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TECHNO-ECONOMIC ASSESSMENT OF INTEGRATING ELECTROLYSERS IN FUTURE ENERGY SYSTEMS

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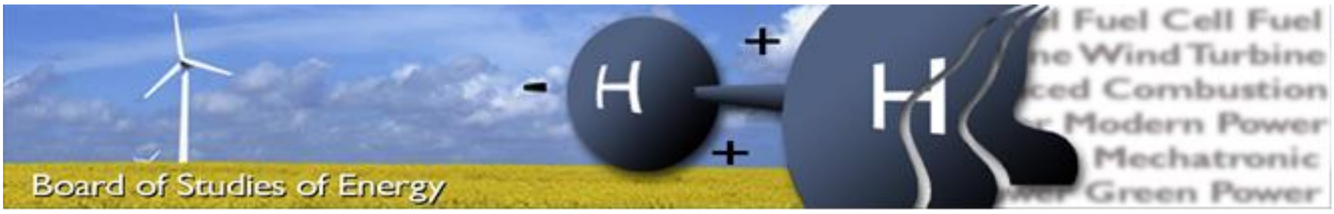

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Supervisor:	**Jayakrishnan Radhakrishna Pillai, Iker Diaz de Zerio Mendaza**
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SYNOPSIS:

This project is focused on the assessment of integration for electrolyser based hydrogen systems in high wind power penetrated systems. The proposed system will be analysed for its grid supporting capabilities. The issues it has to address and solve are based on the ones present in local distribution networks with high wind power penetration. The main task of the proposed system will be voltage regulation and local power management control. Furthermore, the system responses to NordPool electricity market scenarios are investigated in order to analyse its capacity to bring additional revenue from the electricity price fluctuations. Based on the obtained results, the successfulness of the system will be assessed in its grid support capabilities and accumulating additional income from the energy market to the owner or operator of the system

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Appendix:	2
Supplements:	CD

By signing this document, each member of the group confirms that all group members have participated in the project work, and thereby all members are collectively liable for the contents of the report. Furthermore, all group members confirm that the report does not include plagiarism.

Preface

The current report, entitled “Techno-economic assessment of integrating electrolysers in future energy systems” was written by Stoyan Ivelinov Shivachev, master student in Wind Power Systems, at the Department of Energy Technology, Aalborg University, Denmark.

The Master thesis writing was supervised by Jayakrishnan Radhakrishna Pillai and Iker Diaz de Zerio Mendaza. The span of the project was one school year, started on 1st of September 2014 and finished on 27th May 2015, hence being the master thesis project of the author.

I would like to hereby express my gratitude towards both supervisors, for their continuous support and guidance during the project writing. Secondly, I would want to thank my parents for their extensive support throughout my entire studies. Last but not least, I want to thank my friends and flatmates for their help and tolerance during my endless project writing.

27.05.2015

Stoyan Ivelinov Shivachev

Summary

The following report was conducted by accepting the master thesis project proposal by Jayakrishnan Radhakrishna Pillai and Iker Diaz de Zerio Mendaza. This study addresses the issues in the future energy systems and the impact assessment of integrating electrolyser system in them. The following report is divided into 7 main chapters and 2 appendixes. In order to guide the reader through the report a short summary for each of the chapters is presented.

The present work is divided into 7 main chapters and 2 appendixes

The first chapter introduces the growing trends that relate to future power systems. Additionally, a short retrospective regarding wind power growth and evolution is presented to the reader. Taking into account the abovementioned information and assumptions, the issues associated with the forthcoming wind power expansion in the future power systems are defined. Based on them, a solution is proposed in the form of the developed hydrogen systems. The project objectives, limitations and methodology are also defined and described in the last section of the chapter.

In the second chapter of the project introduces to the reader the state of art technologies required for the proposed hydrogen system. An analysis regarding all of the advantages, shortcomings and project requirements for them is carried out. Based on it, the most suitable technological elements for the hydrogen system are selected as well as the overall structure and all of the technologies required for implementing the hydrogen system.

The 3rd chapter presents the mathematical models applied for all of the elements required for the hydrogen system. The defined models are adjusted based on the project requirements and its main focus. Consequently, the models are created in Matlab/Simulink and connected in order to form the complete hydrogen system. Test cases are analysed in order to verify the model and asses the overall hydrogen system behaviour.

The 4th chapter of the report introduces the network which is to be implemented for the study. Its location, characteristics and main points are described and illustrated. Furthermore, steady state analysis for the network using DIgSILENT/PowerFactory software is conducted. Based on the obtained data, the main grid issues and limitations of the network are defined. What follows is a steady state analysis for the network implemented with the hydrogen system. On basis of the analysis from the obtained results, the sizing, location and control strategy to be implemented for the proposed system are also defined.

In the 5th chapter of the report the focus is placed on the implementation of the proposed hydrogen model in to the DIgSILENT/PowerFactory. The modelling of the hydrogen system and the implemented types for grid support controls are presented. The chosen control strategies, their implementation in the model and their main points are defined. Different study cases are analysed in order to assess the long-term behaviour of the proposed system and the network. Based on the obtained results, an analysis of the network support capabilities for the proposed systems is carried out.

The 6th chapter introduces the electricity market NordPool Spot. The main operation principles, price setting and overall structure of this energy market are discussed in the beginning. Based on this information, it is explained how the proposed system can take advantage of the electricity price fluctuations in order to accumulate revenue from this market. The control strategies, based on following the electricity prices, are developed and integrated in to the hydrogen system. Different operating scenarios are analysed in order to assess the full capability of the system, following market price control and its possible limitations.

The last chapter of the report provides the conclusions regarding the proposed system following the obtained results throughout the study. Future work that results from the overall assessment of the hydrogen system is proposed in the last part of this chapter.

Appendix A: Lists all of the variables used for modelling the hydrogen system proposed in this report.

Appendix B: Shows the medium voltage network used in this study integrated with the hydrogen system implemented in the DIgSILENT/PowerFactory software.

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Acronyms

AE	Alkaline electrolyser
AFC	Alkaline fuel cell
CHP	Combined heat and power plant
DG	Distributed generation
DK1	Western Denmark
DSO	Distribution system operator
EV	Electrical vehicle
FC	Fuel cell
H2	Hydrogen gas
KOH	Concentrated potassium hydroxide
$\mathbf{L_{1-n}}$	Network line name
LV	Low voltage
$\mathbf{LV_{1=n}}$	Low voltage bus number
MCFC	Molten carbonate fuel cells
MV	Medium voltage
$\mathbf{MV_{1-n}}$	Medium voltage bus number
O2	Oxygen
PAFC	Phosphoric acid fuel cell
PEMFC	Polymer electrolyte membrane fuel cell
SOFC	Solid oxide fuel cell
TSO	Transmission system operator

1 Introduction

1.1 Background

In recent years the development of renewable energy technologies becomes more crucial and rapid. The reason for this is the need to find an alternative energy source to the combustion technologies which are the backbone of the power system today [1]. It is evident that for the future power sector, given the decrease in the reserves from coal and petrol based products, conventional energy sources relying on this fuel will be phased out. Government subsidies and private sector investments focus more on the research and implementation of green technologies. Even more, the agreements regarding the decrease in carbon emissions will require a shift towards a greener renewable energy technology based power system for the future energy sector [1] [2].

At the moment, Denmark has one of the highest global shares for covering its power needs from installed renewable energy technologies. Fig 1.1 shows the percentage of each renewable technology from the total generated amount of power in Denmark. As it can be observed, there is a significant domination by wind power in terms of renewable energy technologies. However, the total amount of generated power does also include some of the other renewables like biogas, biomass (straw and wood), photovoltaics and biodegradable fraction of the waste. At this stage, these represent a smaller share of the total amount of generated power but the trends are to develop these types of technologies further in the nearby future [1] [2].

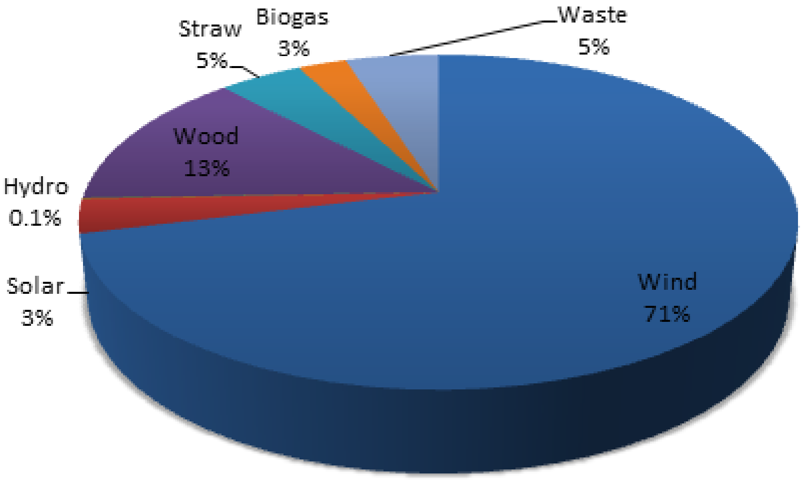


Fig 1.1 Percentage distribution of Renewable Energy based electricity generation in Denmark [2]

In 2012 a new Energy agreement regarding more rapid and broader implementation of renewable energy technologies was accepted in Denmark. The agreement sets the framework for a continued enhanced focus on research and development of new green energy technologies. Furthermore, the financial and political support for the green energy transition has advanced even more. The main points of the agreement are divided into targets to be achieved in the upcoming years. The first target on the list sets out that 50% of the Danish electrical consumption is to be covered by green energy until 2020. The second target aims at phasing out entirely the use of oil and coal for heating until 2030. The final goal is to have a carbon free energy system based entirely on green energy power in 2050 [3] [4] [5].

The progress of the main targets is divided into smaller milestones to be achieved until 2020. Based on their development, the future advance and key points in the upcoming years will be decided. Some of the most important tasks to be completed until 2020 are the following:

- 50% of the electrical energy consumption to be supplied by wind power;
- renewable energy sources (wind power, solar energy, biogas) to cover at least 35% of the total energy consumption in heating and electricity;
- to reduce greenhouse gas emissions by 34% in relation to 1990;
- to reduce gross energy consumption by 7.6% in relation to 2010.

The presented milestones focus on the acceleration of the green energy integration by increasing the wind energy capacity even more. The trend of increasing the generation from renewable energy during the years is illustrated in Fig 1.2. As it can be seen from the data, the wind energy has been steadily developing during the years. This has consequently led to higher integration of wind energy into the Danish energy system [3] [4].

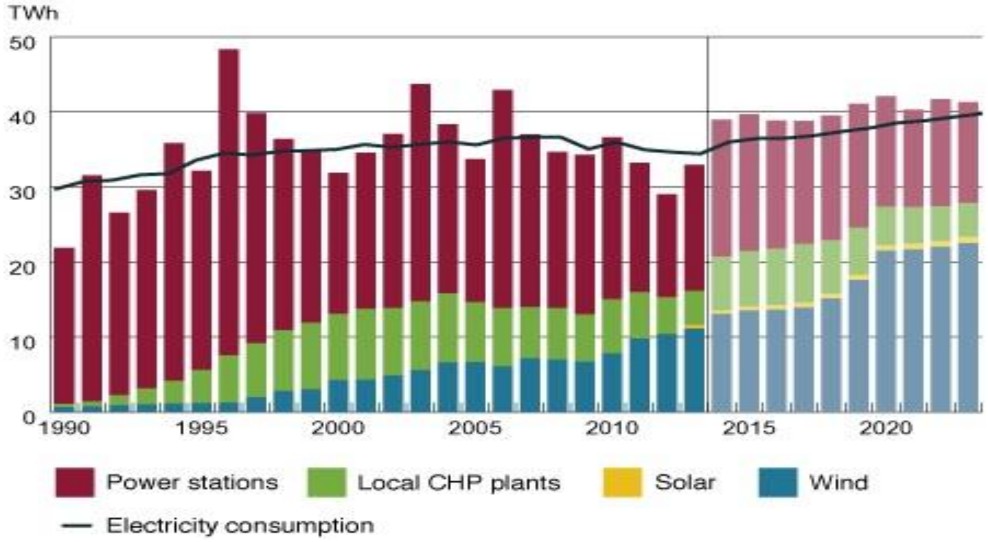


Fig 1.2 Electricity consumption and generation in Denmark [2]

However, integrating such high amount of wind power represents a challenge for the power system as a whole. The variations for this type of weather dependent energy sources are always high, which causes challenges in such large scale integration initiatives. If a large portion of the generation is transferred to the wind power sector, this will affect the balance between supply and demand in the system due to the high variability of the wind generated power. Hence, such initiative will require a better energy strategy where the focus is laid on increasing the flexibility in the consumption and generation. Additional reserves will be needed for the system in order to compensate for the reduction of conventional energy units which provide reserves at the existing system [4] [6] .

1.2 Wind power integrating issues

Wind power is a fluctuating energy resource with poor load following characteristics. With the increase of wind power generation into the energy system, the fluctuations in the electricity supply will become more apparent when compared to the conventional fossil fuel technology dominated energy systems. At the moment, the regulation of electrical generation is mainly dictated by following the customer consumption with its peak and minimum demand periods. However, wind power has poor load following characteristics as the generation is mainly dictated by the wind levels. In energy systems with high wind energy penetration, one of the main challenges is to manage the high variability and stochastic nature of the generated power and keep the balance between the generation and demand. For maintaining this balance, good demand strategies are required. One of them is increasing the flexibility in the system demand in order to have a more efficient and reliable system [1].

The imbalances of electricity in the current power system are covered mostly by the conventional large power plants, CHP’s and international interconnections. The grid operators are able to vary the power generated from the power plants in predefined limits and transfer the surplus energy via interconnections. This provides flexibility in the generation and balances the supply-demand in the grid. However, following the future Danish energy trends, the conventional power plants will be replaced with wind parks.

Wind energy is limited in its balancing capability as its power output is closely related to the wind levels and its variability. Even though Denmark has strong energy interconnections with Germany and Sweden, they won’t be enough to cover the high stochastic nature of wind. Thus, additional measures will be required to maintain the balance of the system. The flexibility of the electricity consumption, generation and the ability to predict the variability in wind energy generation through accurate weather forecast will become crucial. Without the proper energy balancing tools, a surplus of power generation or even worse – a lack of wind power generation during peak demand hours - may occur. Some of the main issues related to these cases are listed below.

Excess production of electricity can cause:

- Overvoltages;
- Frequency deviations;
- Financial losses due to inability of grid to utilize the generated power.

On the other hand, lack of generation can lead to:

- Excessive voltage dips;
- Decrease in system frequency;
- Financial losses if the required energy has to be imported through interconnections.

Additional power system operation and control problems that may occur include issues in system protection, stability, power quality etc. These types of scenarios demand the need of additional power reserves and large storage capacities to balance the system [1] [3] [4] .

In addition to the above, the highly dynamical nature of the market for electrical prices should also be considered. Denmark is a part of the Nord Pool Spot market - the largest market for electrical energy. The prices of electricity in the Nord Pool Spot are determined by the balance between supply and demand for the market [7] [8]. The main factors affecting the price are the expected generation and demand for electrical power. The byers state the amount of electrical power required for the day ahead and the seller states the amount they can generate. Based on these two factors, the prices for the day ahead are formed. Any deviations from this number on the following day are connected with distortion of the demand/supply balance, increase of the electricity prise and losses for one of the sides [7] [8]. However, renewable energy technologies tend to undergo rapid changes in the price of the generated electricity due to their high fluctuation generation. This is valid especially for wind power, since it is characterized by the highest intermittency from all of the used renewable technologies. Hence, the varying amounts of wind levels force the electricity price to change very rapidly over the day.

All the more, according to the Danish Electricity Supply Act, electricity from renewable energy sources has prioritised access to the supply grid. This forces the grid operators to focus mainly on this power source with limited options of obtaining power from other energy sources until all of the renewable energy is utilized [8]. Situations with unexpected overproduction from a wind plant due to forecast errors are not rare. In these cases the electricity price may not only fall but even become negative. This means that the wind farm owners have to pay the consumer to buy energy, thus introducing considerable financial losses. Negative prices generally occur when the power system is not flexible enough for it to adapt to the change in the supply or demand [9]. The negative price for generating power introduced from Nord Pool can go as low as 500 €/MWh [7] [1]. However, a reliable energy storage unit can overcome this issue. If energy storage is available in the system, it can cover for weather forecast errors, as well as to increase the system flexibility and minimise the financial losses for wind farm owners.

1.3 Wind energy integration solution

Storing wind energy in other energy sectors during high wind penetration and utilizing it later on during high demand periods is a viable solution. This measure will provide the needed flexibility in the system and allow smoother transfer towards high wind power integration. However, in the current power systems, it is not possible to store large amounts of electrical energy for later utilization when the demand requires it. In order to find a solution for this issue, it is essential to focus on different technologies for electrical storage or potentially converting the electricity to another type of fuel as a medium [4] [10]. One of the main challenges when dealing with storage technologies is to develop a cost-effective storage unit while keeping the conversion losses low. At the moment, there are several technologies under development with high potential in terms of storage units, some of them are [11]:

- Smart management of electrical and hybrid vehicles batteries, utilizing them in the electrical grid when they are parked;
- Generation of hydrogen gas using electrolysis;
- Compressed air storages;
- Flywheels;
- Batteries.

However, all of the above technologies present different issues with their integration into the energy system.

In the case of utilizing the electrical vehicles battery, the main issue is the lower than expected penetration of EV’s in the Danish society [11].

Compressed air storages are closely related to geographic locations and usage of geological structures under the ground. Usually abandoned coal mines and salt domes are used as underground storage for them. Nonetheless, this constitutes a limiting factor as not many areas offer such topography and possibility [11].

Batteries have been always a hot topic for energy storage. However, they too have limited usage and are focused more on small-scale systems. Commercially available solutions for efficient large-scale battery storages have not yet been demonstrated on the market [11].

Flywheels are a form of kinetic storage option with good efficiency but they are limited to under 50kW as energy storage [11].

On the other hand, electrolysis and hydrogen generation can be considered to be one of the most promising technologies. Hydrogen gas is the most versatile in terms of usage and offers the greatest flexibility compared to the other alternatives. It has the capability to store energy of very high quality up to three times more than gasoline. All the more, Denmark has a very well developed gas network which can be used for long term storage and transportation of the generated hydrogen [12]. Furthermore, hydrogen can be considered as a very versatile storage medium as it can be used for different sectors and applications in the power system. Hydrogen can namely be [13]:

- used for electrical generation using fuel cells;
- converted to methane and used in the gas grid;
- fed to combined heat and power plants for electrical and heating purposes;
- used in the transport sector;
- used in welding and metal fabrication;
- utilized by fuelling stations for hydrogen powered transportation units;
- used when refining and upgrading heavy crude oils.

The broad application of hydrogen and the fact that it is basically a clean green energy source implies that its uses in the future will only increase. Therefore, the trend is a steady growth of the hydrogen market and an increasing demand for the coming years. The expected development for hydrogen in the long term perspective can be seen in Fig 1.3.

