \tfrac{2\pi}{3}) \qquad (3.47)$$

And by applying Clark and Park transformation gives:

$$\begin{bmatrix} V_{\alpha} \\ V_{\beta} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \frac{2}{3} * Vcos\theta \\ \frac{2}{3} * Vsin\theta \end{bmatrix}, \begin{bmatrix} V_d \\ V_q \end{bmatrix} = \begin{bmatrix} V \\ 0 \end{bmatrix} \qquad (3.48)$$

After the transformation V_q becomes zero and

$$V_d\text{=V} \qquad (3.49)$$

3.7.10 Power control[7:26]

In the Simulink system the DC is converted into AC and transferred to infinitive AC bus. Each IGBT transistor are controlled by a PWM system to generate the required AC waveform.

By taking into consideration of Clark and Park transformation of the system and by using grid voltage V_d and $V_q = 0$ the active and reactive power can be written as shown in formula 3.50 and formula 3.51.

$$P = \frac{3}{2} V_d * I_d \qquad (3.50)$$

$$Q = \frac{3}{2} V_d * I_q \qquad (3.51)$$

The power from the fuel cell can be used for power improvement for the grid system. By adjusting the reactive power, the angle between can lower the apparent power shown as VA on Figure 32 Reactive power corrected. This can be used to ensure minimum loss of power.
After formula 3.52 and 3.53 we have:

$$P = \frac{3}{2} V_d * I_d \qquad (3.52)$$

$$Q = \frac{3}{2} V_d * I_q \qquad (3.53)$$

These formulas show that the power factor in the grid could be improved by changing the reactive power injected into it. Figure 32, shows the relationship between reactive power and power factor $cos\theta$. The power that could be used for the house load is real power (p). With θ angle higher than 0, the power factor will decrease. This will cause some of the power produced to disappear as heat in the grid cable without being used. The best power factor is when $\theta = 0$, which is when $Q = 0$. Figure 18 shows when the power regulator is set to 0kVar, resulting in a power factor 1.

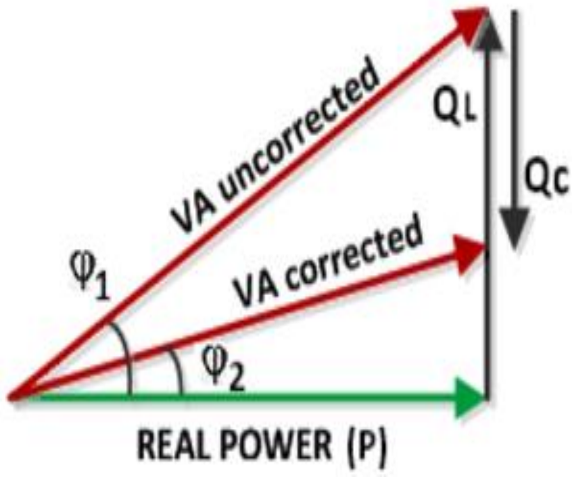


Figure 32 Reactive power corrected

$$tan\theta = \frac{Q}{P} \qquad (3.54)$$

$$cos\theta = power\ factor(pf) \qquad (3.55)$$

3.7.11 PLL based measurement system

The inverter uses feedback from output voltage and current from the grid. V_{abc} is measured and it is given as input to PLL. The signal gets processed and gives out the phase angle (ωt) which is used for synchronizing purpose. Shown in Figure 33.

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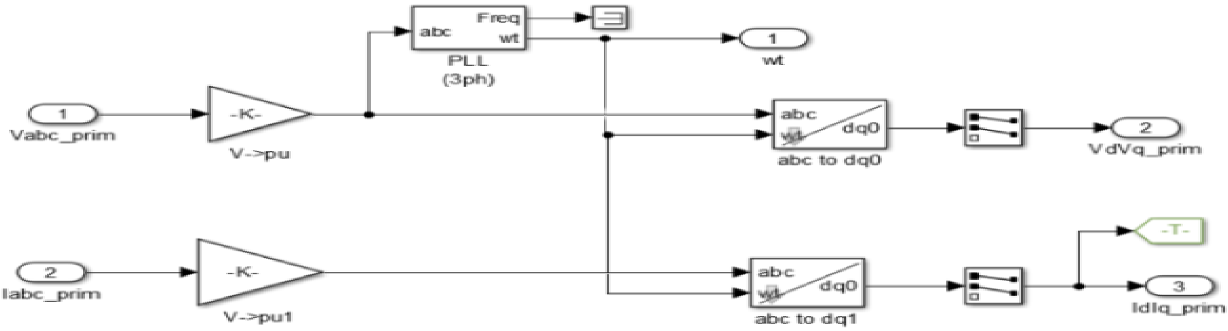

Figure 33 PLL and measurement

3.7.12 Voltage controller

Figure 34 shows the voltage controller in the system. It used the measured DC voltage from the DC link. It calculates:

$$I_{d_{ref}} = \frac{(V_d - V_{d_{ref}})}{V_{nomDC}} * PID_z \qquad (3.56)$$

Where $V_{nomDC} = 690 * \sqrt{3}\text{Vdc}$

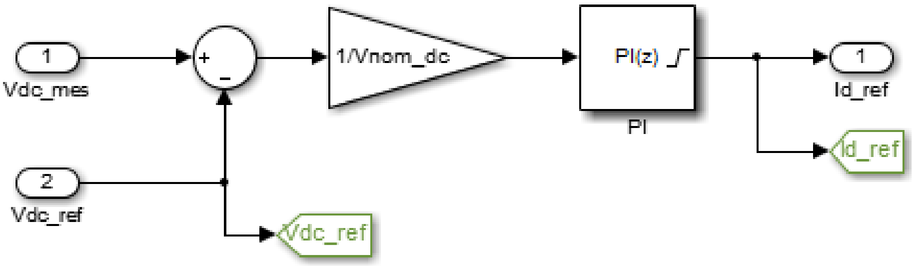

Figure 34 VDC regulator

3.19 Current regulator

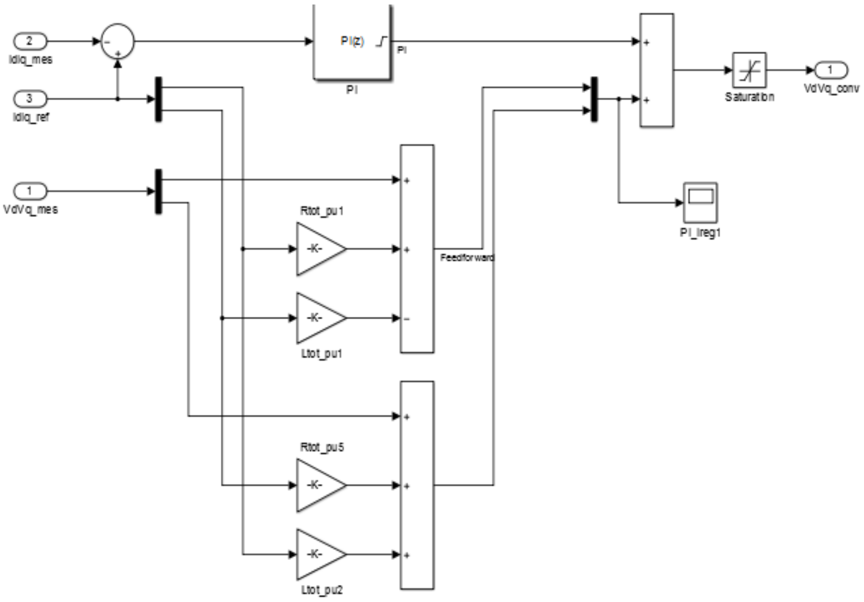

Figure 35 Current regulator

Figure 35 shows the current controller. It calculates the error between I_d and I_q reference and between I_d and I_q measured. This error signal goes through PI controller which gives output for V_dV_q reference which is used for PWM block reference voltage.

The current regulator also uses a feed forward system which decouple the dq components of current and voltages as formula 3.57 and formula 3.58 shown below.

$$V_{d,conv} = Ri_d - \omega Li_q + \frac{Ld_i}{dt} + v_d \qquad (3.57)$$

$$V_{q,conv} = Ri_q + \omega Li_q + \frac{Ld_q}{dt} + v_q \qquad (3.58)$$

3.20 Voltage reference signal for PWM

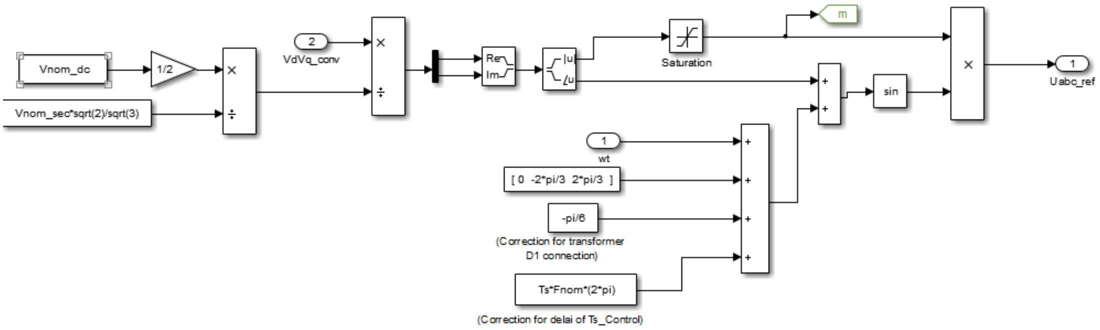

Figure 36 Voltage reference for PWM

The PWM block requires reference signals which Figure 36 shows how is generated. Input signal are from V_dV_q and uses the measured phase angle from the grid AC. V_dV_q signal is normalized by following factor.

$$V_d, V_q signal\ normilized\ factor = \frac{0{,}5V_{dc}}{V_{sec}*\frac{\sqrt{2}}{\sqrt{3}}} \qquad (3.59)$$

Where $V_{dc} = 690 * \sqrt{3}$ and $V_{sec} = 22kVrms$ (3.60)

3.21 Pulse width modulation, PWM[8]

As shown in Figure 37, the PWM block uses the U_{abc} reference signal to generate pulses for carrier-bases pulse width modulation(PWM) converters using three-level topology. The reference signal is sampled and compared with two symmetrical level-shifted triangle carriers. Figure 37 shows a single-phase, half-bridge three-level converter. In this project, the signal that is used is three phase with a phase shift of 120 degree between them.