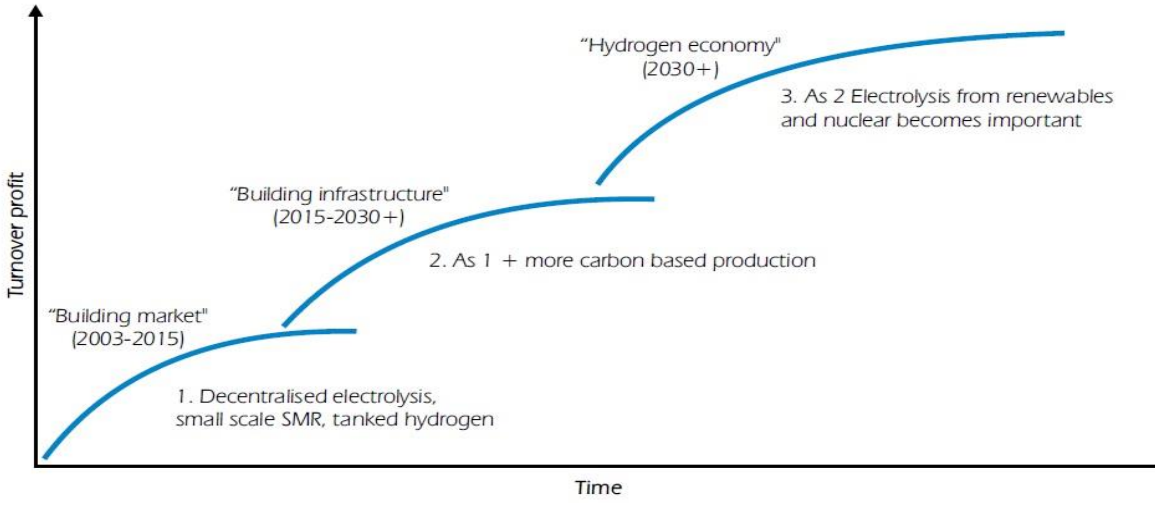


Fig 1.3 Expected future trends in hydrogen gas utilization [14]

All of these facts lead to the point where hydrogen can be considered as one of the potential main energy sources and fuels in the future. Hence, this determines the choice for the energy storage strategy to be studied in this project [15]. An example of the proposed hydrogen system integrated in to the power grid can be seen in Fig 1.4. Typically, the hydrogen system energy storage consists of a hydrogen producing unit – the electrolyser, a hydrogen storage unit – the fuel tank, and a hydrogen utilization unit - the fuel cell.

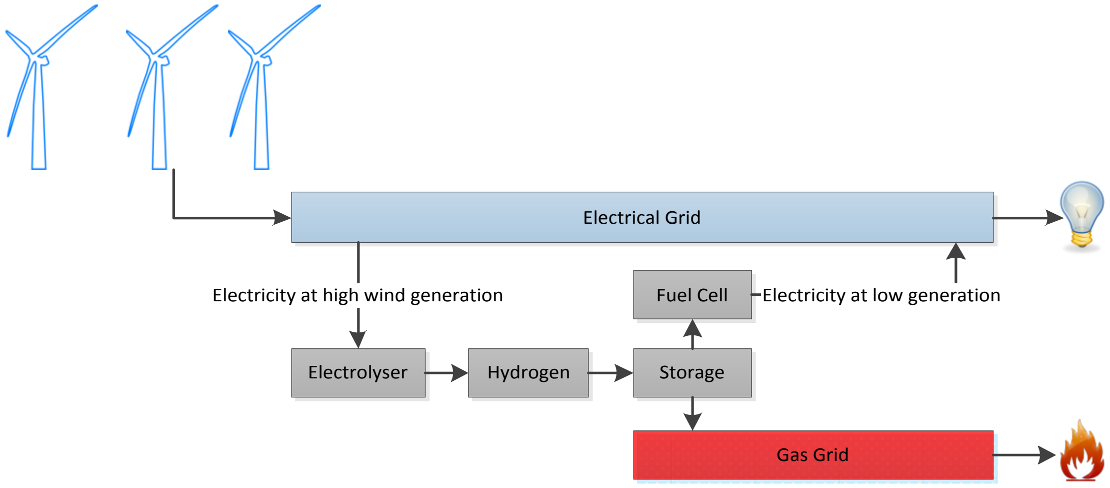


Fig 1.4 System utilizing WP energy for electrolysis during high production and low demand periods [15].

This study will focus mainly on usage of electrolysis to produce hydrogen with combination of fuel cells to provide an adequate and flexible solution for the high wind energy penetration and the required balancing of supply and demand in the system. By using electrolysis to produce hydrogen during high wind power generation and low demand, the gas can act as a storage medium. The stored gas can be used later on with fuel cells to generate electricity during high demand periods. Essentially the hydrogen gas and the gas grid can be used as a storage unit to absorb excess wind power and stabilise the system while at the same time feed the network during high demand periods.

1.4 Project objectives

The goal of this project is to analyse the behaviour of a high wind energy penetrated electrical distribution grid integrated with the proposed hydrogen system. The study will focus on the hydrogen system as a flexible energy storage unit for the excess wind power presented in the network. Voltage control and demand side management capabilities for such a system will be analysed. Demand response management following the electricity market signals for bringing additional revenue from the proposed system will also be evaluated.

Moreover, different scenarios with high and low wind penetration data will be simulated to analyse the overall system behaviour. Based on the obtained results, an assessment of the grid support capabilities and potential economic benefit that such a system can introduce will be evaluated. Furthermore, voltage deviation control, local energy management and demand response service for the proposed hydrogen system will be implemented. Upon the assessed data and the defined issues, the best control method for the system will be chosen.

The main users interested in such a system are assumed to be DSOs, wind farm owners and energy traders. Based on the obtained data for the study it will be assessed how beneficial is the proposed system for any of this users.

1.5 Methodology

First, a literature review for the state of art technologies for electrolyser and fuel cell systems will be completed. Based on the information obtained, the most suitable technologies for the requirements of this project will be chosen. Mathematical models of the different components of the systems will be implemented in Matlab/Simulink. The next step will be to implement the whole system into DIgSILENT /PowerFactory with an existing model of medium voltage grid, chosen for the study. Steady state analysis of the system will be conducted using simulations via DlgSIlent/PowerFactory and different scenarios for wind penetration and electrical demand. Based on the data attained from the model, different control strategies will be implemented in the system. Dynamic analysis of the system using the same software tool will be carried out in order to assess the long term behaviour of the system. The main steps to be carried out can be separated in the tasks below.

- Literature review for the state of the art technology for the electrolyser and fuel cell systems.
- Selection of the appropriate technology based on the scope of the project and its requirements.
- Creating a model for the hydrogen system in Matlab/Simulink.
- Modelling the system in DIgSILENT/PowerFactory integrated with the network under study.
- Steady state analysis of the system which will include:

    - Analysis for the best placement of the hydrogen system location in the grid;
    - Assessment of the impact of the hydrogen system on the network under study;
    - Simulation of different scenarios for the system and how it is responding to them.
- Long-term study of the system:
    - Analysis of the grid support capabilities of the installed hydrogen system.
    - Economic control strategy for using the system on the electricity market for bringing additional financial benefit

1.6 Project limitations

Because of limited time and/or resources, some limitations have to be imposed to the project:

- The hydrogen system proposed in the project will operate at constant temperature of 70˚C.
- Given the lack of reactive power data for the feeder profiles of the chosen network for the study, constant power factor of 0.95 for all load feeders will be used.
- Based on the small values of the reactive power presented in the network, it was chosen to focus only on the active power control for the proposed hydrogen system. Additionally, in order to avoid additional losses in the hydrogen system, it will only operate with active power for its input/output.
- The converter model for the proposed hydrogen system is not included in the scope of the study. It is assumed that the system is connected to the grid through ideal converter.
- The voltage coordination and deviation controls from the transformers tap changers (OLTC), wind turbines and CHPs are not considered in the study. This is done in order to emphasize the voltage regulating capabilities of the proposed system.
- The coordination between controllers implemented from the DSO control center is not investigated explicitly. No communication technology to realize the control and coordination is analyzed.

- The wind turbine model used in the study is a simplified one and includes only the optimal active power output based on the wind levels used in the system.
- Due to lack of wind penetration data for the network under study located in Himmerland Denmark, wind data from Aalborg-Denmark is used

2 Trends in electrolyser and fuel cell technologies

2.1 Electrolysis and Electrolysers

Electrolysers convert electricity into chemical energy which produces hydrogen gas. The principle of work of electrolysers is based on the process of electrolysis. Electrolysis is the chemical process of decomposing water under applied electrical current for producing hydrogen gas H_2, oxygen O_2 and heat as a by-product from this process.

$2H_2O$ + Electrical current = $2H_2 + O_2$

Even though there are different types of technologies for electrolyser units, their basic working principle is identical for all of them. The corresponding system consists of anode and cathode electrodes placed inside of a container filled with a solution of water and catalyst. An external DC power supply is connected to the terminals of the electrodes and a current is applied to the system. A chemical process starts forcing the electrons to flow from the anode to the cathode where they are absorbed by the hydrogen ions and form hydrogen atoms. Simultaneously, hydroxide ions move towards the anode where they recombine to form oxygen as a by-product. It should be noted that the generated amount of hydrogen is twice the amount of the received oxygen and both are proportional to the applied electric charge to the system. A schematic of a basic electrolyser unit can be seen in Fig 2.1.

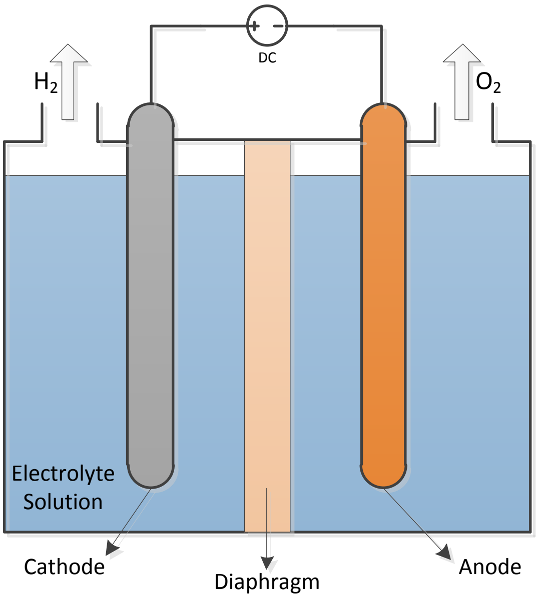


Fig 2.1 Electrolyser system

Electrolysers are characterized by the type of electrolyte they use. Currently there are two main types of technologies for electrolysers being commercially available and undergoing rapid development in the recent years [16]:

- Alkaline Electrolyser;
- Proton exchange membrane electrolysers.

➢ Alkaline Electrolyser

These types of electrolysers are one of the most common electrolytic technologies available at the commercial level. The reasons behind their popularity are due to their simple construction and the low cost of the components needed for their construction. An alkaline electrolyser system is presented in Fig 2.2.

In this type of electrolysers, the reaction occurs in liquid electrolyte which is a solution from highly concentrated potassium hydroxide (KOH) and water. Potassium hydroxide is added because water is a very poor ionic conductor. Applying voltage to the electrodes placed in the solution starts a process of water dissolving reaction with hydrogen collected at the cathode end and oxygen at the anode. The recombination of the obtained gasses is prevented using a diaphragm placed between the electrodes thus separating the product gases from each other [16] [17] .

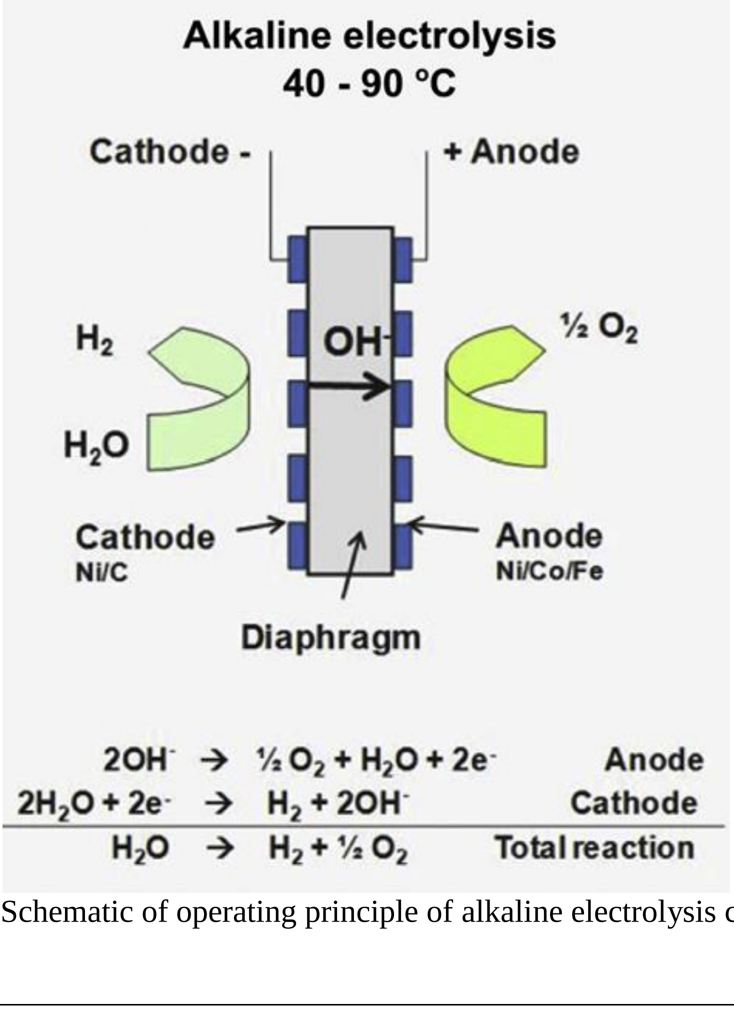


Fig 2.2 Schematic of operating principle of alkaline electrolysis cell [17].

When dealing with alkaline electrolysis technology, three main issues should be considered:

- The diaphragm component is still not efficient enough in separating the product gasses from cross-diffusing which consequently reduces the efficiency of the system considerably;
- These types of units tend to have a low amount of maximum achievable current density the reason for which is high ohmic losses in the electrolyte;
- Duo to the liquid electrolyte used, the system cannot operate under high pressures which make its structure bigger and bulkier [16] [17].

➢ Proton exchange membrane electrolyser

This type of technology is based on solid conducting polymer that is able to conduct ions when submerged in water. The polymer has also the function of separating the product gases from recombination. Compared to the alkaline electrolysers, here the diaphragm is replaced with polymer electrolyte membrane. The polymer membrane is more efficient than the diaphragm as it provides lower gas crossover and higher proton conductivity. The system is able to work under high pressure which makes it more compact than the alkaline technology [16] [17]. Proton exchange membrane electrolyser can be seen on Fig 2.3.

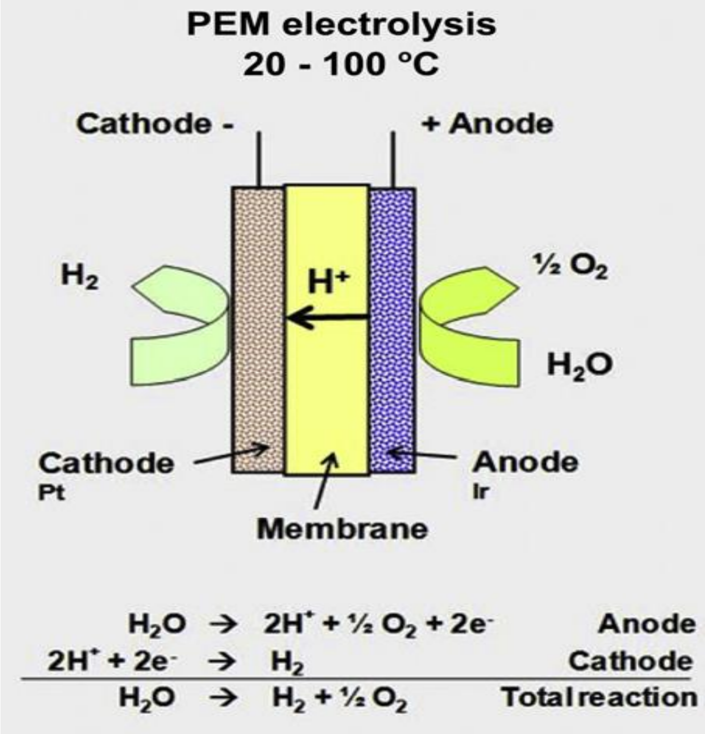


Fig 2.3 Schematic of the operating principle of PEM electrolysis cell [17].

However, this system is also not deprived of drawbacks and some of them are the following:

- High component cost. The reason for this is the acidic environment of the electrolyte. This forces some specific requirements for the materials to be used in this harsh environment. Usually noble materials are used for the catalyst and titanium based materials for the current collectors and separator plates;
- Lower overall durability of the system. The reason for this is the high operating pressures and corrosive environment [17] .

A comparison Table 2-1 is presented with the main point of interest, advantages and drawbacks for the two different electrolyse technologies.

Table 2-1
Electrolyser technologies main points [17] [18] [19]

	Alkaline electrolysers	PEM electrolysers
Cell temperature (C^o)	60-80	50-80
Current density (mA/cm^{-2})	0.2-0.4	0.6-2
Cell area (m^2)	>4	<0.03
Cell voltage (V)	1.8-2.4	1.8-2.2
Efficiency	60-65%	70%
Lifetime of the system (years)	20-30	10-20
Advantages	- Low cost - Long term stability - Simple construction - Longer lifetime	- High current density - Fast system response - Compact system design
Disadvantages	- Low current density - Slower system response - Bulkier system - Corrosive electrolyte	- High component cost - Lower durability and lifetime - Acidic corrosive environment

The electrolyser technology to be used in this project is chosen to be alkaline electrolyser type. The choice is based on the fact that even though its efficiency is lower than PEM type, this technology is more economically appropriate. The lower system cost, higher reliability and the wider commercial accessibility were the key factors that determined the choice.

2.2 Hydrogen storage system

Hydrogen gas is one the lightest elements and is characterized with high diffusion rate and very small density. It is a non-toxic and non-poisonous gas, generally not causing corrosion with the typical container materials. Today there are different technologies used for storing hydrogen. The most widespread ones are the following [14]:

- Compressed gaseous hydrogen

This is one of the most common and widely used methods for hydrogen storing. Special lightweight composite tanks made from aluminium are commonly used and highly commercially available. The shell of the tank is manufactured in such a way as to be thick enough to prevent any hydrogen leakage. However, one of the main disadvantages of such storage is the large physical volume required for the tank [14] [20].

Another method for storing gaseous hydrogen is in above ground caves and cavities. This approach offers the possibility to store big amounts of oxygen at variable pressures determined only by the geological shape of the cavity. This type of storage can be characterized as having the smallest amount of leakage, almost zero in some cases. Nevertheless, the requirements for the cavities and caves that can be used for such purpose introduces a limitation with very specific geological requirements [14] [20].

Storing gaseous hydrogen can be considered as one of the cheapest and most viable solutions to present day. It should, however, be noted that storing hydrogen in its gaseous form is considered as one of the most dangerous methods of all [14] [20].

- Liquid hydrogen storage

Another effective method of storing hydrogen is preserving it in its liquid form. Hydrogen becomes liquid at -253°C. It should be noted that liquid hydrogen has a better energy density than its pressurised gas form [14].

Other options for storing liquid hydrogen include using it as constituent in other liquids such as rechargeable organic liquids, anhydrous ammonia or a borohydrite solution. The main advantage of the liquid storage is the reduced storage risk compared to the compressed gas storage. This type of storage, however, is more expensive due to the complicated and energy consuming process of liquefaction. The storage tank also requires complex insulation techniques and materials which in turn greatly increases the total cost of the system [14] [20].

- Metal hydrides storage

This storing method is based on binding chemically hydrogen with metals, alloys or metal hydrides which reacts with hydrogen under high temperature. To extract the hydrogen back from the compound, high temperature is applied for the reverse reaction to take place. This storage technique is considered as one of the safest for hydrogen storing. Nonetheless, this method requires extra heat energy to be applied to the carrier metal and additional heat management have to be used for the system. Consequently, this complicates the system and introduces additional problems. Furthermore this type of storing system tends to have shorter lifetime due to the high temperatures used. [20] .

Following the review of the available alternatives, the pressured hydrogen storage was chosen to be the hydrogen storage technology used in this project. The choice was based on the notion that this is the most financially and commercially available solution and provides the longest life time. In addition, out of the given options, it is the simplest storing solution and this implies lower maintenance cost.

2.3 Fuel Cells technology review

Fuel cells are becoming a popular technology for the future energy sector. The reason for this is due to their high efficiency and low generated emissions. Their high efficiency is mainly due to their operating principle which relies on converting chemical energy directly to electrical as opposed to the traditional technologies where the fossil fuel is converted to thermal and mechanical energy to finally generate electricity. This additional energy conversion introduces higher losses in to the system and generates a considerable amount of carbon emissions. Some of the main advantages of the fuel cells are [20] [21]:

- Direct conversions of chemical to electrical energy;
- Very small amount of generated carbon emissions;
- Good load following characteristics;
- Wide range of operating temperature which can be used for cogeneration to increase the overall efficiency of the system;
- Good performance even with partial loading;
- No moving parts, hence simpler maintenance of the system.

Fuel cells can be compared to batteries with the difference that they are not limited by the amount of energy stored in them. They can operate as power generators as long as the required amount of hydrogen and oxygen are fed to them. The hydrogen input can be considered as their only limitation [22].

The fuel cells can thus be described as electrochemical devices that combine hydrogen and oxygen to generate electricity with a by-product of water and heat. The basic structure of the fuel cell consists of three main elements – two catalyst coated electrodes (anode and cathode) and an electrolyte placed between them [21].

While there are different technologies and types of fuel cells, their main operating principle remains the same for all of them. At the anode, the injected hydrogen gas reacts with the catalyst coating to create charged particles in the form of protons and electrons. The protons are able to freely pass through the electrolyte. The electrons, however, are unable to pass through it to recombine at the cathode end. This requires the electrons to flow through a different path which is the load in the system, thus generating electrical current. At the cathode end, additionally injected oxygen reacts with the protons and electrons to create a by-product of water and generate heat from the reaction and complete the cycle.

A basic representation of a fuel cell working principle and elements can be seen in Fig 2.4.

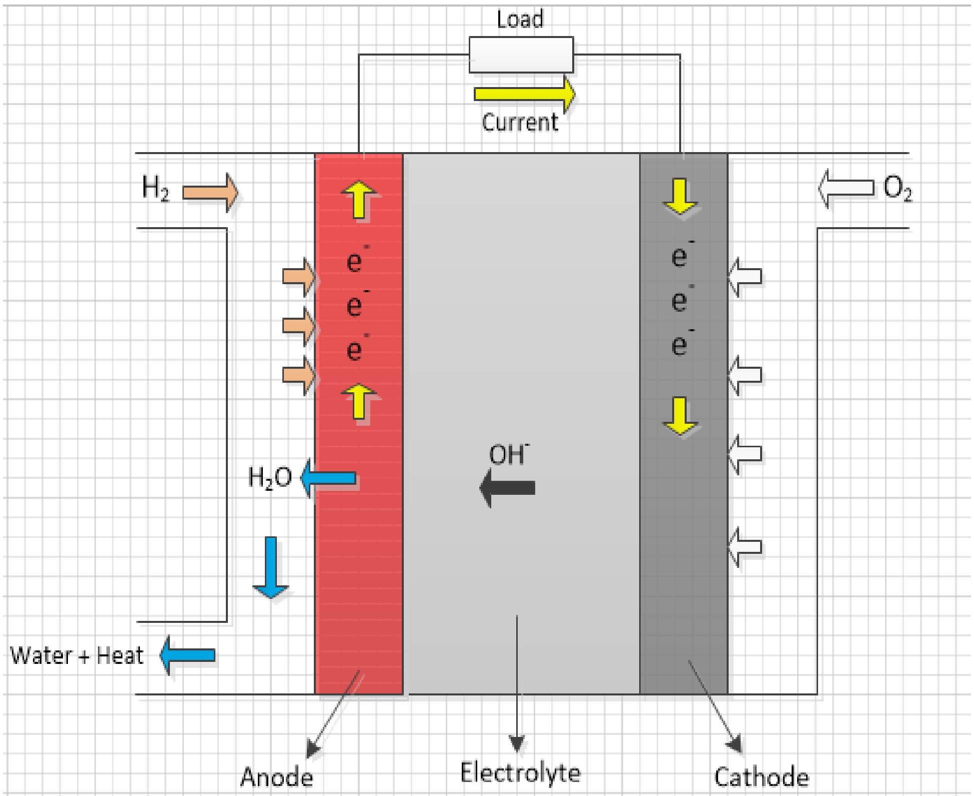


Fig 2.4 Basic fuel cell working principle

There are a number of different types of fuel cells each with their own unique structure, operating characteristics, advantages and drawbacks. The way to categorize them is mainly based on the type of electrolyte they use. The type of the electrolyte determines the chemical reaction to take place in the cell as well as other important characteristics such as [21] [23]:

- the purity of the required hydrogen from the cell to function at maximum efficiency;
- the working temperature of the cell;
- the start-up time;
- the type of catalyst to be used;
- the amount of emissions released from the process;
- the limitations of the cell.

The most renowned and commercially available types of fuel cells today are the following:

Liquid electrolyte type

- Alkaline fuel cells (AFC)
- Phosphoric Acid fuel cells (PAFC)
- Molten Carbonate fuel cells (MCFC)

Solid electrolyte type

- Polymer Electrolyte Membrane fuel cells (PEM)
- Solid Oxide fuel cells (SOFC)

- Alkaline fuel cells

One of the first developed fuel cells and the most developed during the years. The electrolyte in this type of fuel cells is concentrated hydroxide of potassium. This type of fuel cell technology has low operating temperatures between 120°C-250°C in proportion to the electrolyte concentration. A wide variety of catalyst may be used for this particular technology which decreases the overall cost of the cell. It also requires pure hydrogen as fuel which can be considered as limitation in some cases [21] [25].

- Phosphoric Acid fuel cells

As the name implies, the electrolyte in this type of fuel cell consist entirely of phosphoric acid. The operating temperatures are in the range of 150°C-220°C. These types of cells are limited since their inability to operate at lower temperature levels as their efficiency decreases due to reduction of ion conduction. No water management is required for this technology as the electrolyte is entirely a solution of phosphoric acid. However, thermal management is required in order to keep the operating temperatures at their optimal levels [21] [25].

- Molten Carbonate fuel cells

This is a high temperature fuel cell operating in the 600°C-700°C range. Alkaline carbonate salts are used as an electrolyte in its molten state. One of its advantages is that it does not require expensive manufacturing materials. Such cells are mainly used in high power stationary applications and have more flexible requirements for the hydrogen purity. Nevertheless, they do have a slow start up time and bad load following characteristics [21] [25].

- Solid Oxide fuel cells

These are one of the two fuel cell technologies with solid electrolyte. Here, the operating temperatures vary in the 600°C-1000°C range. These fuel cells have been undergoing rapid development in the recent years and are characterized by cheap manufacturing materials. They do not require high hydrogen purity for operation. Some of their disadvantages include limited life time of the cell and issues related to the very high operating temperature [21] [25].

- Polymer Electrolyte Membrane fuel cells

The electrolyte in this fuel cell is an ion exchange membrane which is marked by very good proton conduction. The only liquid existing in the cell is the water from the reaction. Hence corrosion problems for this technology are minimal. The operating temperatures are one of the lowest for all of the presented fuel cells less than 100°C. PEM fuel cells found wide usage in variety of applications with high focus on mobile systems and became one of the most researched and funded fuel cell technologies over the last few years. Even though the manufacturing cost is higher, the electrical efficiency of this type of fuel cells is one of the highest compared to the others [21] [25].

The main characteristics for each fuel cell technology are presented in the following Table 2-2:

Table 2-2

Fuel cell technologies main points [13] [21] [23]

Fuel Cell Type	Operating t°C	Electrical Efficiency	Common applications	Advantages	Challenges
Polymer Electrolyte Membrane (PEM)	<100	60%	- Backup power - Portable power - Distributed generation - Transportation	- Reduces corrosion - Low operating temperature - Quick start-up	- Expensive catalysts - Sensitive to fuel impurities
Alkaline (AFC)	120-250	60%	- Backup power - Transportation	- Lower cost production - Low operating temperature - Quick start-up	- Complicated electrolyte management
Phosphoric Acid (PAFC)	150 - 220	40%	- Distributed generation	- Suitable for CHP - Increased tolerance to fuel impurities	- Expensive catalysts - Long start-up time
Molten Carbonate (MCFC)	600 - 700	50%	- Electric utility - Distributed generation	-High efficiency - Fuel flexibility - Suitable for CHP	- High corrosion and breakdown of cell components - Long start-up time -Bad load following characteristic - Low power density
Solid Oxide (SOFC)	600 - 1000	60%	- Auxiliary power - Electric utility - Distributed generation	- Fuel flexibility - Suitable for CHP	- High corrosion and breakdown of cell components - Long start-up time -Bad load following characteristic - Limited number of shutdowns

Correspondingly, the fuel cell technology chosen to be used in this research is polymer electrolyte membrane fuel cell. The reason for this choice is based on the high electrical efficiency of this particular technology, the good load following and the smaller stack design. Even though the usual choice for distributed electrical generation is MCFC or SOFC technology, the main reason for this is the usage of the high generated heat from them for cogeneration and fuel flexibility in terms of purity. However, heat cogeneration is not included in the study.

Another point which is considered is that the chosen alkaline electrolyser supplies hydrogen with high purity. Hence the requirement for high purity hydrogen from PEM is covered. As stated in [21], scaling fuel cells is not affecting their overall efficiency and performance. This, therefore, gives us the opportunity to use a more innovative approach and choose PEM technology for higher power distributed generation.

2.4 Trends in electrolyser and fuel cell technologies - conclusion

At this stage of the research project, the state of the art technologies for the most relevant parts of the hydrogen system were presented. The shortcomings, advantages and limitations for each technology were listed in order to measure each one of them. Following an analysis of the main characteristics of the proposed technologies and the project limitations and requirements, the most suitable technologies were chosen.

For the electrolyser, the final choice was the alkaline electrolyser technology. Even though it is bulkier than the other proposed technology, it provides a good balance between price and efficiency. Given its simple structure and cheap constructing materials, it also suggests easier and cheaper maintenance.

The choice for the hydrogen storage was done in favour of pressurised hydrogen tanks. In spite of the fact that the rest of proposed storage methods have experienced rapid development in the recent years and provide bigger advantages, all of them require complicated and expensive maintenance. At the same time, storing hydrogen in its pressurised form requires less maintenance and a simpler control mechanism for storing it.

Lastly, in regards to the fuel cell technology, it was chosen to utilize a polymer membrane technology. The fuel cell technology market provides a wide choice of technologies available to the user. However, the chosen one was the most suitable given the project requirements. Good load following characteristics, low operating temperature and the high electrical efficiency were the key points for the choice of the PEM fuel cell.

3 Modelling of the hydrogen system for grid integration

In this chapter the modelling part for the hydrogen system is presented. Equations and variables describing the model in the system are defined and explained. System control for each subsystem following given power reference signal is explained, defined and verified together with the system model.

Prior to the explanation for each part of the system, a simplified block diagram is presented showing its implementation in the overall model and its main input and output parameters.

3.1 Modelling of the alkaline electrolyser

The model is based on a steady state electrochemical operation of the system. It combines heat transfer theory, fundamental thermodynamic and empirical electrochemical relationships. The number of used parameters for the model is kept to a minimum and simplified in order to make it more suitable for the project study. However, this simplification of the model is done in such a way, that it ensures the relevant transient and steady state behaviours are captured in the analysis.

An illustration of the system blocks of the hydrogen system interfaced with the grid is shown in Fig 3.1.

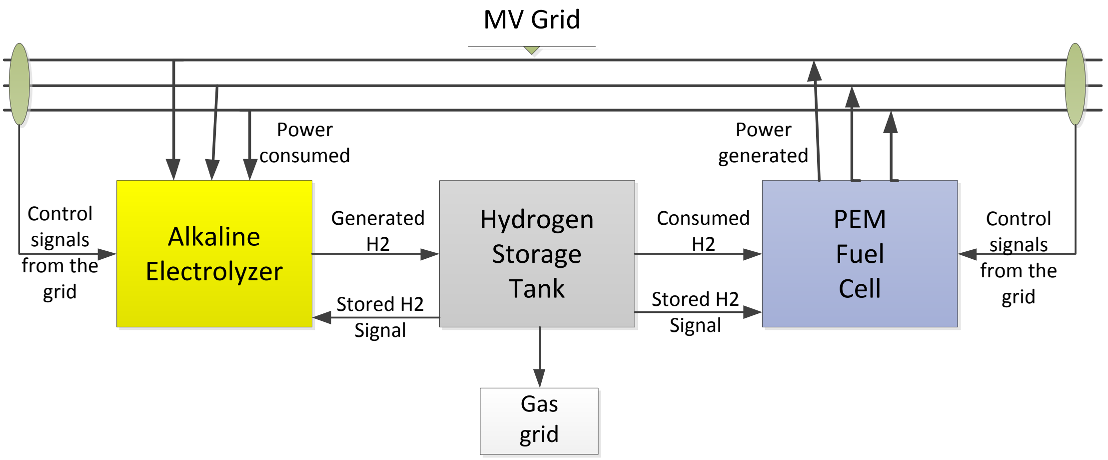


Fig 3.1 Overall system preview

For the alkaline electrolyser, the main aspects of interest are the electrochemical model and the hydrogen production rates.

The model of the alkaline electrolyser used in this project is based on the work published in [24] and [25]. That model has been modified following the requirements and objectives of this project. Some of the limitations that are included in the modified version is to keep the temperature in the electrolyser constant during the process. This is done in order to simplify the system and focus more on the steady state model and its hydrogen generating capabilities, rather than on the transient processes of the AE.

The explicit model of the alkaline electrolyser can be seen on Fig 3.2 where it is presented as a block diagram with all of the implemented equations for the model. All of the used equations will be explicitly defined in the following sub-chapters.

The inputs for the system are the generated extra power in the network and the grid signals for the implemented control. Depending on the control used for the system, the grid signals may be the voltage at the buses, the active power flow in the grid or the electricity market price. In accordance to the used control signals, the system defines the power set point for the alkaline electrolyser to follow. The electrochemical model purpose is to define the alkaline electrolyser voltage and current based on the given power set point. Afterwards, the hydrogen production model generates hydrogen gas based on the calculated current in the system. The output of the alkaline electrolyser is the generated hydrogen gas.

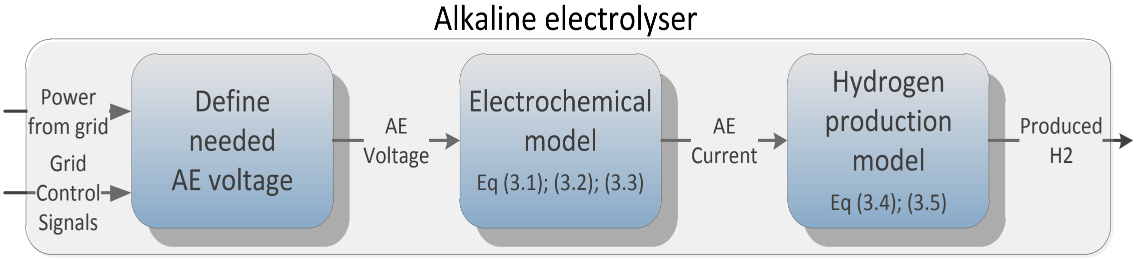


Fig 3.2 Alkaline electrolyser block diagram

3.1.1 Electrochemical model

Electrode kinetics of alkaline electrolyser can be expressed as an empirical function between the current and voltage relationship. The present equation is for given cell temperature and includes the overvoltage dependence based on it [24], [25] .

$$U_{cell} = U_{rev} + \frac{r_1 + r_2 T_e}{A_{cell}} I + (s_1 + s_2 T_e + s_3 T_e^2) \log\left(\frac{t_1 + {t_2}/{T_e} + {t_3}/{T_e^2}}{A_{cell}} I + 1 \right) \qquad (3.1)$$

In (3.1) the calculated voltage “U_{cell}” is for one cell of the electrolyser only. To obtain the voltage of electrolyser composed from stack of cells, it needs to be multiplied with the number of cells in the stack.

$$U_E = n_c U_{cell} \tag{3.2}$$

The current-voltage characteristic curve obtained from (3.1) for different voltages is given in Fig 3.3. This non-linear characteristic shows how the electrolyser cell current changes on basis of the voltage input. Two specific points on the characteristic curve should be noted - the “U_{rev}” voltage and the overvoltage limit of the cell. They define the minimum and maximum limits for the voltage that can be applied to the alkaline electrolyser cell.

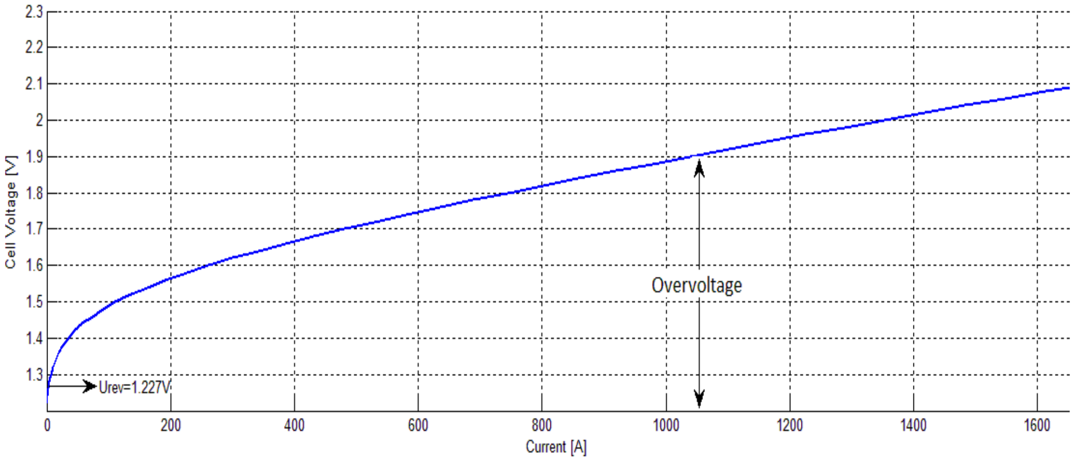


Fig 3.3 Current-voltage characteristic for electrolyser cell operating at 80^0C [25]

In order for a chemical process to occur, a minimum amount of electrical energy is needed to split the water. Thus, a minimum amount of voltage “U_{rev}” needs to be applied to the system in order to start the electrolysis process. For the calculation of the reversible cell voltage “U_{rev}” based on the 80°C constant working temperature in the electrolyser, the polynomial equation proposed in [25] is used:

$$U_{rev} = -2.483e^{-10}{T_e}^3 + 2.9004e^{-7}{T_e}^2 - 0.000733T_e + 1.2845 \tag{3.3}$$

The maximum amount of voltage and the overvoltage point that the cell of the alkaline electrolyser can withstand have been determined based on the data given in [25]. Hence, the two limiting values for the AE cell have the following voltage limitations for their minimum and maximum voltage input:

$V_{min}^{electrolyser} = 1,27$ V

$V_{max}^{electrolyser} = 1,9$ V

3.1.2 Hydrogen production model

According to the Faraday's law, the production rates of hydrogen gas are directly proportional to the current drawn from the electrolyser stack. For a number of cells connected in series, the following equation can be defined for the hydrogen production in mol/s [25].

$$n_{H_2} = n_f \frac{n_c I}{zF} \tag{3.4}$$

The Faraday efficiency factor is defined as the ratio between the actual amount of hydrogen gas produced from the electrolyser and the maximum theoretical amount. Faraday efficiency is closely related to parasitic current losses along the gas ducts. This efficiency factor is defined by the following equation [24] [25]:

$$n_F = a_1 exp\left(\frac{a_2 + a_3 T_e}{I/_{A_{cell}}} + \frac{a_4 + a_5 T_e}{\left(I/_{A_{cell}}\right)^2}\right) \tag{3.5}$$

3.1.3 Alkaline electrolyser implementation and control

For the test case, it is chosen that the electrolyser power is set at 500 kW. Thus, this is set as a limitation for the maximum amount of power that it can consume.