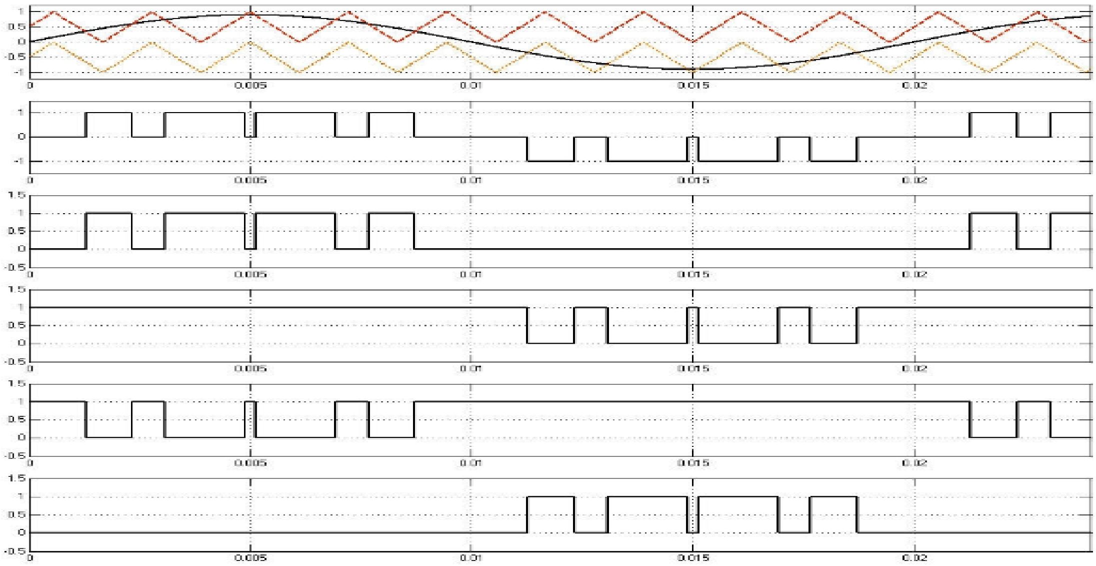

Figure 37 PWM

3.22 Boost inverter

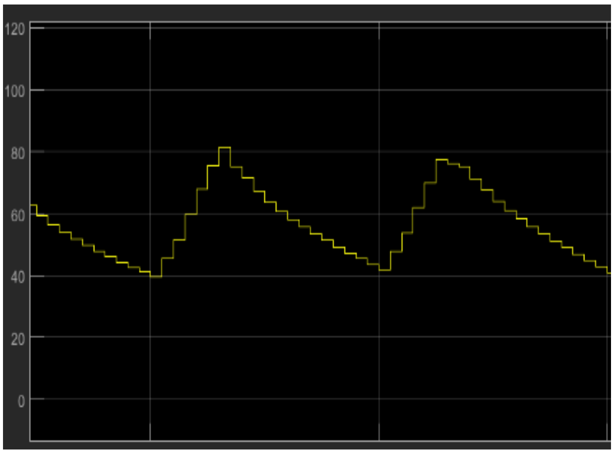

Figure 38 IL boost converter

The voltage output from the boost converter should be held constant at 690 $*$ √3Vdc and the input is 625Vdc when the fuel cell is giving maximum power. The equation for boost converter is:

$$D = 1 - \frac{Vi}{Vo} = 0{,}477 \qquad (3.61)$$

The critical minimum current for the boost converter with L value of 0,001 and frequency of 5000Hz is:

$$I_{Lcrit\ boost} = \frac{V_{in}}{2Lf_S} * D = \frac{625Vdc*0{,}477}{2*1*10^{-3}H*5000Hz} = 29{,}8125A \qquad (3.62)$$

When simulating this in Simulink, the inductor current value ranged between 40A and 80A, which is far away from discontinues mode when $I_{Lcrit\ boost}$. The output is taken when the fuel cell had a maximum power output of 50kW.

Chapter 4 Results

This chapter contains result from simulation in Simulink and calculation done in Excel.

4.1 Result in Simulink

The following section has the result from simulation done in Simulink.

4.1.1 Fuel cell flow

The PEMFC need 54,22 litre per minute[15] in order to give nominal power of 50kW. Since this a model, the data needs to be multiplied with a factor to show the correct value for the project. The factor that needs to be used is 93,2 as shown in equation 4.1. This gives nominal fuel cell flow of 5053,3,4 litres per minutes for the system to produce 4,66MW, as shown in equation 4.2 We can see in Figure 39 that the tank level is being reduced in the period 0-4 sec. This is when power extracted from the wind is at 40%. Furthermore, it is shown on Figure 39 that the H_2 used is fluctuating between 400 and 600 litres per minutes between 0-4 sec and 6-10 sec. The lowest graph shows the produced H_2 from the electrolyzer. This produces 350 litres per minutes of H_2 in period 4-6 seconds. This is when the power from the wind is at 100%.
Figure 40 shows the result calculated in kg/min. It shows that the electrolyzer produces 20,8Kg of hydrogen per min, and that the fuel cell use 3,7 Kg of hydrogen.

$$\frac{4,66MW}{50KW} = 93,2 \tag{4.1}$$

$$93,2 * 54,22 \; liter \; per \; minte = 5053,3 \; liter \; per \; minute \tag{4.2}$$