Additional modelling for the electrolyser I-V curve equation is needed due to the high non-linearity of the alkaline electrolyser characteristic equation (3.1). Hence, a more suitable model for the calculation of the alkaline current and voltage was created using a look-up table. The values for the voltage are based on the data extracted using a step input for the current in (3.1).

A block diagram representing the main points of the control for the alkaline electrolyser system can be seen in Fig 3.4

The main inputs for alkaline electrolyser are:

- Excess power generated in the grid;
- Signal from the storage unit monitoring hydrogen gas levels;

- Control signals from the grid defining in which mode the electrolyser is working (bus terminal voltage control, power flow balancing or optimal hydrogen production)
  - ➢ Bus voltage
  - ➢ Power flow in the system
  - ➢ Electricity market prices.

The main output values for the fuel cell system are:

- Power consumed from the alkaline electrolyser
- Hydrogen production rate.

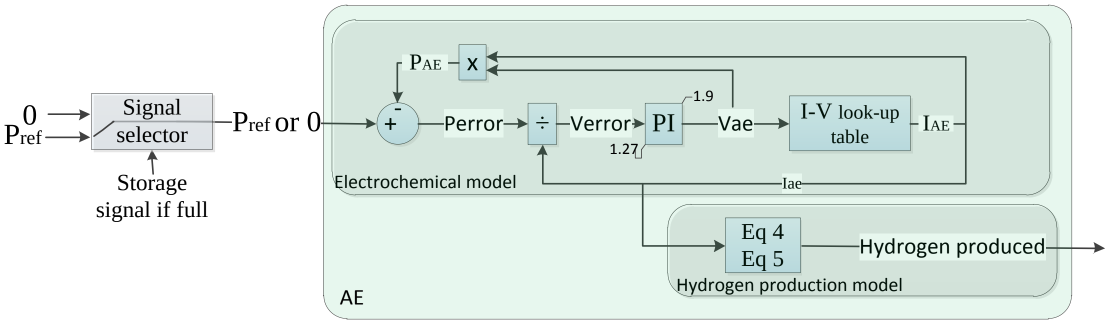


Fig 3.4 Block diagram for the electrolyser implemented control

A closed loop control with a PI controller is applied to the system. The control loop follows power set point given to the system “P_{ref}”. The set point is defined by the implemented control which can be bus voltage regulation, power flow or the electricity/hydrogen market prices. The characteristic limitations for the minimum and maximum operating alkaline cell voltages are implemented internally into the applied PI controller. Selection switch logic is utilized at the beginning of the system to follow the amount of hydrogen available in the storage unit at any given time and to stop the system once it is full.

The generated hydrogen gas based on the power input for the alkaline system can be seen in Fig 3.5. The plot is intended to show how the model behaves and follows the input set point. On the first part of the figure load response to the input signal of the implemented AE system is shown. It is assumed that AE is being loaded with excess power from the grid and shows how the developed control copes with it. The second part of the figure shows the generated hydrogen from the system.

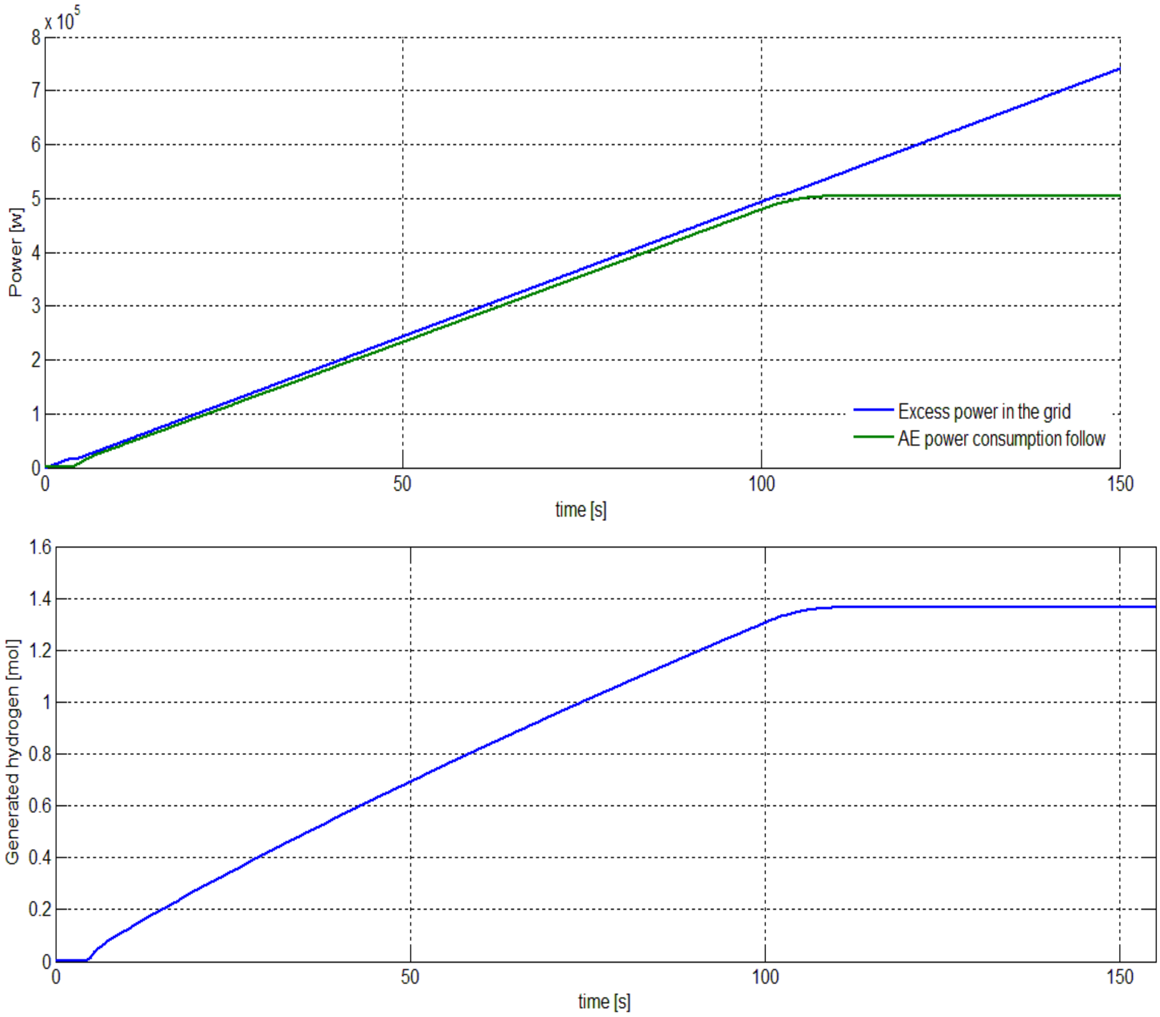


Fig 3.5 Electrolyser hydrogen production based on input power

3.2 Fuel cell modelling

The proposed model is based on theoretical fuel cell model for which some of the values were defined empirically and validated on a real fuel cell setup. The main focus is on the steady state operation of the fuel cell and its hydrogen consumption rates for different power outputs. The values used in the parameters for the model are primary based on manufacturing data and the ones given in [26] and [27].

A more explicit model of the fuel cell is a presented as a block diagram in Fig. 3.6. Each of the blocks represents one of the sub-models of the fuel cell (electrochemical model and consumption model) with the equations characterising it.

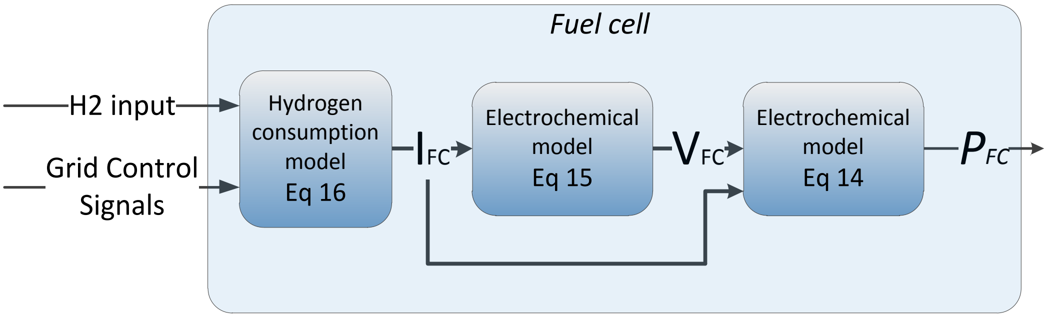


Fig 3.6 Fuel cell block diagram

The inputs for the fuel cell are the hydrogen feed and the grid control signals. The grid control signals may vary depending on the control strategy used for the hydrogen system at the moment. The main grid inputs for the fuel cell are the following:

- Bus voltages in the network;
- Power flow in the network;
- Spot market electricity prices.

The output of the system is the generated power from the fuel cell stack "P_{FC}".

3.2.1 Electrochemical model

In order to obtain energy from a fuel cell, current has to be drawn from it. When current is drawn from the fuel cell, a deviation from the thermodynamic potential occurs corresponding to the power supplied from the fuel cell. The cell voltage "V_{cell}" is dependent on the reversible thermodynamic potential "E", activation over potential "V_{act} " ohmic over potential "V_{ohmic}" and concentration over potential "V_{conc}". The expression for the voltage of a fuel cell has the following form:

$$V_{cell} = E - V_{act} - V_{ohmic} - V_{conc} \tag{3.6}$$

The reversible thermodynamic potential of the fuel cell is defined as:

$$E = 1.229 - 8.5 * 10^{-4} * (T - 298.15) + 4.3085 * 10^{-5} * T * \left[\ln p_{H2} + \frac{1}{2}\ln p_{O2}\right] \tag{3.7}$$

The activation overpotential is caused by the slowness of the reactions taking place on the surface of the electrodes. Losses are due to the chemical reaction that transfers the electrons to and from the electrodes. This voltage loss can be expressed as:

$$V_{act} = -(\xi_1 + \xi_2 * T + \xi_3 * T * [\ln C_{O2}] + \xi_4 * T * [\ln I]) \tag{3.8}$$

Where "C_{O2}" is the oxygen concentration at the cathode membrane defined by the following equation:

$$C_{O2} = \frac{P_{O2}}{5.08 * 10^{6} exp\left(\frac{-498}{T}\right)} \tag{3.9}$$

Ohmic overpotential results due to the ionic resistance in the membrane and the resistance of the electrodes, contacting plates and terminal conditions. It can be expressed using an equation similar to the Ohm's Law:

$$V_{ohmic} = I * \left(R_p + R_e\right) \tag{3.10}$$

The term "R_p" represents equivalent resistance for protons passing through the solid membrane, which can be obtained using the following equation:

$$R_p = \frac{\rho_p * L}{A} \tag{3.11}$$

Where "ρ_p" represents specific resistivity for the flow of hydrated protons. It is computed using the following equation:

$$\rho_P = \frac{181.6 * \left[1 + 00.3 * I + 0.062\left(\frac{T}{303}\right)^2 * I^{2.5}\right]}{(\beta - 0.634 - 3 * I)\exp(4.18 * \left[\frac{T - 303}{T}\right]} \tag{3.12}$$

Concentration overpotential is caused by the limitations on the availability of the reactants near the electrodes. It can be expressed using the following semi-empirical equation:

$$V_{conc} = -B \ln\left(1 - \frac{I}{i_{max}}\right) \tag{3.13}$$

The output power of the fuel cell is defined by the following equation:

$$P_{FC} = I_{FC} * A * V_{FC} \tag{3.14}$$

The presented equations for the fuel cell model are highly nonlinear in terms of the voltage as a function of the current. This nonlinearity can be observed in Fig 3.7. The figure shows how the voltage of the fuel cell and the voltage drops change, based on the current Ifc.

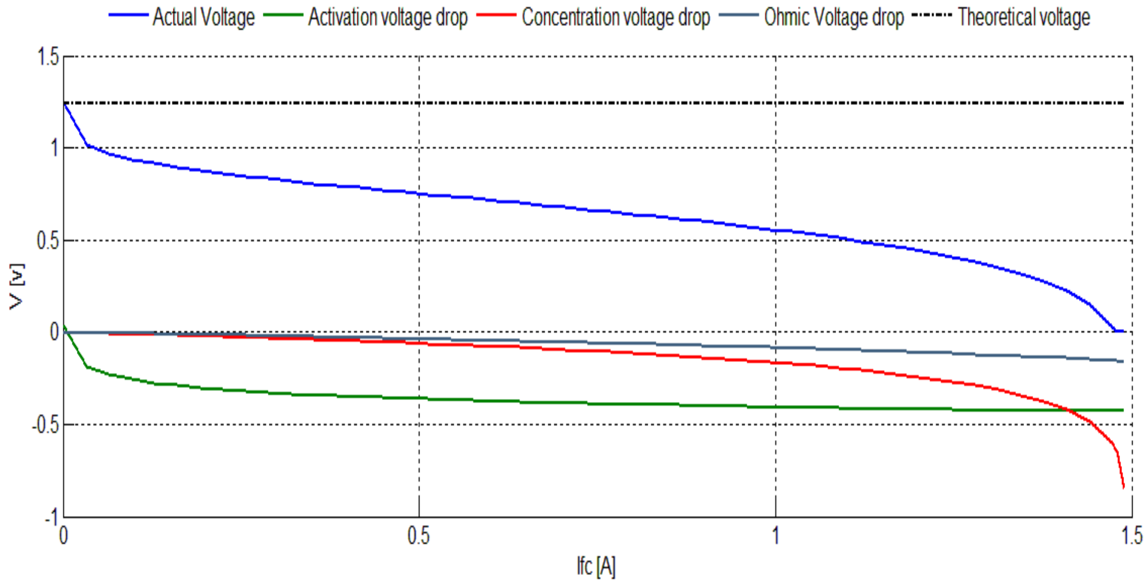


Fig 3.7 Fuel cell voltages based on Ifc

Due to this high nonlinearity, a more simplified model is applied in the development of the system and the control loop method in this project. This was done by implementing the proposed model in Simulink and using ramp input for the current. Thus, the needed data was extracted for the I-V curve of the fuel cell. Using this data, a polynomial interpolation was done in order to obtain the simplified model for the system. The new simplified equation for the I-V curve of the fuel cell has the following form:

$$V_{fc} = -1.439 * {I_{fc}}^5 + 4.8213 * {I_{fc}}^4 - 6.0835 * {I_{fc}}^3 + 3.5322 * {I_{fc}}^2 - 1.3078 * I_{fc} + 1.0321 \qquad (3.15)$$

Comparison between the V-I curve of the new interpolated model and the original proposed one is shown on Fig 3.8. As it can be seen from the plot, the data points obtained using the simplified model are identical to the original one. Hence the new model can be implemented into the system without affecting its accuracy while at the same time reducing its complexity.

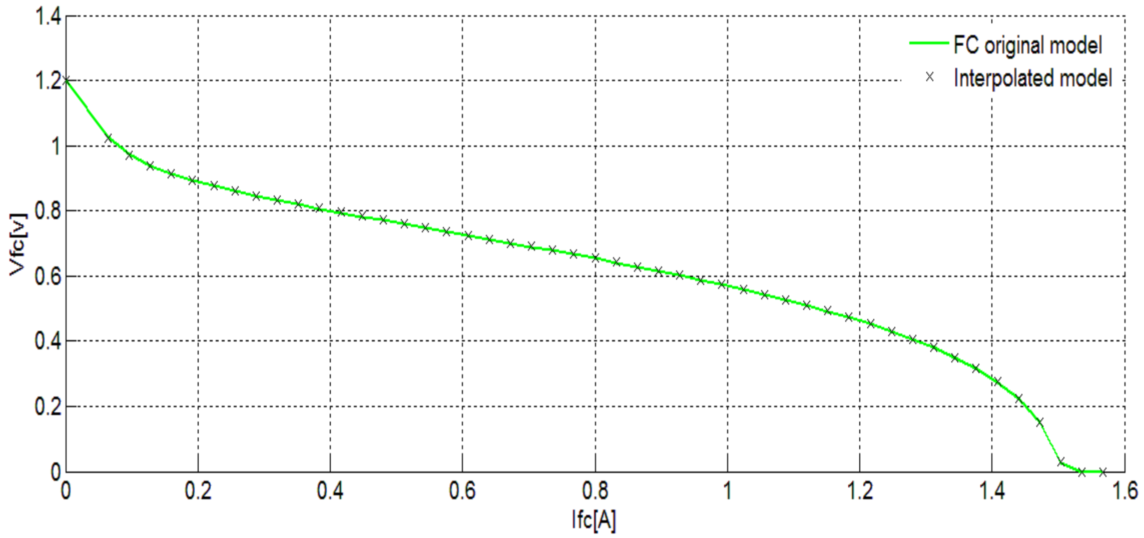


Fig 3.8 Comparison between FC interpolated model and originally proposed one

3.2.2 Hydrogen consumption model

The hydrogen consumption model of a fuel cell is based on the one defined in [27]. The relationship between the stack current of a fuel cell system and the molar flow fed to it, is defined as:

$$q_{H2} = \frac{N_o * I}{2 * F * U} \tag{3.16}$$

Using this equation the flow of hydrogen can be used to control the power output from the fuel cell.

3.2.3 Fuel cell implementation and control

The model of the fuel cell system with control loop with power set point input,”Pset”, is shown in Fig 3.9. The maximum output power of the fuel cell system is chosen to be 500kW for the model validation. This way, it will always be limited at this value for the energy supplied to the grid.

Another input reference signal is used in order to determine if there is enough hydrogen in the storage. If there is no hydrogen gas in the storage, the system set point for the power will be zero and it will not produce any power. Once the storage is empty, the fuel cell shut downs thus providing no power to the grid.

For the control feedback loop, a proportional-integral (PI) lag controller is used in order to follow the required reference value. The main inputs for the fuel cell system block are:

- Power set point to follow “Pset”. The set points for the power to follow can be the power shortage in the grid or spot market for electricity prices in order to generate financial income using the system.
- Signal from the storage unit monitoring hydrogen gas levels.

The main output values for the fuel cell system are:

- Power generated from the fuel cell system to the grid “Pfc”
- Hydrogen consumption of the fuel cell

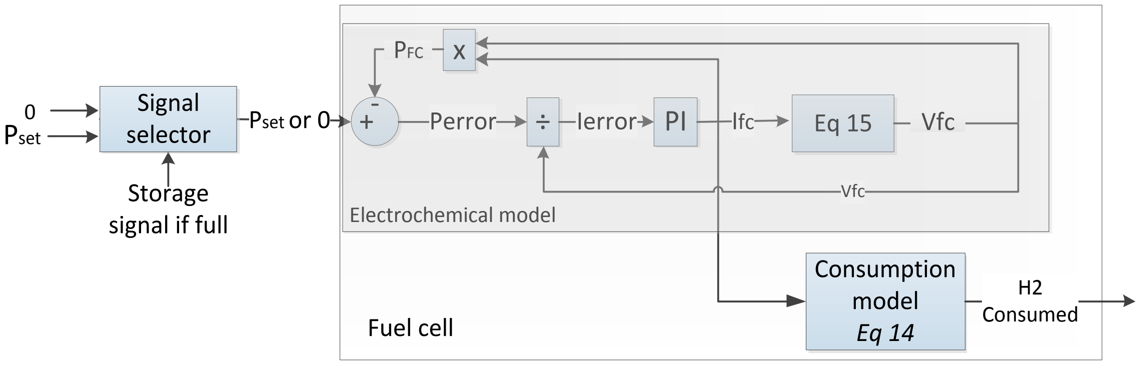


Fig 3.9 Fuel cell system model with implemented control

The consumption levels for a 500kW fuel cell stack can be seen in Fig 3.10. As the fuel cell is limited to 500kW, the generated power is kept at this level and not reaching the set value given as a reference. On the first part of the plot, the load response of the implemented FC system is shown. The consumed hydrogen from the system can be observed accordingly in the second part of the plot.

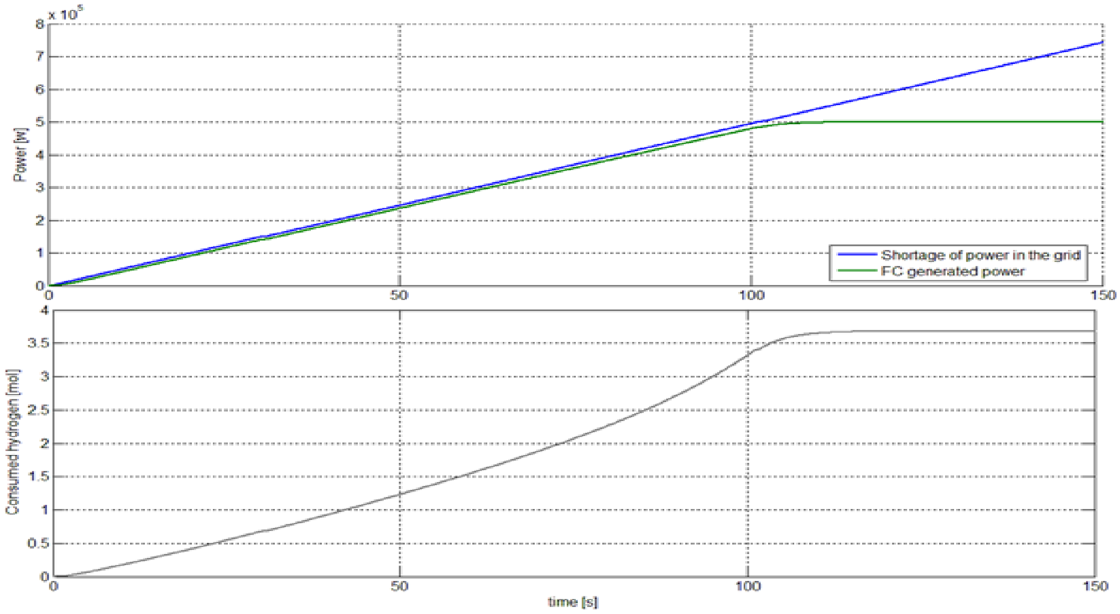


Fig 3.10 Fuel cell hydrogen consumption based on the output power from it

Based on the acquired results from the fuel cell consumption ratios and alkaline electrolyser hydrogen generation ratios, the efficiency of the system can be defined. The overall electrical efficiency of the system can be represented as the power generated from the hydrogen system and the power given to it:

$$\eta = \frac{P_{H2\_in}}{P_{H2\_out}} = 0.369 \tag{3.17}$$

Where “P_{H2_in}” is the power fed to the system, while “P_{H2_out}” the power received back.

3.3 Storage unit modelling

The proposed storage model is based on the requirements for storing pressurized hydrogen in a tank unit. The control for the storage unit is achieved via monitoring the pressure in the tank. When the generated hydrogen fills up the storage tank and reaches the limit value for the maximum pressure, the system sends a reference signal to stop the electrolyser. On the other hand, the current amount of hydrogen in the storage unit is also monitored. Once the hydrogen pressure levels reach zero, a signal is send to the fuel cell to shut it down. The equation representing the stored hydrogen inside the tank has the following form:

$$H2_{stored} = \int q_{H2\ generated} - \int q_{H2\ consumed} \tag{3.18}$$

The implemented model of the storage unit can be seen in Fig 3.11. It should be noted that at this point the exact size of the storage is not yet defined. The size of the storage will be chosen after conducting the long-term analysis of the system with the network under study. The used sizing for the hydrogen tank in this section is chosen arbitrary in order to show how the model is implemented as well as its overall behaviour.

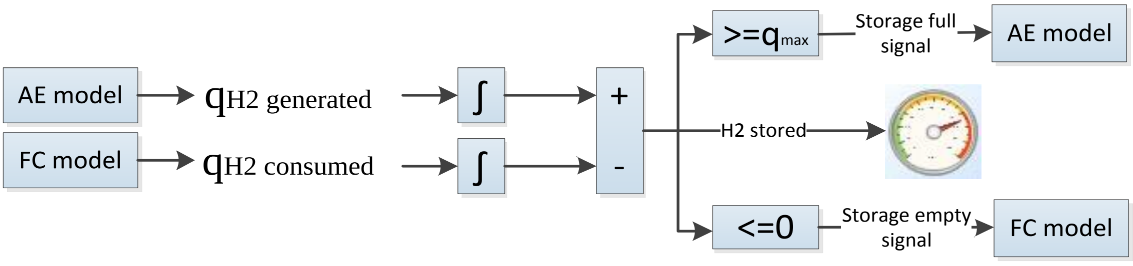


Fig 3.11 Storage unit model

The main inputs for the storage unit system are:

- Hydrogen generated from the electrolyser model $q_{H2generated}$;
- Hydrogen consumed from the fuel cell model $q_{H2consumed}$.

The main output values for the storage system are:

- Control signal to the alkaline electrolyser system that the storage is full;
- Control signal to the fuel cell system that the storage is empty.

The model stores the given signal for the generated and consumed hydrogen from the AE and the FC system. The stored hydrogen signal "H2stored" is then compared to the maximum volume of the tank "q_{max}" and zero. If the signal fulfils the given conditions for the hydrogen level, a signal is sent to one of the systems AE or FC to state that the storage is either full or empty.

In the following Fig 3.12, the control implemented for the storage can be seen. In order to show the behaviour of the system, the storage is set to a 100 kg capacity. Thus, when the stored hydrogen reaches 100kg, the control sends signal to the system to stop the alkaline electrolyser. When the fuel cell is turned on, it starts to consume hydrogen from the storage and when the storage is depleted, the control turns off the fuel cell.

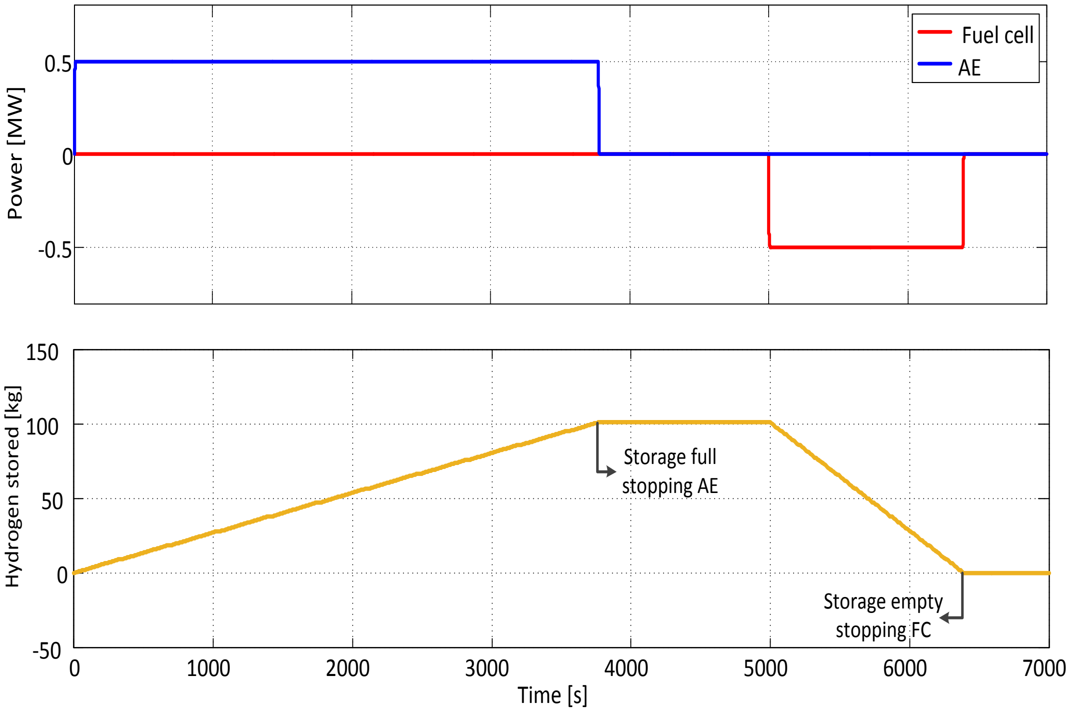


Fig 3.12 Storage unit control

3.4 Conclusions for the system modelling

In this chapter, a mathematical model for the proposed hydrogen system was presented. The modelling was divided into three sub-models, each representing one of the sub-systems of the hydrogen system; these were namely:

- Alkaline electrolyser model;
- Fuel cell model;
- Storage unit model.

Based on the requirements of the project and the focus of the study, only the most relevant parts of the models were used. Block diagrams describing each sub-system were defined and explained explicitly in order to demonstrate the physics behind each of the models used. Afterwards, model verification using Matlab/Simluink was carried out. The results were compared to the expected values in order to verify the models and show their overall behaviour. Finally, the overall hydrogen system efficiency was defined based on the hydrogen gas consumption/generation ratios of the fuel cell and the alkaline electrolyser.

4 Grid Integration of Hydrogen System: Steady state analysis

This chapter describes the distribution grid used in the project study. An overview of the network and its main elements is presented. The grid location, characteristics and main points are described as well as the reasons for choosing this network.

In the second part of the chapter steady state analysis is carried out for the proposed network in order to define any possible issues and challenges it presents. Based on the findings from the base case steady state analysis the issues that can be solved using the proposed hydrogen system are defined.

Consecutively steady state analysis for the network under study implemented with the proposed hydrogen system is carried out. Different study cases are used in order to highlight the main operation points and limitations of the network and the hydrogen system. Based on the results from this study the sizing, location and control strategies to be implementing for the proposed system are defined.

Finally a conclusion regarding the most relevant findings from the steady state analysis is presented. It provides a summary of the main tasks and issues for the network under study and the proposed hydrogen system. Based on the findings from this chapter the control methods to be implemented in Chapter 5 are defined.

4.1 Network and data set description

The test case network chosen for the study is a 20 kV distribution network owned by Himmerlands Elforsyning located in Himmerland, Denmark. The single line diagram of the distribution system is shown in Fig 4.1 [28] [29].

The network consists of ten radial feeders rated at 20kV connected to it. However, considering the integration of the proposed hydrogen system the study will focus only on the SORP and STKV feeders.

One of the reasons for this choice is that detailed information for the consumption of the chosen feeders is available for the study. The second one is the variety of the users (households, industry commercial) and generating units (CHP plant, wind turbines, external grid) connected to this section of the grid. This will show how the proposed system will react to generation from different generation units such as renewable energy and a conventional combined heat and power plant. These two factors allow us to simplify the system to those two feeders on basis of their diversity in generation and consumption.

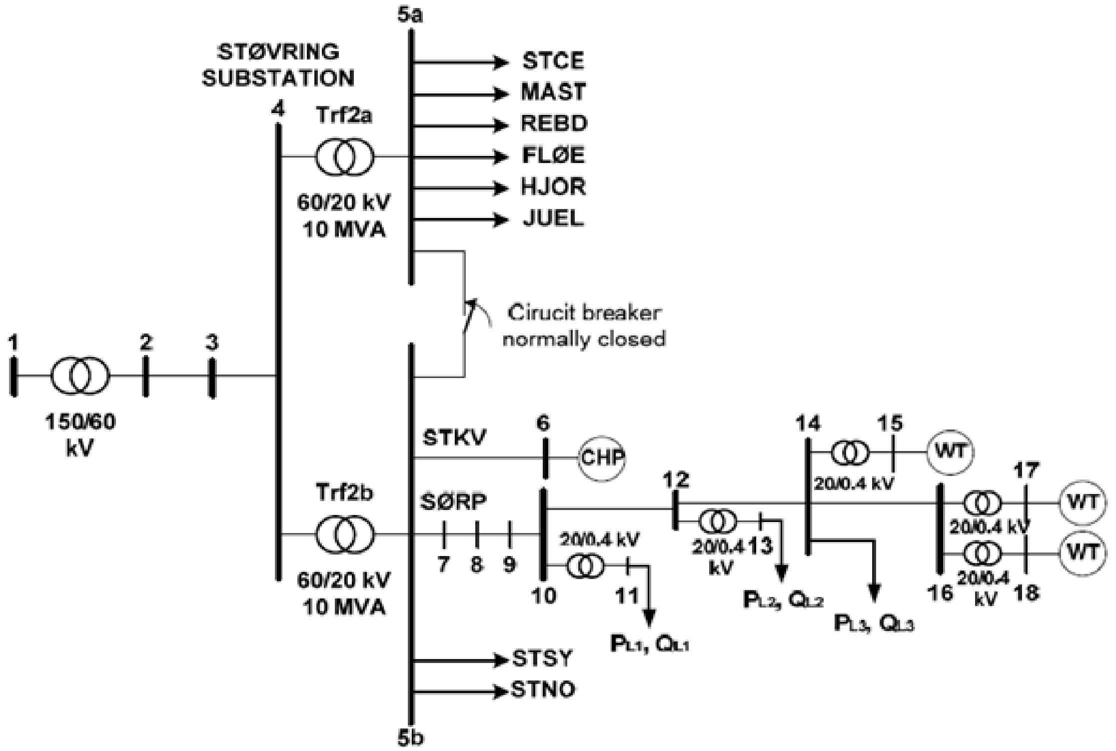


Fig 4.1 Network configuration of Stovring distribution system [29]

Fig 4.2 present the detailed network configuration for the Stovring distribution system and the 20kV feeders included in the study.

Over 221 users are connected to the SORP feeder through fifteen 20/0.4kV transformers distributed along the line. The connected users are a combination of industrial, commercial, agricultural and household consumers. At this feeder, 3 fixed speed wind turbines are connected to the network. All of the wind turbines are located in the same area and each of them is rated at 0.63 MW. However, in order to test the capability of the grid to handle high intermittent generation of renewable energy, the power ratings of the wind turbines have been increased to 2,5MW per turbine. The choice for the size is based on the averages size of the wind turbines installed in Denmark. As per the statistics released in 2015, the average wind turbine size in Denmark is 2,473 MW [30].

At the STKV feeder, a combined heat and power plant - CHP with 3 gas turbines is connected to the network. All the gas turbines of the plant are rated at the same power at 3MVA. The main operation of the CHP unit is based on the heating demand and electrical energy is generated only as a by-product. Hence the CHPs electrical generation does not follow the users demand patterns.

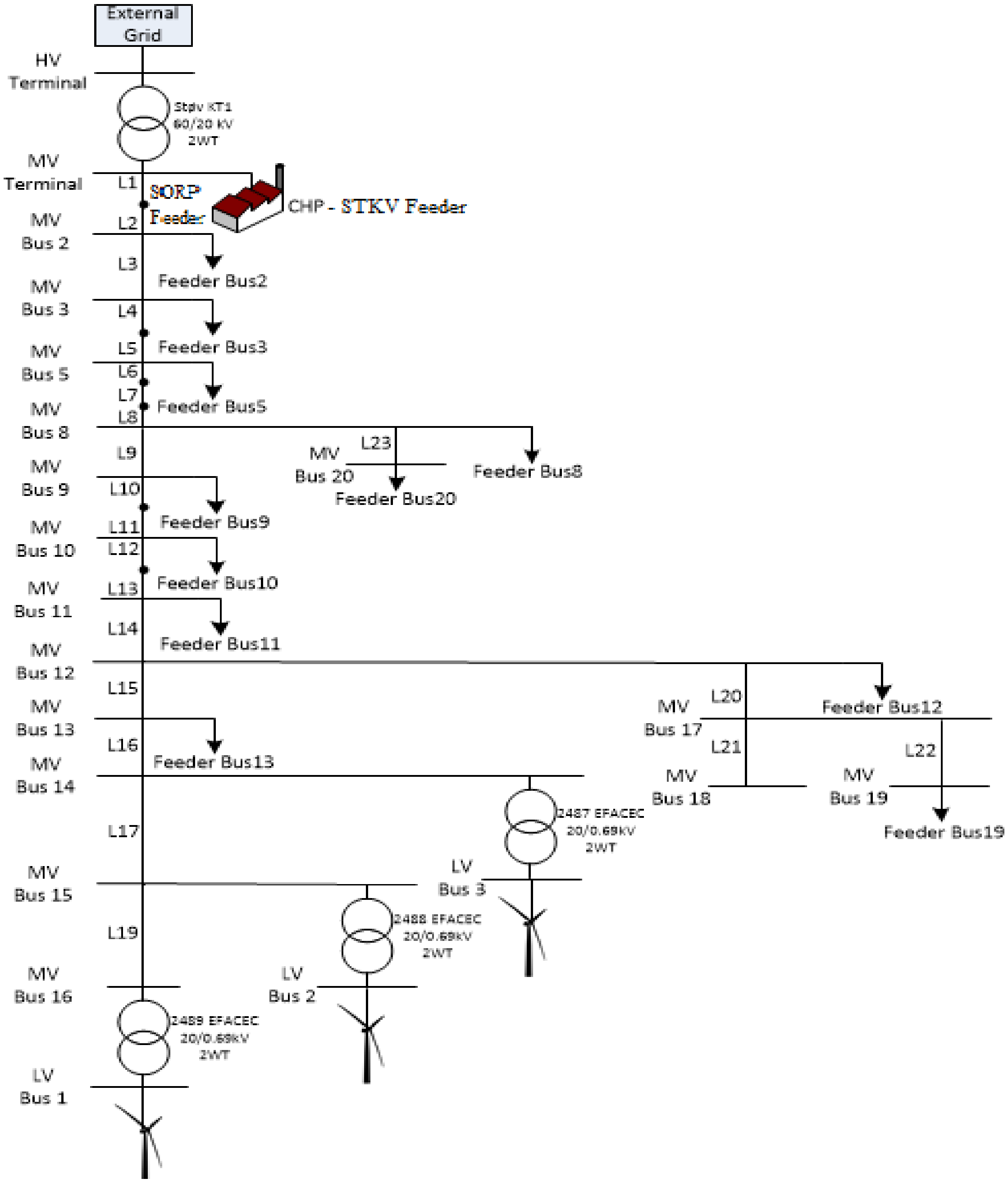


Fig 4.2 Network configuration of STKV and SORP feeders

For the purposes of the project, all of the loads connected to the network have a constant power factor of 0.95. Even though the connected users vary between households and industry, it is expected that the commercial users have an integrated system for power factor correction. Based on this it is assumed that all of the consumers have the same power factor value in order to simplify the system

The hourly load measurement for the users connected to the SORP feeder is available. Two different weekly load profiles have been chosen to test the network capabilities and detect any possible issues in the grid.