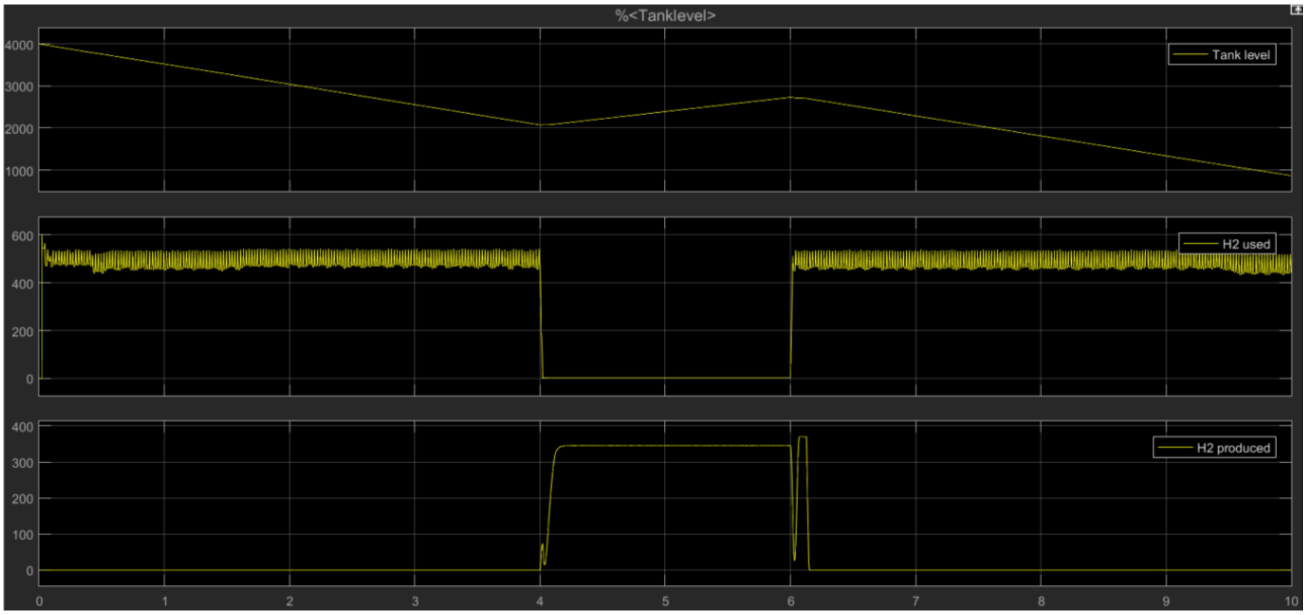

Figure 39 Fuel flow electrolyzer and fuel cell

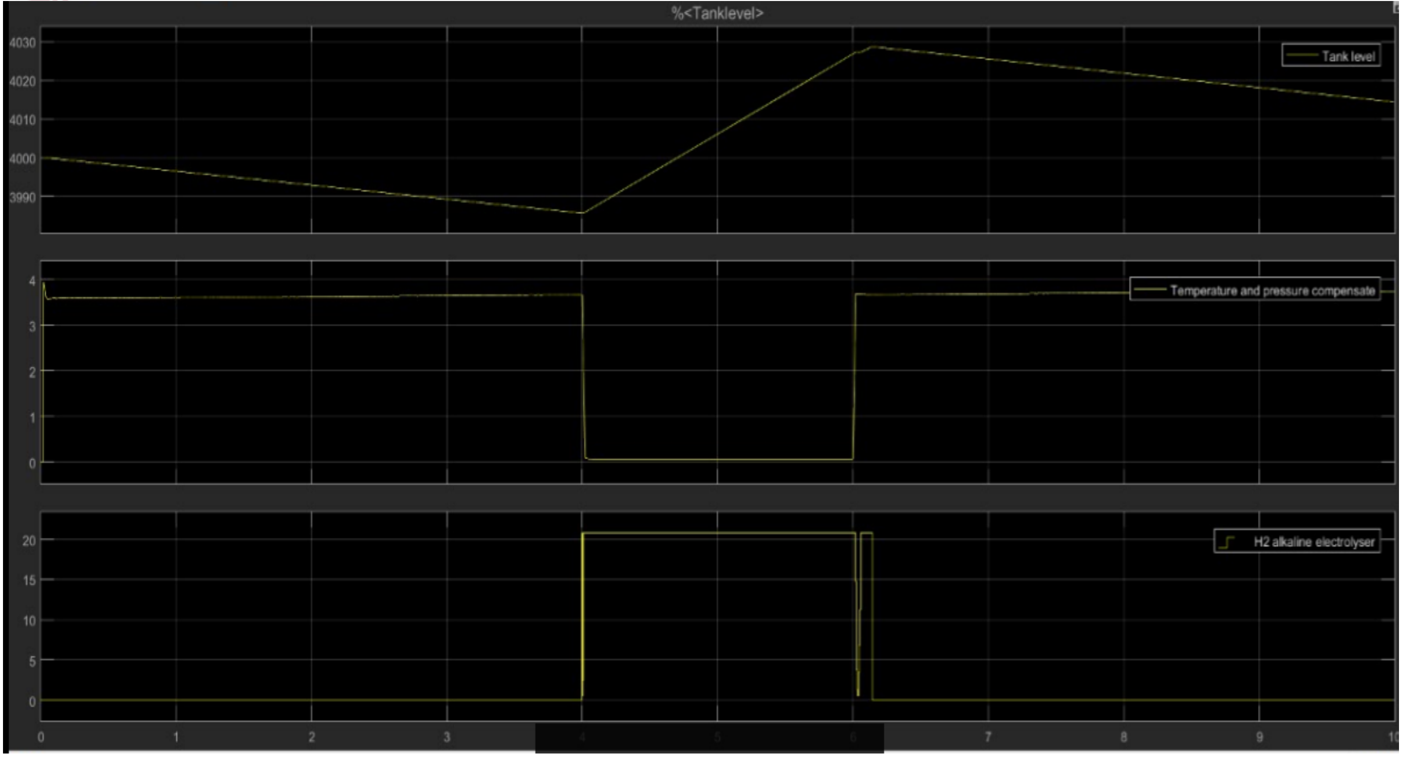

Figure 40 Flow rate Kg/min

4.1.2 Power consumption and production of electrolyzer and fuel cell

Figure 41 shows the power usage from the electrolyzer and the power supply from the fuel cell. This shows that when the power from the wind is at 40% and 0% at time 0-4sec and 6-10sec, the fuel cell kicks in and supply between 30 and 50Kw in the model, which is between 30 and 50 MW multiplied with a factor of 1000. Furthermore the figure shows the power consumption from the electrolyzer ranging between 50-60kW when the power from the wind is at 100%, at time range from 4-6 seconds. The consumption is between 50-60 MW when multiplied with a factor of 1000.