In order to test the system, the load profiles chosen to be used are from the first weeks of January and July 2012 accordingly. The load demand for the chosen time frame can be seen in Fig 4.3. As visible from the graphs, we can separate the load profiles into two categories.

- During January we have peak load values up to 1,2MVA and average value of 0,5MVA. This will be considered as a high feeder loading scenario for the network;
- July week load profile shows considerably lower load values, with peak values at 0.43MVA and average loading value at 0.3MVA. This load profile will be considered as a low loading feeder scenario for the network in our study.

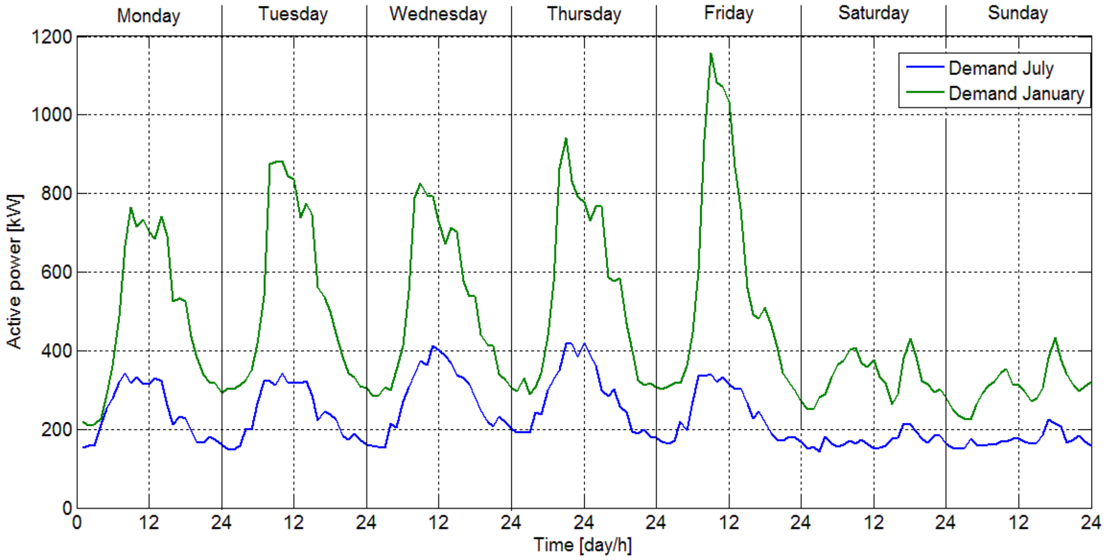


Fig 4.3 Load profiles for Storving substation SORP feeder

4.2 Steady state analysis of the grid - base case

In order to analyse how the grid behaves under high and low load conditions, a steady state analysis of the network was carried out. Its focus is to show how the network responds to the different generation and consumption levels of the CHP, wind turbines and loads. From this analysis, any network violations beyond nominal operating limits will be defined.

The main parameters of interest for the grid analysis are the loading of the lines and the voltages at the local buses. For the study, the limits for the voltage at the buses have been decided to be ± 4% for the medium voltage buses and ± 6 for the low voltage buses based on the power quality requirements [31] .

Two different operating scenarios for the network are chosen to show how it behaves under the worst operating conditions, namely:

- Scenario 4.1 - Minimum loading in the grid with maximum generation from the CHP and the wind turbines. The obtained data from this scenario will show the capability of the system to handle high power generation from the local generators. The voltage deviations of the local buses and the loading of the lines will be the main points of interest for this case.
- Scenario 4.2 – Maximum grid loading from the feeders without internal generation from the CHP or the wind turbines. This scenario will test the robustness of the distribution network fed only from the external grid. This test case scenario will show any potential lack of enough power feed from the external grid and possible voltage drops at the local buses in the grid.

4.2.1 Steady state analysis of the grid scenario 4.1 – minimum loading

For this scenario the demand of the grid is chosen to be the minimum value available from the demand data of the feeders. As it can be seen from Fig 4.4, the minimum loading of the feeders occurs in July, Saturday at 02:00 AM. The demand at this point is at its minimum at 142 kW distributed between all of the feeders in the grid.

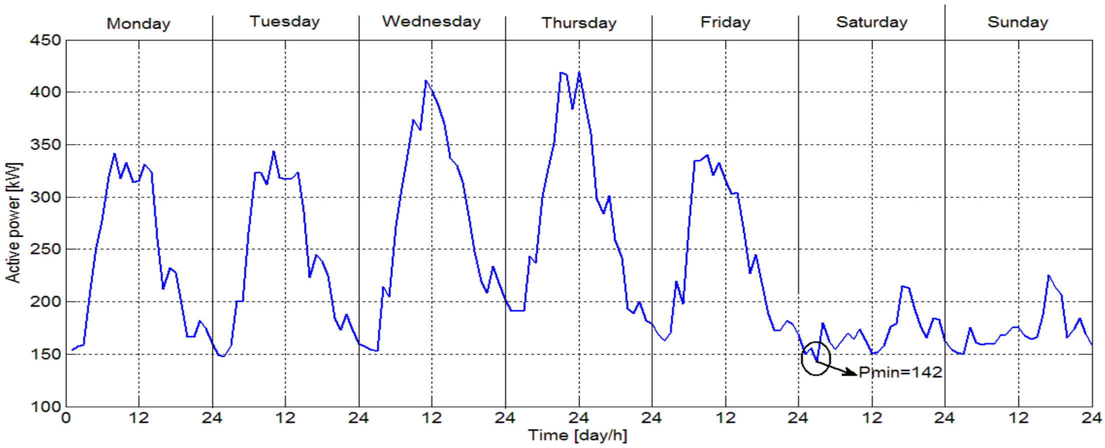


Fig 4.4 Minimum loading of feeders in July

The generation for the internal power units of the distribution grid is set to be at their maximum operational limits accordingly:

- Combined heat and power plant generating at its peak operating point at 3x3MVA;
- Wind turbines operating at optimal wind penetration level generating 3x2,5MW of power into the grid.

The loading of the lines and the transformer for the minimum feeder loading scenario can be seen in Fig 4.5

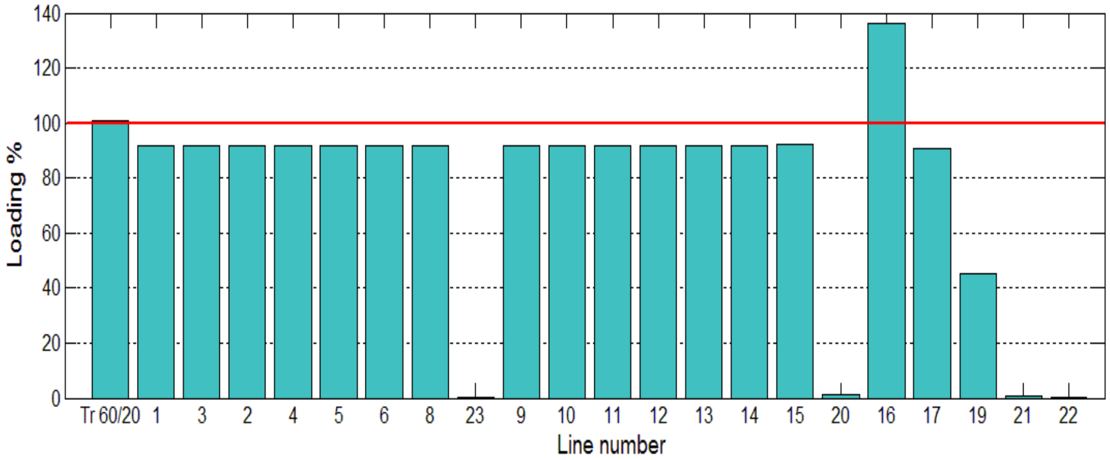


Fig 4.5 Loading of the lines with minimum feeder consumption

From Fig 4.5, it can be observed that most of lines are loaded to levels close to their maximum operating capacity. Line 16 is loaded over its maximum capacity and the external transformer is operating at its peak limit. The reason for such high loading is the low consumption in the network and the overgenerated power that has to be transferred through the external grid causing congestions.

The bus voltages for this study case can be seen in Fig 4.6

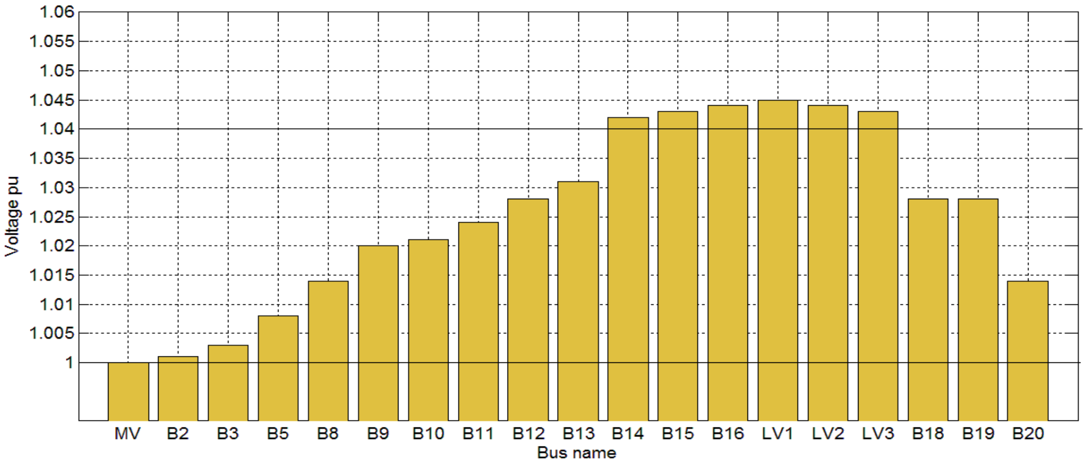


Fig 4.6 Bus voltages at minimum loading of the feeders

The plot illustrates the voltage at the buses increasing up to 4.5% of its nominal value due to overgeneration of power in the network. Such voltage rise is observed when the local demand of the buses is not enough to consume the generated excess power in the network. This causes the electricity to flow in opposite direction compared to the normal operation and lead to increase in the bus voltages.

The increase on the buses is exceeding the predefined limit of ± 4% for medium voltage. Hence the proposed hydrogen system will be implemented in order to decrease the overvoltage under the predefined operational limits

From the data it can be concluded that the buses with the highest voltage increase are located close to the wind turbines' connection points. In order to test how much the CHP plant and the wind turbines are affecting this voltage increase, a simulation in which the CHP generated power is set to zero is conducted. The voltage for the buses with and without the CHP generating can be seen in Fig 4.7.

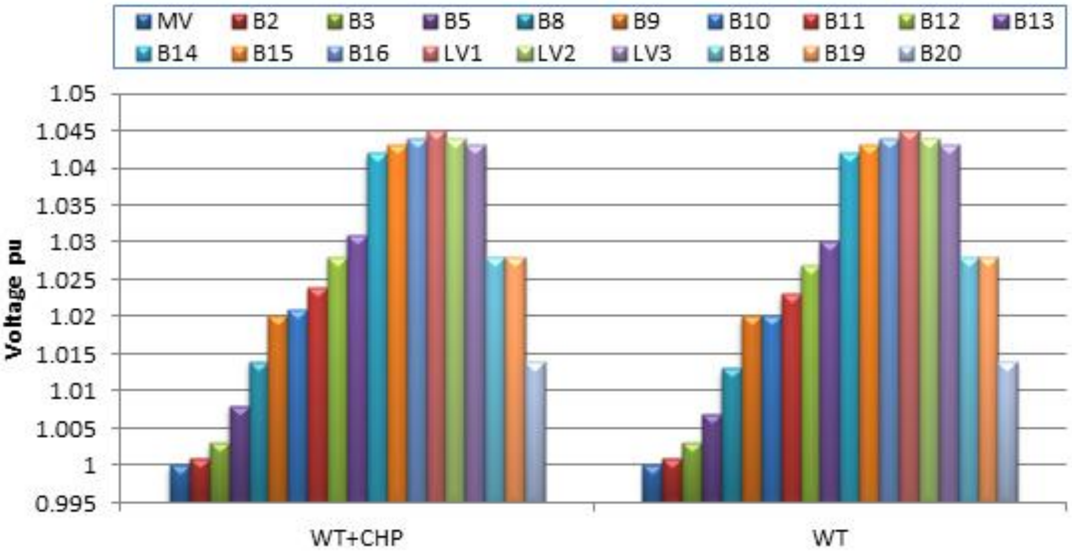


Fig 4.7 Bus voltages for CHP+WT generation and only WT generation

As the obtained data shows, the voltage change on the buses with and without the CHP generating in the network is very small. Such an increase is too insignificant to have any negative effect on the integrity and capability of the network. From this, it can be concluded that the increase of the bus voltages is mainly due to the wind turbine local excess power generation in to the network. Therefore, the main focus of the hydrogen system will be to reduce the excess power generated locally. By following this strategy the voltage increase will be brought under the predefined operational limits.

4.2.2 Steady state analysis of the grid scenario 4.2 – maximum loading

For this operating scenario the demand of the feeders is chosen to be the maximum value from the available demand data. As it can be seen from Fig 4.8 the maximum loading of the feeders occurs in January, Friday at 08:00 AM. The demand at this point is at its peak at 1158 kW distributed between all of the feeders in the network.

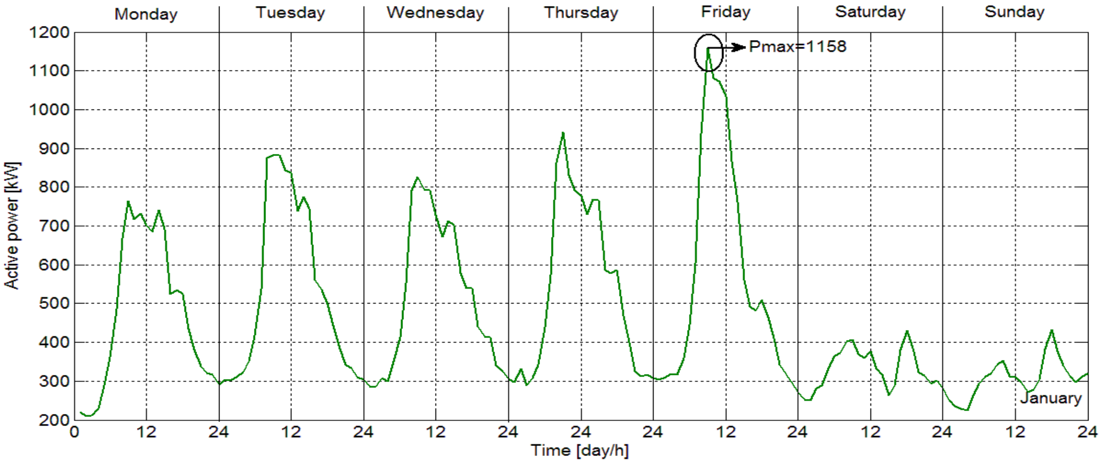


Fig 4.8 Maximum loading of feeders in January

The generation for the internal power units of the distribution grid is set to be at their minimum operational limits accordingly:

- Combined heat and power plant generating 0 power;
- Wind turbines operating at no wind scenario generating 0 power into the grid.

The grid loads are will be supported only from the external grid connection.

The loading of the lines and the transformer for the maximum feeder loading scenario can be seen in Fig 4.9.

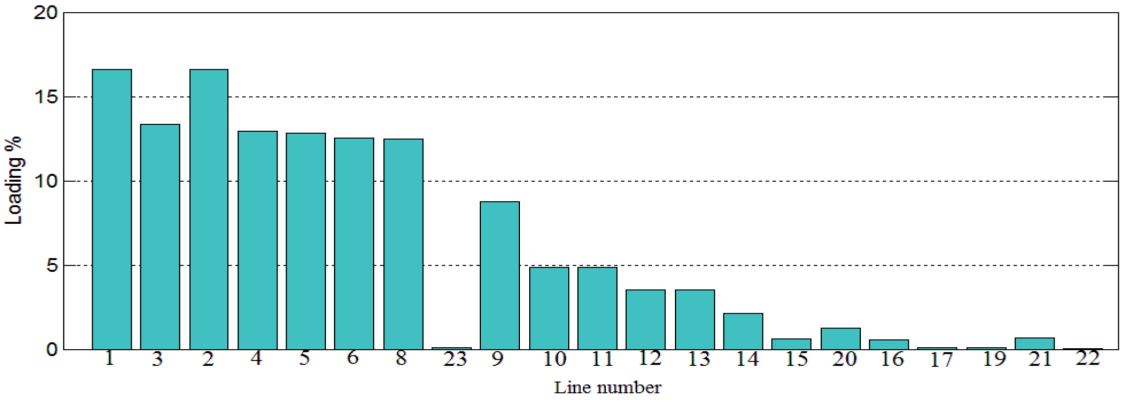


Fig 4.9 Loading of the lines with minimum feeder consumption

As observed from Fig 4.9 the loading for the lines is low (not exceeding 20 %.) The reason for this is that no excess power is flowing through the gird. The only power transferred in the grid is from the external network to the feeders. At such low loading levels of the lines no additional issues or problems for the grid would be observed.

The bus voltages for this operating scenario can be seen in Fig 4.10.

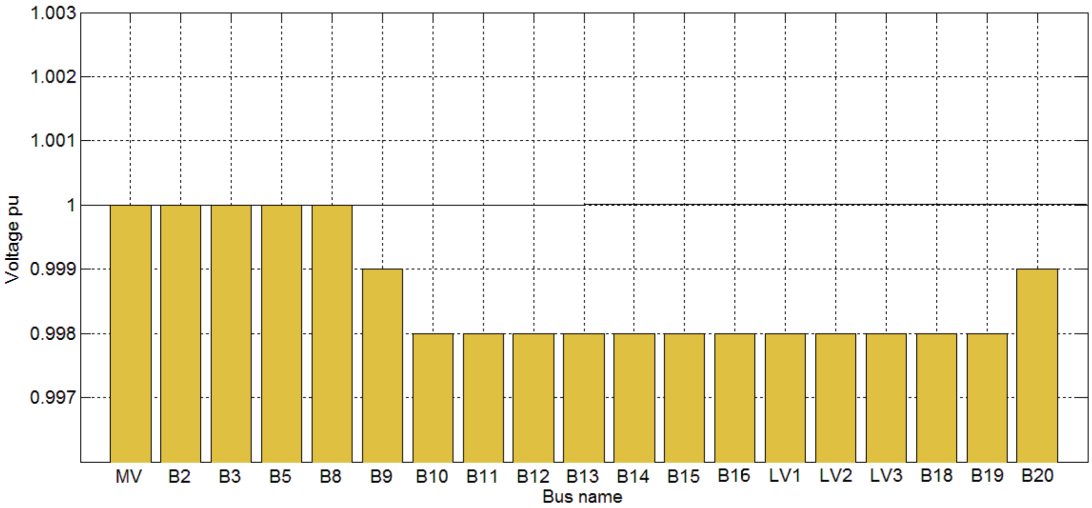


Fig 4.10 Bus voltages at peak loading of the feeders

The plot makes it visible that the bus voltages are decreasing along the network. However, the decrease is less than 1% - something, which is inside the predefined limits of ± 4 % and at such low voltage drop, no additional issues in the grid are expected.

From the obtained data for the line loading and bus voltages, it can be concluded that the network for the Sorup substation and the external grid is very strong. The voltage levels are kept at their nominal values with negligible deviation along some of the buses. The external network is more than capable to cover the generation's needs for SORP feeder and its consumers.

4.3 Hydrogen system steady state analysis

For the integration of the proposed hydrogen system, its sizing and location have to be defined. In order to define them, scenarios with different sizing and location of the system have to be analysed. The main issues defined from the steady state analysis of the grid are overvoltages at the buses and high loading of the lines. Thus, the focus of the proposed system will be:

- Reducing the deviation of the bus voltages to ± 4% at medium voltage buses and ± 6 at low voltage buses as main target;

- Lower the loading of the lines in the network as supplementary target.

In order to solve the problem with the overvoltages during peak generation, an analysis is conducted with different hydrogen system power levels and its location. The system is placed in the proximity of the most affected busses in the network. The chosen potential busses for the system are MVBus13, MVBus14 and MVBus15 which can be seen in Fig 4.11.

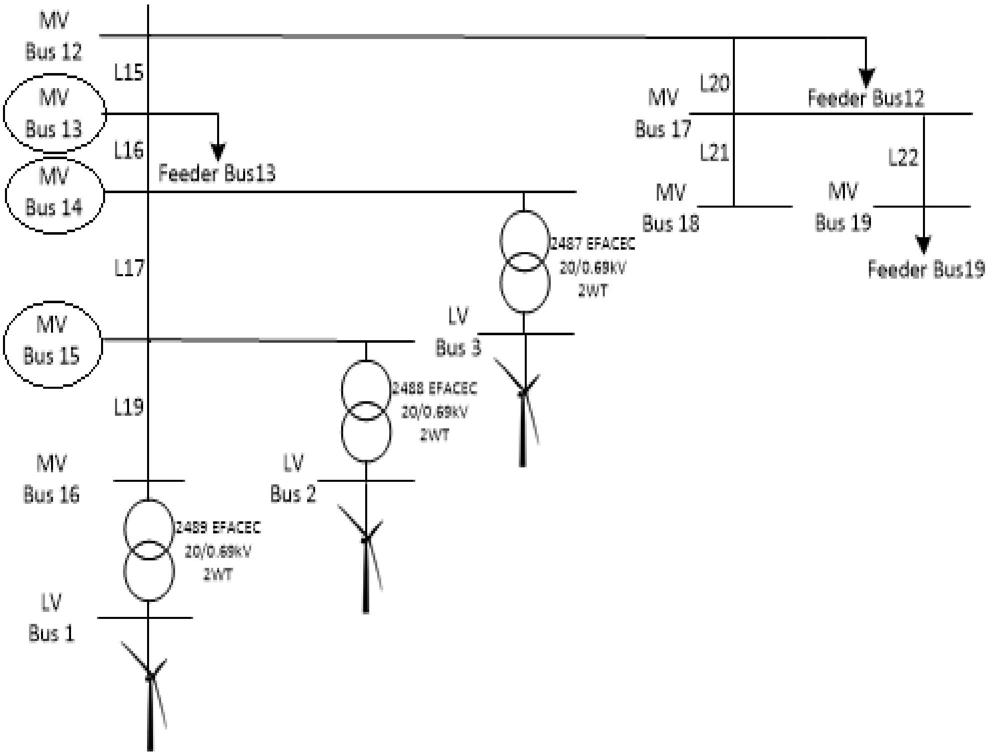


Fig 4.11 Bus selection for the hydrogen system

After connecting the alkaline electrolyser to the designated bus, its power is steadily increased until the bus voltages deviations are reduced below the predefined levels.

The results for the bus voltages for the different bus connections and alkaline electrolyser power sizes can be seen in Fig 4.12.

The obtained bus voltage data illustrates that the optimal results are obtained connecting the alkaline electrolyser to buses B15 and B14. At these connections the required amount of power to be consumed from the alkaline electrolyser decreasing the overvoltages under 4% is 0,8MVA. Meanwhile, a connection at B13 requires the power rating of the alkaline electrolyser to be at 1,1MVA.

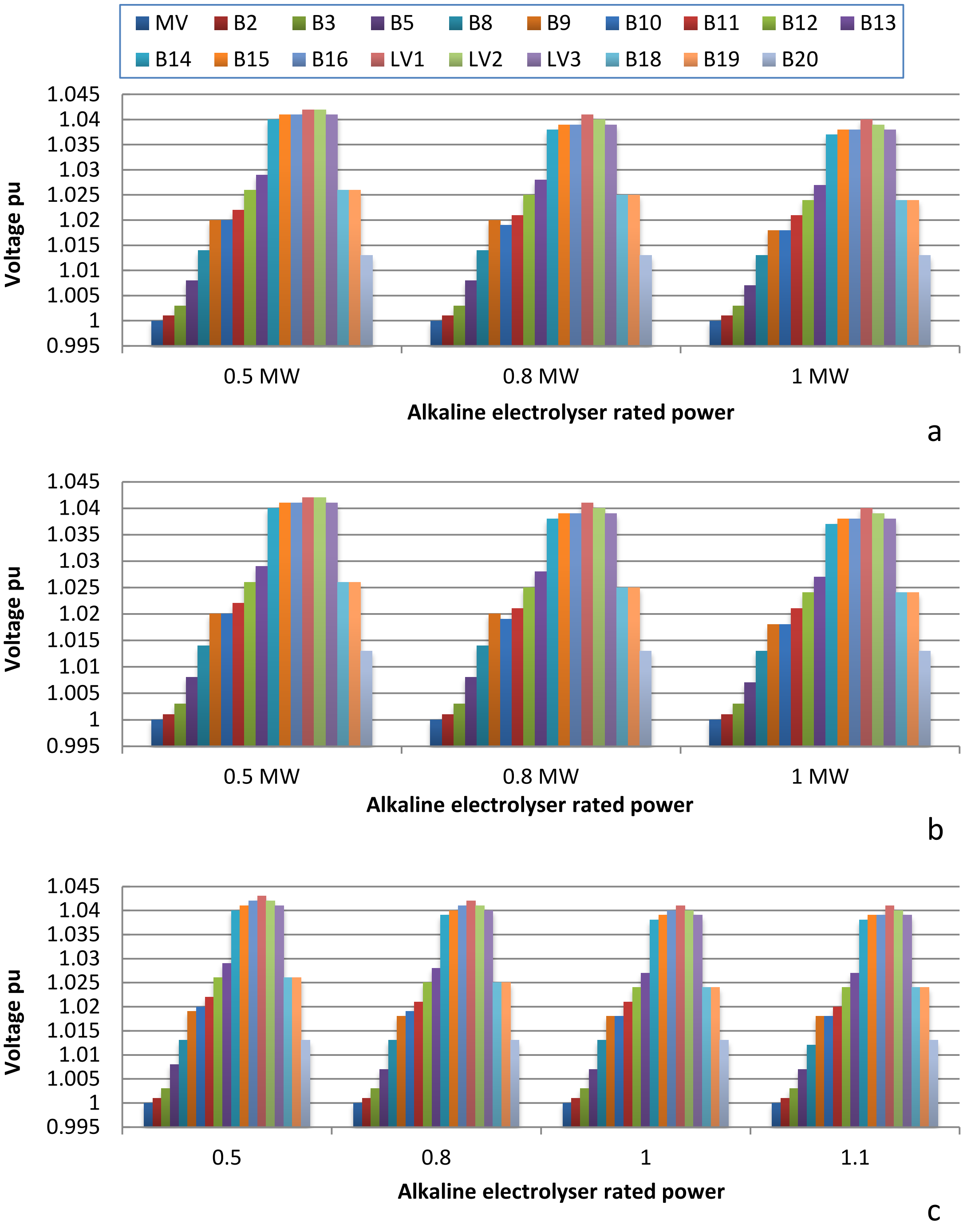


Fig 4.12 Bus voltages at different alkaline electrolyser connections and power levels connected at B15 b) connected at B14 c) connected at B13

Consequently, the choice for the bus connection for the hydrogen system lies between buses B15 and B14. In order to assess which of the buses to be used the loading of the lines with the two different points of connection is analysed.

Fig 4.13 shows the line loadings for the system connected at B14 and B15.

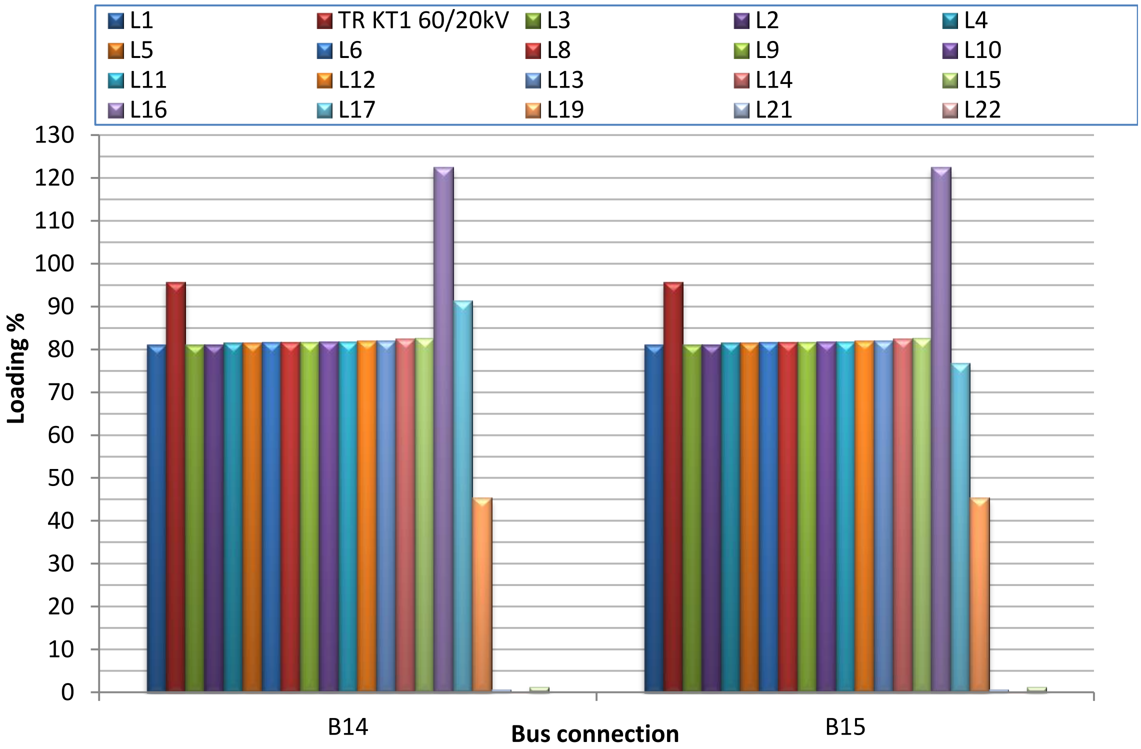


Fig 4.13 Loading of the lines for different points of connection for the alkaline electrolyser

As visible from the line loading data most of the lines have identical loading values for the 2 different points of connection. However, when connected to B15, line 17 is loaded at 76% while at B14 the loading is 92%. Hence B15 will be chosen as a point of connection for our system as its decrease in line loadings is higher than if connected at B14 bus.

4.4 Conclusions from the steady state analysis of the network

From the steady state analysis of the network several problems in the network operation were found. For the scenario with the grid operating at peak generation, three different issues were defined:

- Increase of the bus voltages over maximum operational limits for the network;
- Very high line loading reaching over 100% for some of the lines due to congestion in the grid;
- Peak loading for the external grid MV/HV transformer.

Following an analysis of the power flow in the grid, it has been concluded that even at peak generation from the CHP unit, it has a negligible effect on the bus overvoltage. The reason for this is the CHP unit's close connection to the external grid for transferring the excess power. The main cause for the bus overvoltages was defined to be excess power generation from the 3WT located at the bottom of the grid. Therefore, high local increase of the bus voltage can be monitored in close proximity to the wind turbines connection point.

The main task is to decrease the deviation for the bus voltages into the required limits of ± 4% of the nominal value. It has been analysed that an alkaline electrolyser system with 0,8MVA power rating should be connected at MVBus 15 in order to achieve those limits. Connecting the system to any of the other buses will require bigger power rating in order to achieve the same amount of voltage decrease.

Connecting the 0,8MVA alkaline electrolyser system will also decrease the line and transformer loadings with up to approximately 10% of their initial value. Nonetheless, it should be noted that line L16 is still loaded with more than 100% of its peak value.

The analysis of the high loading of the grid scenario showed a deviation for the bus voltages of less than 1% which lies in the predefined limits. The loading of the lines and the transformer is also kept at low values not exceeding 20%. Based on these results, it may be concluded that the external grid supplying the network is extremely strong and more than capable to meet its load demand. No additional issues were defined in this test scenario.

Taking into consideration the lack of issues that would require additional generation of power into the system. The analysis for the role of the fuel cell will be conducted in the long-term dynamic analysis of this study in the next chapter. Based on the accumulated amounts of hydrogen gas, the role of the fuel cell in the system will be defined. The potential roles for the fuel cell in the system that should be considered in the dynamical analysis are the following:

-Voltage regulations of the local buses;

- Power flow balancing;

- Back up power generation for the grid in case of zero local generation and disconnection of external grid scenario.

5 Control Strategies and Grid Support using Hydrogen System

In Chapter 4 the steady state analysis of the grid was conducted. However, in order to investigate the long-term behaviour of the grid with the hydrogen system, a dynamical study is carried out. It is conducted in order to further analyse and verify the issues defined in the steady state analysis and how the system responds in a weekly time frame. Based on the obtained results any additional limitations for the system are defined. Secondly the production/consumption ratios for the hydrogen generation are evaluated and based on them the storage strategy used for the hydrogen gas is chosen.

The grid under study is tested using one week data for the power consumptions and generations in the system. This chapter is focused only in solving technical problems that occurred during the operation of the network and how the proposed hydrogen system is able to solve them.

First, the hydrogen system model presented in Chapter 3 is implemented in the test network under study. The controls implemented for the system are explained along with their main input and output signals.

In the second part of the chapter, the network under study is tested in the absence of the hydrogen system. The purpose is to assess its overall long-term behaviour.

Next, the network response is tested in presence of the alkaline electrolyser. Following the results from this study and the amount of hydrogen generated, the hydrogen storage is sized accordingly.

The last part of this chapter analyses the role of the fuel cell in the distribution system (voltage support, backup power or load balancing). The fuel cell is assessed based on the overall hydrogen generation/consumption rates and the issues defined in the distribution grid analysis it could solve.

5.1 Network control model of the hydrogen system

A detailed explanation of the hydrogen system proposed has been provided in Chapter 3. This section, however, shows how such technology gets integrated in the grind under study with the implemented control strategies.

5.1.1 Hydrogen system control

Two types of control are implemented for the hydrogen system based on the findings in Chapter 4:

- Voltage deviation control;
- Local power management control.

Based on the network issues monitored in the grid, the DSO or the owner of the hydrogen plant may choose which control to use. For example the DSO may want to implement both types of control for maximum support of the grid. On the other hand, a private owner may choose to implement only voltage control and utilize the generated hydrogen gas elsewhere.

It is possible to use both controls at the same time; however, the voltage deviation control will always have higher priority as it is acting as technical support for the grid. Voltage control is implemented locally for the system and follows the control signals for the implemented network while the local power management retains the capability to follow external signals and follow external power flow signals.

- Voltage deviation control

This control strategy is focused on limiting the deviations of the bus voltages in the network. The main purpose of this control is to use the hydrogen system to bring down the voltage deviations to under 4% for the medium voltages buses and under 6% for the low voltage buses. The system monitors the voltages for all of the medium and low voltage buses of the network. Once the voltage fluctuates over the limit, the hydrogen system will be started in order not to allow further deviation. Depending on the voltage deviation, the system will choose which subsystem to start. For overvoltages the alkaline electrolyser is used, while for undervoltages the fuel cell is started. The set points for the hydrogen system to follow for this control are the following:

$$0{,}96 \leq V_{MediumVoltage}^{set} \leq 1{,}04$$

$$0{,}94 \leq V_{LowVoltage}^{set} \leq 1{,}06$$

The block diagram representing the voltage control implemented can be seen in Fig 5.1.

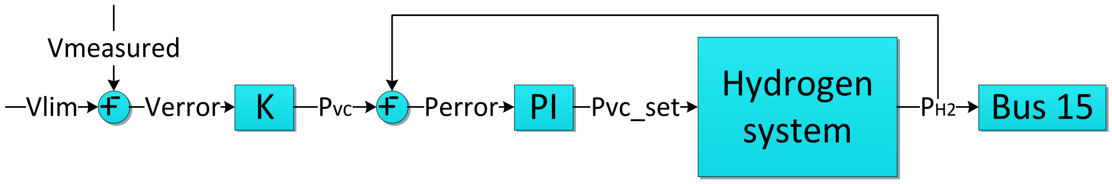


Fig 5.1 Voltage control block diagram

The power set point given to the hydrogen system from the voltage control is defined as:

$$P_{vc} = (V_{lim} - V_{measured}) * K \tag{5.1}$$

Where "V_{lim}" is the bus voltage limit of ±4% and "$V_{measured}$" is the measured highest bus voltage in the network. Based on the voltage devitiona a power reference value for the system is calculated

- Local power management control

This control is based on the local distribution system balancing in the grid and maximum hydrogen production. When activated the system monitors the generation from the connected wind turbines, the power flow from the external grid and the consumption in the network. The set point for the power given to the hydrogen system from the local power management control is defined as:

$$P_{pm} = P_{Wind\_Turbines} - P_{Consumption} \tag{5.2}$$

The block diagram representing the local power management control can be seen in the following Fig 5.2

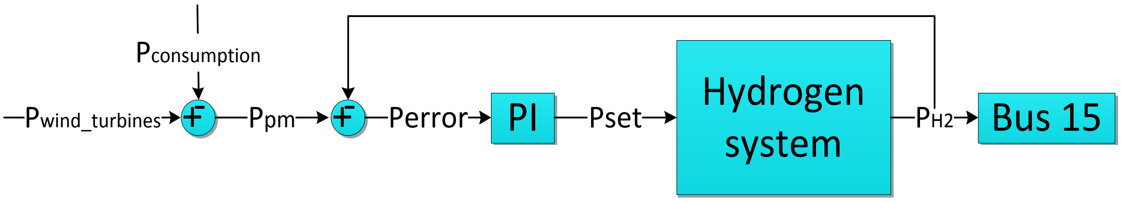


Fig 5.2 Local power management control block diagram

Once the system detects overgeneration, it will start the electrolyser in order to produce hydrogen gas. This way excess energy from wind power will be used for hydrogen production. On the other hand, if the system detects shortage of infeed from the network generators (CHP and wind turbines), it will support the network using the fuel cell. This would allow the system to be able to sustain itself without additional power from the external grid using the fuel cell as a backup power source.