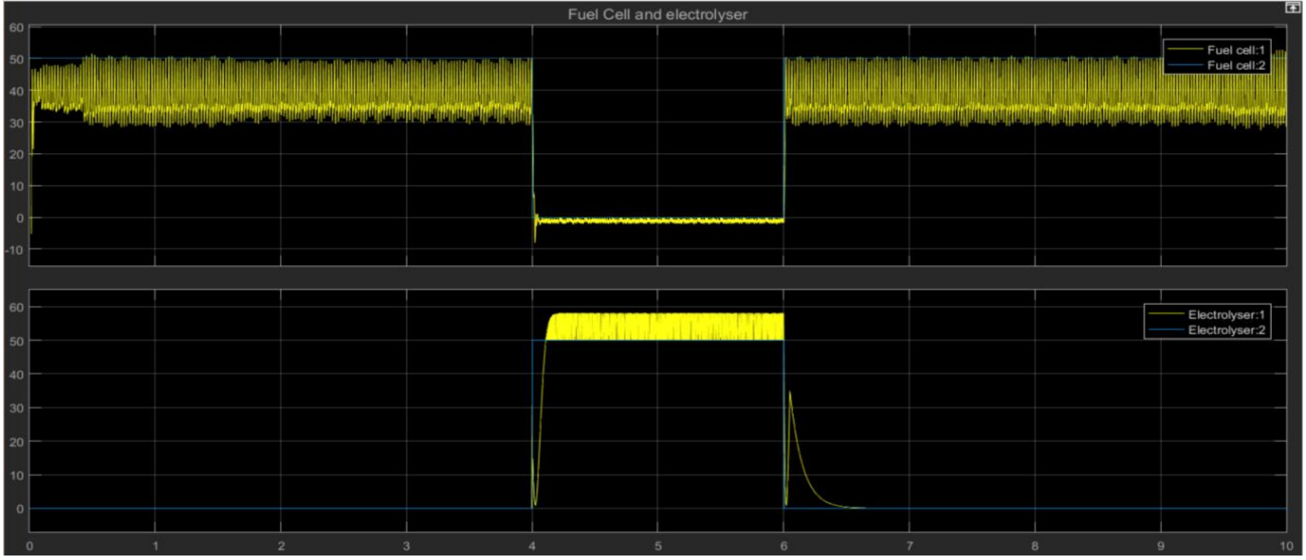

Figure 41 Electrolyzer and fuel cell power

4.1.3 Total power

Figure 42 shows the sum of power production which is the power supplied to the grid. The blue line is the power extracted from the wind. This is 40% between time range 0-4 sec, 100% from time range 4-6 seconds and 0% from 6-10 seconds. The graph shows that the power from the wind is 80kW or 80MW multiplied with factor of 1000 from time 0-4sec. When the power from the fuel cell is added, then the total power delivered to the grid is fluctuating around 120kW or 120MW multiplied with the factor. From time 4-6 seconds, the power extracted from the wind is 200,53Kw or 200,53MW scaled up, and the total power delivered to the grid is fluctuating around 150,4kW or 150,4MW scaled up. From time rang 6-10 sec, then there is no power extracted from the wind, and the total power delivered to the grid is fluctuating around 50,13kW or 50,13MW scaled up.

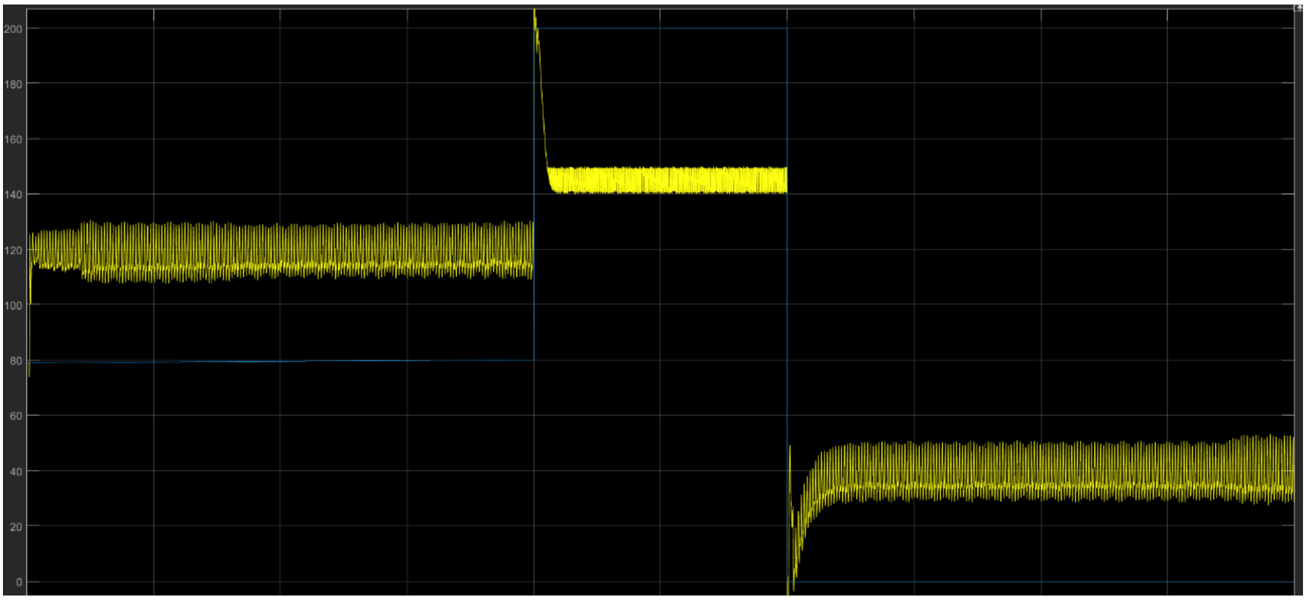

Figure 42 Sum of power production/use

4.2 Yearly production result

The following section shows the result using production data from 2015.

4.2.1 Grid utilization with hydrogen as energy carrier

The green line in Figure 43 shows the expected power production with fuel cell and hydrogen storage tank. The red line shows the actual power production with the wind farm expansion to 200,52MW, but since there is loss in the electrolyzer compressor and fuel cell, the actual power produced to the grid is lower.

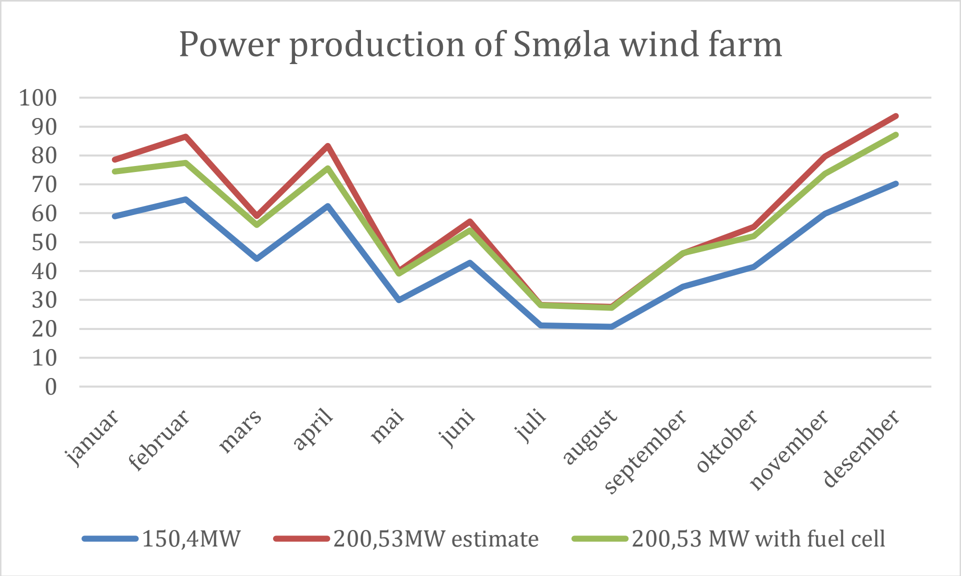

Figure 43 Power production of Smøla wind farm

$$\frac{45.737}{155} = 29{,}51\% \qquad (4.3)$$

$$\frac{57{,}329}{155} = 36{,}99\% \qquad (4.4)$$

$$57{,}329MW - 45{,}737MW = 11{,}592MW \qquad (4.5)$$

The average utilization of the grid capacity is increased from 29,51% to 36,99%, as shown in equation 4.3 and equation 4.4. The extra power production that is fed to the grid is 11,592MW, as shown in equation 4.5, throughout the years production. The average power production which is possible to achieve with a total power production of 200,53MW, is 60,955MW[28:Prod 15]. Due to the loss in fuel cell and compressor, this leaves a total effectiveness of the system of 94,05%, as shown in equation 4.7. The total yearly production is 502,202GWh, as shown in equation 4.8.

$$60{,}955MW - 57{,}329MW = 3{,}326MW \qquad (4.6)$$

$$1 - \frac{60{,}955MW - 57{,}329MW}{60{,}955MW} = 94{,}05\% \qquad (4.7)$$

$$57{,}329MW * \frac{24h}{day} * \frac{365day}{year} = 502202{,}04\frac{MWh}{year} = 502{,}202\frac{GWh}{year} \qquad (4.8)$$

4.2.2 Economic overview

When finding the cost for the different component that needs to be installed then it is used approximant value supplied by vendors and for previously studies.

The cost for PEM fuel size was given to be between 3000 and 3500€/kw[30:35] with estimated price for 2017. Converted to 2015 value[28:219] with an annual interest rate of 2% and conversion rate NOK/EUR 8,953[29] this gave present price of 10327936NOK as shown in equation 4.9

The cost of the alkaline electrolyzer and compressor was given by NEL[11] to be between 300 and 400 million. Taking the average estimated price this gave the present value in 2015 of 336409073NOK as shown in equation 4.10.

The price for storing hydrogen in gas were given as 0,5M€/t in 2012, for a storage size of 79,19 ton [27:Tank size] this gave the present value in 2015 of 368815594NOK as shown equation 4.11. The cost of installing 50,13MW of additional wind turbines is given as 1,23M€/MW in 2009 value[31:27], this gave the present value in 2015 of 621687923NOK as shown in equation 4.12.

It was not possible to find any data for maintenance cost for this system, partly because there are not that many installation with this type of equipment and partly because time did not allow to investigate the cost any further.

The price that has been used for calculating the maintained cost is based on cost for maintaining wind turbine at a European site which were between 1,67 and 2,5 € per kW[31:32]. The average cost of 2,085€ per kW have been used for calculating the percentage maintenance cost for the wind turbines installed. This was calculated to be 0,15% as shown in equation 4.13.

This percentage is then used for calculating the maintenance cost for the entire installation were the sum of the installation cost is used. The total installation cost of the equipment is calculated to be 1457240526NOK as shown in equation 4.15

This gave an annual maintenance cost of 2185860NOK for the system. By using the formula for present cost with annual cost and with an estimated life time for the system of 20 years this gave a total maintenance cost of 35741944NOK as shown in equation 4.17. Figure 45 shows the overview of total cost of the different cost type when converted to present value in 2015.

$$PV = \frac{K_n}{(1+\frac{p}{100})^n} = \frac{\frac{3250€}{\mathrm{kW}} * 4{,}66\mathrm{MW} * \frac{10^3 kW}{MW} * 8{,}953\frac{NOK}{€} =}{(1+\frac{2}{100})^2} 130327936NOK \qquad (4.9)$$

$$PV = \frac{350000000}{(1+\frac{2}{100})^2} = 336409073NOK \qquad (4.10)$$

$$PV = \frac{0{,}50\mathrm{M€}}{\mathrm{t}} * 79{,}19\mathrm{t} * 8{,}953\,\frac{\mathrm{NOK}}{€}\left(1 + \frac{2}{100}\right)^2 = 368815594\mathrm{NOK} \qquad (4.11)$$

$$\frac{1{,}23\text{M€}}{\text{MW}} * 50{,}13\text{MW} * 8{,}953\,\frac{NOK}{\text{€}} * \left(1 + \frac{2}{100}\right)^6 = 621687923NOK \tag{4.12}$$

$$\frac{2{,}085\frac{\text{€}}{kW} * 50{,}13MW * \frac{10^3kW}{MW} * 8{,}953\frac{NOK}{\text{€}}}{621687923NOK} = 0{,}15\% \tag{4.13}$$

$$(130327936 + 336409073 + 368815594 + 621687923)NOK = 1457240526NOK \tag{4.14}$$

$$1457240526NOK * 0{,}15\% = 2185860NOK \tag{4.15}$$

$$\frac{1-(1+0{,}02)^{-20}}{0{,}02} * 2185860NOK = 35741944\text{NOK} \tag{4.17}$$

$$\begin{gathered}
Maintenance\ cost = 35741944NOK \\
Cost\ of\ new\ wind\ turbines = 621687923NOK \\
Cost\ of\ 4{,}66MW\ PEM\ fuel\ cell = 130327936NOK \\
Cost\ of\ 50MW\ alkaline\ electrolyser\ with\ compressor = 336409073NOK \\
Cost\ of\ 79{,}19ton\ hydrogen\ storage\ tank = 368815594NOK
\end{gathered}$$

Figure 44 Overview of costs

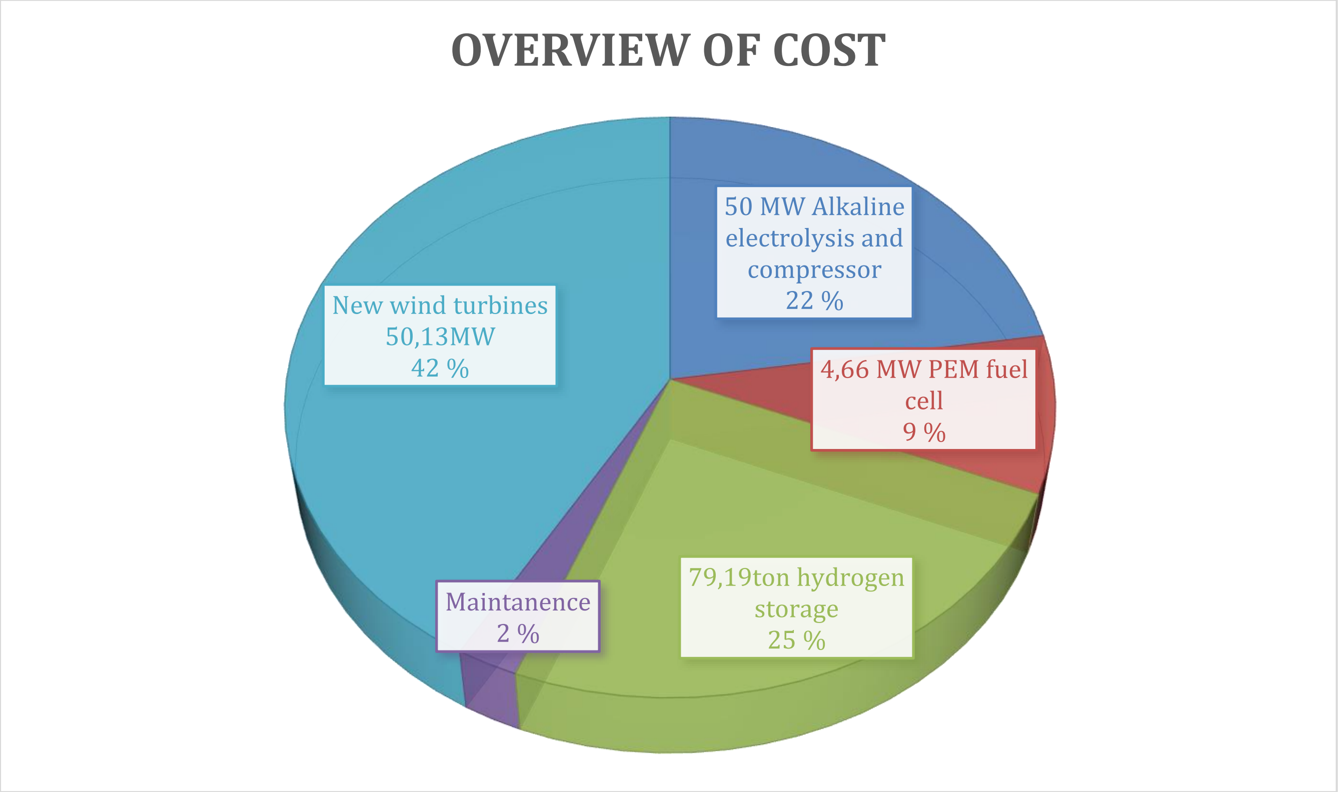

Figure 45 Overview of installation cost present value 2015

4.2.3 Income

The income calculation is based on power price of 31,7NOKøre/kWh[32] and an average yearly production of 11,594MW each hour. This gives an yearly income of the extra installed production of 32195610NOK/year as shown in equation 4.18. The total cost for the installation with an estimated lifetime of 20 years is -966538099NOK as shown in equation 4.19. The power price for when the cost is equal to the income is at 0,899NOK/kWh as shown in equation 4.20 and equation 4.21

$$11{,}594MW * 10^3 \frac{kW}{MW} * \frac{365day}{year} * \frac{24h}{day} * \frac{0{,}317NOK}{kWh} = 32195610NOK/year \tag{4.18}$$

$$PV = \left[\frac{1-(1+0{,}02)^{-20}}{0{,}02} * (32195610NOK - 2185860NOK)\right] - 1457240526NOK = -966538099NOK \tag{4.19}$$

$$11{,}594MW * 10^3 \frac{kW}{MW} * \frac{365day}{year} * \frac{24h}{day} * \frac{0{,}899NOK}{kWh} = 91305533NOK/year \tag{4.20}$$

$$PV = \left[\frac{1-(1+0{,}02)^{-20}}{0{,}02} * (91305533NOK - 2185860NOK)\right] - 1457240526NOK = -6133NOK \tag{4.21}$$

Chapter 5 Discussion

When we look at the choice 4,66MW of fuel cell, this is based on power production data from 2015. In these data processes, production loss has been included where at times some of the wind turbines are not in use. This happens when some of the wind turbines do not work and need maintenance. By expanding the wind farm of 50.13MW, this could lead to another relationship with wind turbines that do not produce power. This along with that wind speed will vary from year to year, means that the optimum sizing of fuel cell and hydrogen tank will vary from year to year.

The increase of wind power of 50.13MW gives an increase in utilization of the network capacity of 11,592MWh. However, all of this increased power does not get produced by the fuel cell alone. At times when the wind turbine produces less power than the grid capacity of 155MW, there would not be need to use the system. The actual extra power that comes from fuel cell, electrolysis and hydrogen tank capacity is 1.5578MWh. This shows that without installing fuel cell, electrolyzer and hydrogen tank, it is possible to extract 10,034MWh from the expansion of the wind park. By doing this, it would also be necessary to install a dump load or a control system for the wind turbine to limit the maximum power production to 155MWH each hour.

When looking at the overview of the different cost from Figure 45 we can see that the biggest cost, with 42% of the total installation cost is new wind turbines with 50,13MW capacity. The second largest cost with 25% of the total cost is for storing the hydrogen. The large cost for storing the hydrogen is since the tank needs to store a big volume of hydrogen with hydrogen weight if 79,19ton and since the hydrogen is gaseous stage. The alkaline electrolyzer has the third largest cost with 22% of the total. The large cost is since the alkaline electrolyzer has big installed power of 50MW and can produce a high volume of 25ton hydrogen each day. The cost of the electrolyzer also includes compressing the hydrogen gas up to 8 bar. The PEM fuel cell has only 9% of the total cost of the installation. The cost of the fuel cell is reduced since the size have been optimization for using all the stored hydrogen throughout the year 2015. When calculating the total cost of the project in the chapter about income it shows that there will be a enormous loss if the project will be realised with a power price that was for the year 2015. The price when the project will go out in plus is with a power price of 0,899NOK/kWh.

Chapter 6 Conclusion

In this thesis, hydrogen, has been used as an energy carrier for storing overcapacity for an expansion of the wind farm at Smøla. Real power measurements have been used from the year 2015, with an increase of 50,13MW. Excel and simulations have been used in Simulink to exploit grid capacity to determine the size of the fuel cell, electrolysis and storage. By using these methods this showed that the optimal size of the installation would be 4.66MW fuel cell, 50MW electrolysis plant and tank size that could store 79 tonnes of hydrogen. By using 4,66MW of fuel cell, it is enough to utilize hydrogen storage at the peak of the year. By using 50MW electrolysis plant it was possible store all of the excess energy from the wind. The size of the hydrogen tank would be big enough for storing the longest periods with maximum power production. The effectiveness of the power production is getting reduces when going through the alkaline electrolyzer compressor and PEM fuel cell. This gave an total effectiveness of the system to 94,05%. The average production has been increase from 45,7MW to 58,3MW. This gave an improvement of the grid utilization from 29,5% to 37,0%.
The model used in Simulink shows how the system integrated with the grid will be used. It varies the power to the electrolyzer and hydrogen usage to the fuel cell depending on the grid capacity and power production. The system for producing reactive effect shows that it is possible for changing the power factor cosϴ to maximize the active power which is used in the grid. Since there was not any specific detail about the system data there was not possible to get detail calculation on how much the power factor could get improved. The cost of the project gives a net loss of 966millionsNOK over a

time period of 20years with use of the same power price as 2015. For the project to go out in plus it is necessary to get an power price over 0,899NOK/kWh.

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