The power set point for the hydrogen system to follow when both types of control are implemented is defined as:

$$P_{set} = \begin{cases} P_{vc}, & V_{bus} \geq 1.04 \\ P_{pm}, & 0.96 < V_{bus} < 1.04 \end{cases} \tag{5.3}$$

5.1.2 Hydrogen system implementation

Additional modelling blocks are required in order to convey the signals between the hydrogen system and the network model. The integration of the proposed hydrogen model together with the main control signals in the test case network presented in Chapter 4 Fig 4.2, connected to MV Bus15 can be seen in Fig 5.3.

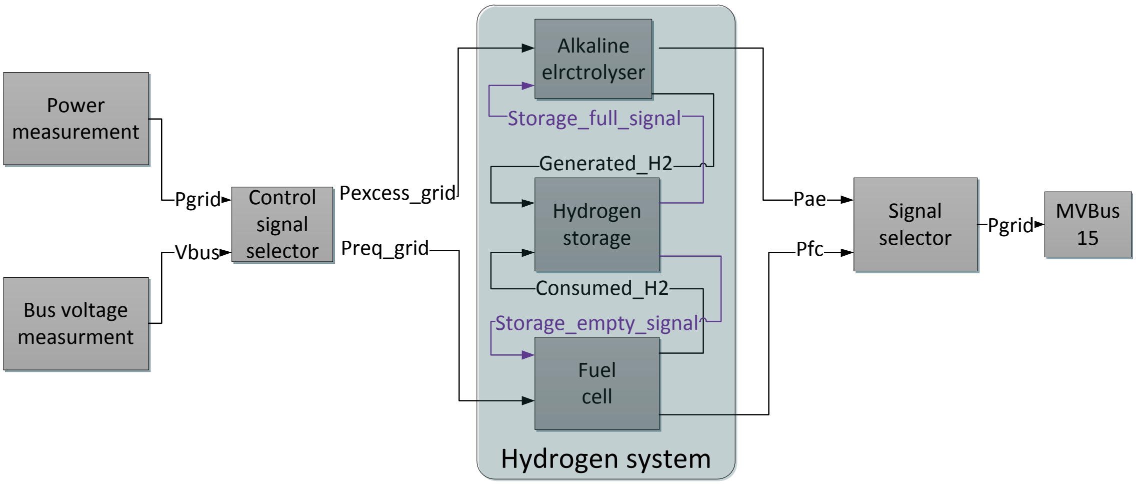


Fig 5.3 Hydrogen model network implementation

The supplementary blocks used for conveying the network signals to the hydrogen model are the following:

– Power measurement – measures the grid power flow (generated power from WT+CHP plant, consumption of the network and infeed from the external grid), its output “Pgrid” is the active power flowing in the network;

– Bus voltage measurement – monitors all of the bus voltage levels in the network. The measured points are the medium voltages buses in the grid and the low voltage buses of the connected wind turbines. The output of the block “Vbus” is the highest/lowest bus voltage in the network.

– Control signal selector – based on the control used for the hydrogen system, it decides which of the input reference signals to output. When voltage control is selected the system monitors the “Vbus” signal and outputs the power set point based on the voltage value. When local power management control is used, the block outputs the set point based on the “Pgrid” signal. At cases when both controls are used, the block outputs the set point based on the local power management control. However, if deviation from the bus voltage limitation is detected, the block starts to follow the voltage control set point signal. The block is defined by equation (5.3)

– Signal selector – this block is required in order not to mix the signals between the alkaline electrolyser and fuel cell to the grid. The block outputs the power difference between the 2 values:

$$P_{grid} = P_{AE} - P_{FC} \tag{5.4}$$

5.2 Distribution grid analysis base case

In order to analyse how the hydrogen system contributes to the network and affects the whole grid, first a base case analysis without implementing it is conducted. The scenario used for this test case is the one defined in Chapter 4 based on the steady state analysis as:

- Scenario 5.1 - Minimum loading of the grid with high wind penetration (high power generated from the wind turbines).

As it was found in the steady state analysis of Chapter 4, due to increase of wind power in the generation, local overvoltages are one of the technical bottlenecks for such a network. The same scenario will be used for the base case dynamical study of the network. The purpose is to see how frequent overvoltages in the system occur as well as the power flow of the network.

In order to assess the same case scenario during the long-term dynamical study, load profiles for peak generation in the grid and minimum loading of the feeders are used.

The demand profile for the feeders chosen for this case should have low consumption. As it was defined in Chapter 4, the first week of July has the lowest peak and overall consumption values for one week available. That is why this load profile is used for this study case. The demand data for the chosen profile can be seen at Fig 5.4.

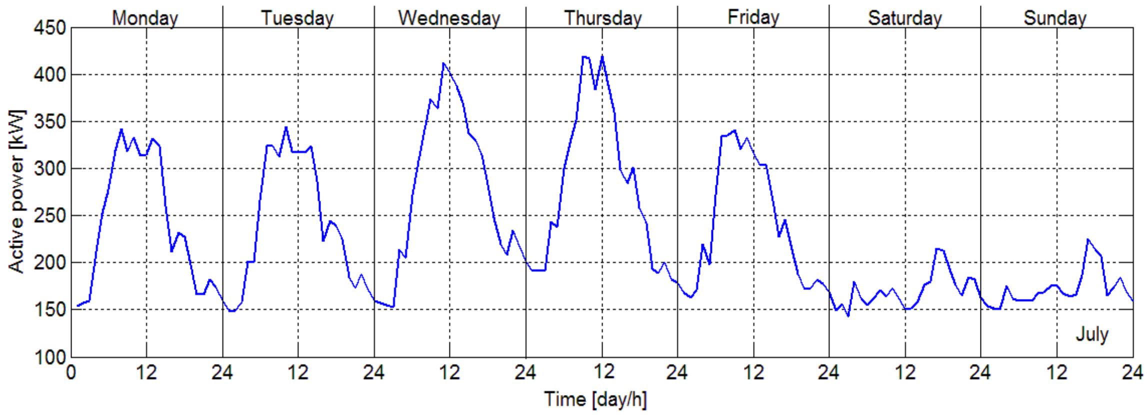


Fig 5.4 Feeder data July

As it can be seen from the plot, this week provides sufficiently low load demand for the system with frequent minimum values of 150 kW and an overall consumption of 250 kW during the week. The weekend is characterised with even lower overall consumption with peaks of no more than 220 kW.

The profile for the power generated from wind turbines was set to follow high wind penetration profile. Data for the profile was obtained from [32] using measuring station located in Aalborg with 15 minutes sampling time.

The chosen wind profile is unique by having high alternating peak values during the week. Generated amount of power for one wind turbine connected to the network following the high wind penetration profile is shown in Fig 5.5.

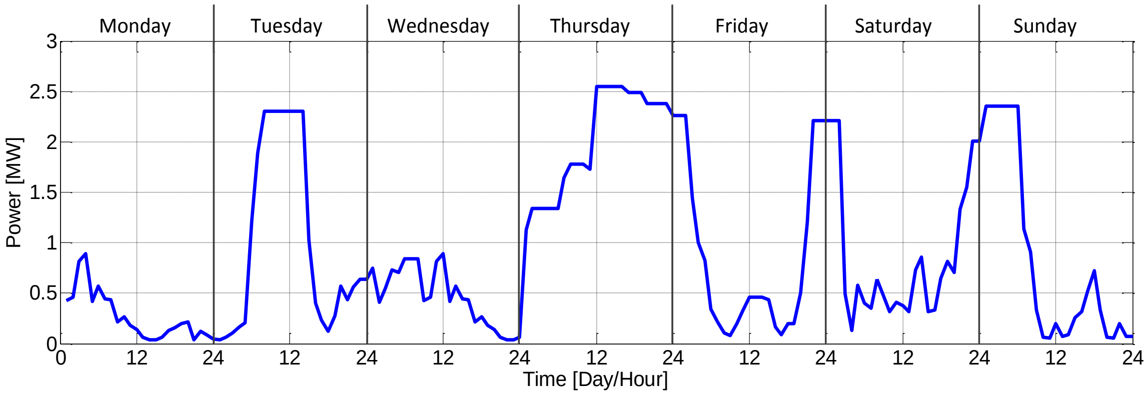


Fig 5.5 Wind turbine power generation – high wind penetration

The bus voltages and the power flow from implementing this high generation/low demand operation scenario can be seen in Fig 5.6.

Negative power in the plots represents power generated in the grid while positive sign shows power consumed. As it can be seen from the plots, the network is experiencing high excess power flow. This can be monitored at the external grid interconnection. The high amount of negative power flowing in to the external grid shows that excess power is being transferred out of the network.

The voltage plot shows the minimum and maximum value at the moment for all of the buses together with the most crucial buses in the network. It can be seen that during the peak wind power generation points, high positive voltage deviations for the buses are monitored and shown in black on the voltage plot. The overvoltage deviating points exceeding the 4% limit can be observed for 3 specific periods during the week:

- Tuesday 08:00-14:00 voltage exceeding upper 4% limit at V=1,042;
- Thursday 12:00-02:00 on Wednesday voltage exceeding upper 4% limit at V=1,045 peak value;
- Sunday 01:00-06:00 voltage exceeding upper 4% limit at V=1.043.

Even though the wind power generation is high on Friday/Saturday, the bus voltages are not exceeding the 4% (6% for LV) barrier to activate the voltage control. This validates the issue defined in Chapter 4 steady state analysis. The peak generation points match the overvoltage points during the week. This confirms that the high excess power from the wind turbines causes overvoltages at the local buses. The buses exceeding the overvoltage limit in the network are the following:

- Medium voltage - buses B14, B15 and B16;
- Low voltage - Buses LV1, LV2 and LV3.

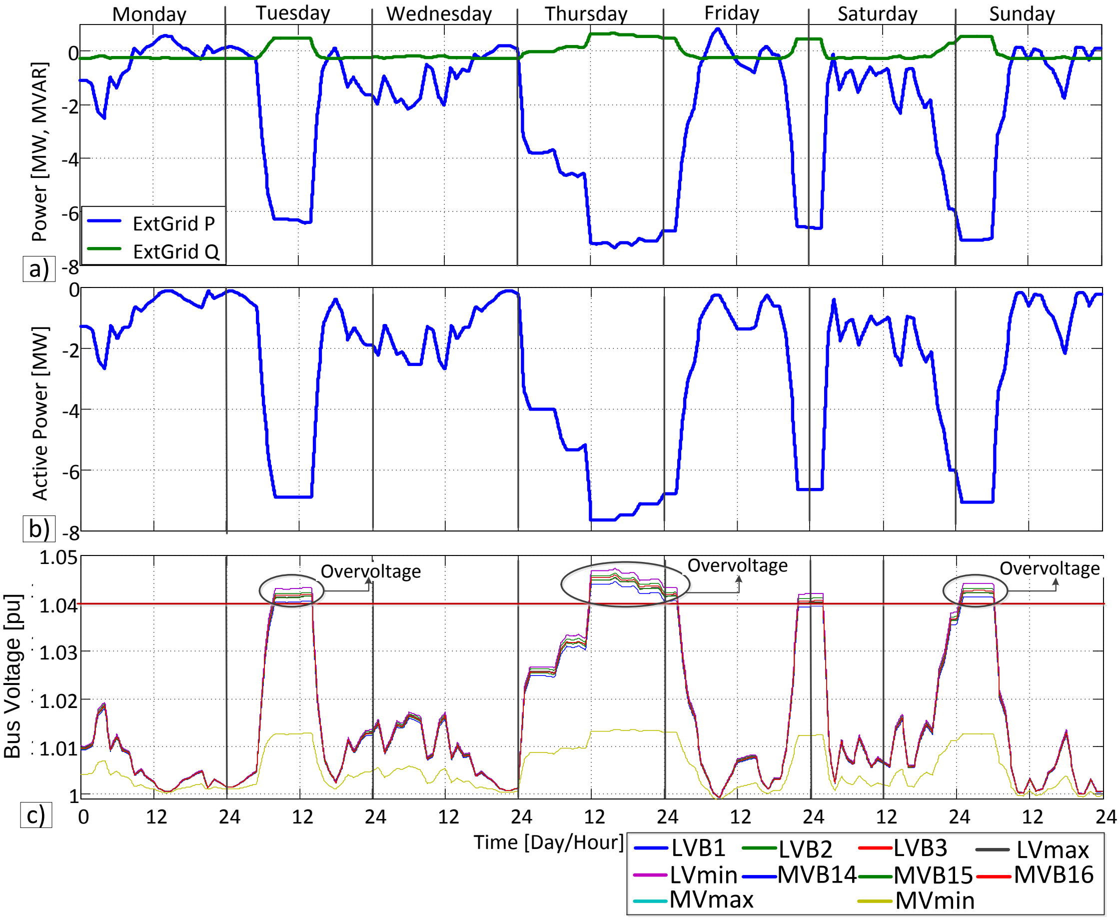


Fig 5.6 Dynamical analysis with high wind generation – base case
c) External grid power flow (MVBus Fig 4.1) b) Generated power from all WT
d) Bus voltages

5.3 Distribution grid long-term analysis with alkaline electrolyser

In order to resolve the issue with the overvoltages at the buses (MVB14, MVB15, MVB16, LV1, LV2 and LV3), the proposed model of the alkaline electrolyser is implemented into the system. The system is connected at MVB15, rated at 0,8MW as defined in Chapter 4.3. The operating scenario is the same as the one used for the base case scenario 5.1 - minimum loading of the grid with high wind penetration. The purpose is to make comparison between how the system behaves with and without the alkaline electrolyser under the same operating conditions. The alkaline electrolyser is working in voltage control. The control will attempt to shed all overvoltages at the buses under the predefined limit.

It should be noted that at this point, the storage size is not yet defined. The size for the hydrogen tank will be chosen after obtaining data for the hydrogen generation ratio from this high excess power generation scenario. The bus and load flow data when the alkaline electrolyser is connected can be seen in Fig 5.7.

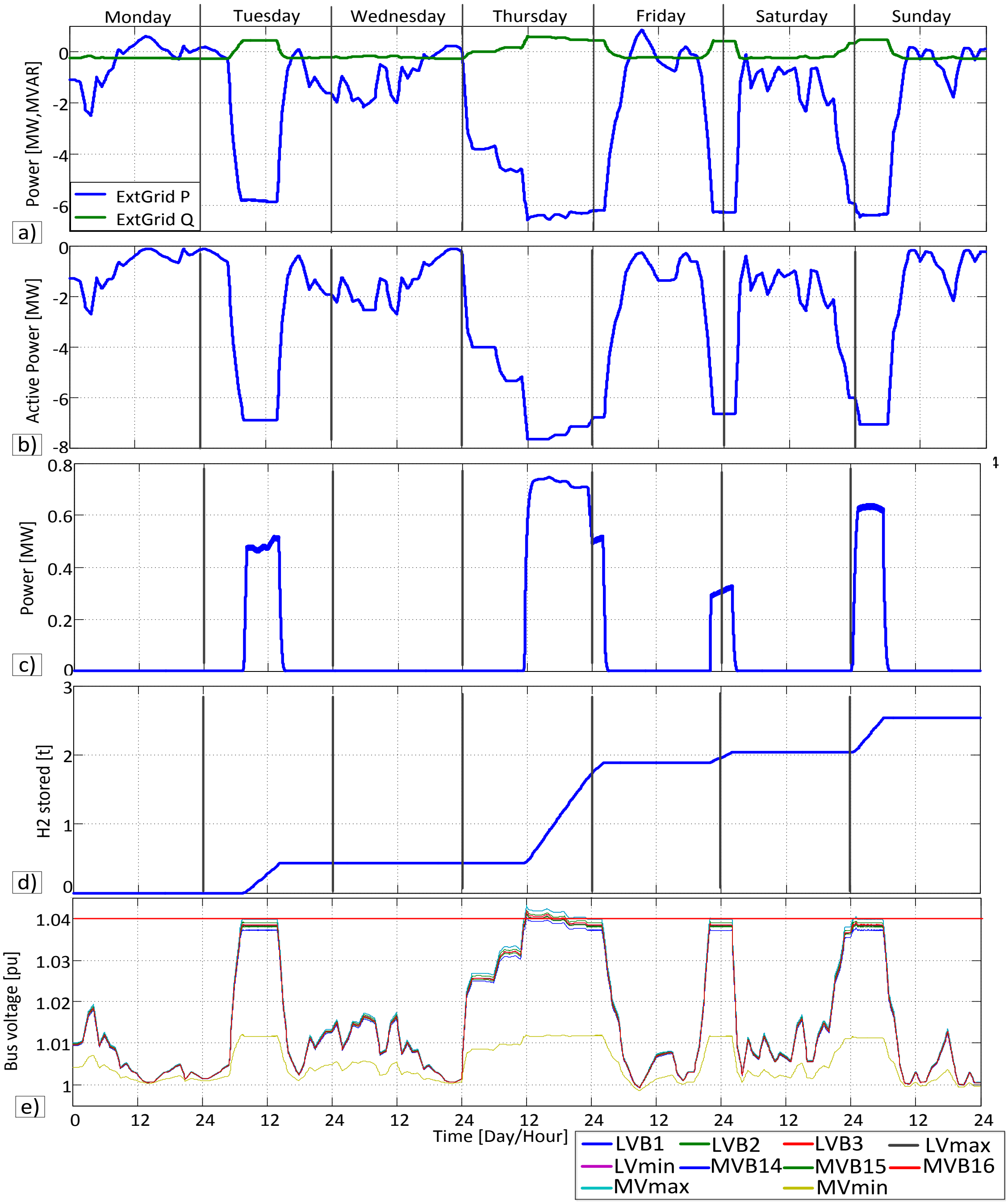


Fig 5.7 Dynamical analysis with high generation and AE in voltage control External grid power flow (MVBus Fig 4.1) b) Generated power from all WT c)AE power d) Generated H2 e) Bus voltages

The bus voltage plots show only the buses exceeding the voltage deviations limits. In order to show the results more clearly, the biggest and lowest bus voltages at each point of time for all of the buses are shown as well.

As it can be observed from Fig 5.7, the same situation as the one presented in the base case occur. High excess power from the wind turbines is transferred over the network and through the external grid. However, when the excess power reaches its peak (which was causing the overvoltages during the basic case), here the alkaline electrolyser is turned on. This can be clearly observed for the most crucial hours presented in this case:

- Tuesday 08:00-14:00 the electrolyser is turned on shedding part of the excess power and keeping the medium and low voltages buses under 4% deviation;
- Thursday 12:00-02:00 the electrolyser is absorbing part of the excess power from the grid. The medium voltage buses voltage deviations are kept under 4%, while the low voltage ones is kept under 6%;
- Sunday 01:00-06:00 the alkaline electrolyser is turned on removing part of the over generated power in the grid and keeping the bus voltages under 4%.

From this it can be concluded that the alkaline electrolyser is capable of reducing the overvoltage and controlling the voltage deviations in the system.

The line loading comparison with the base case can be seen in the following Fig 5.8.

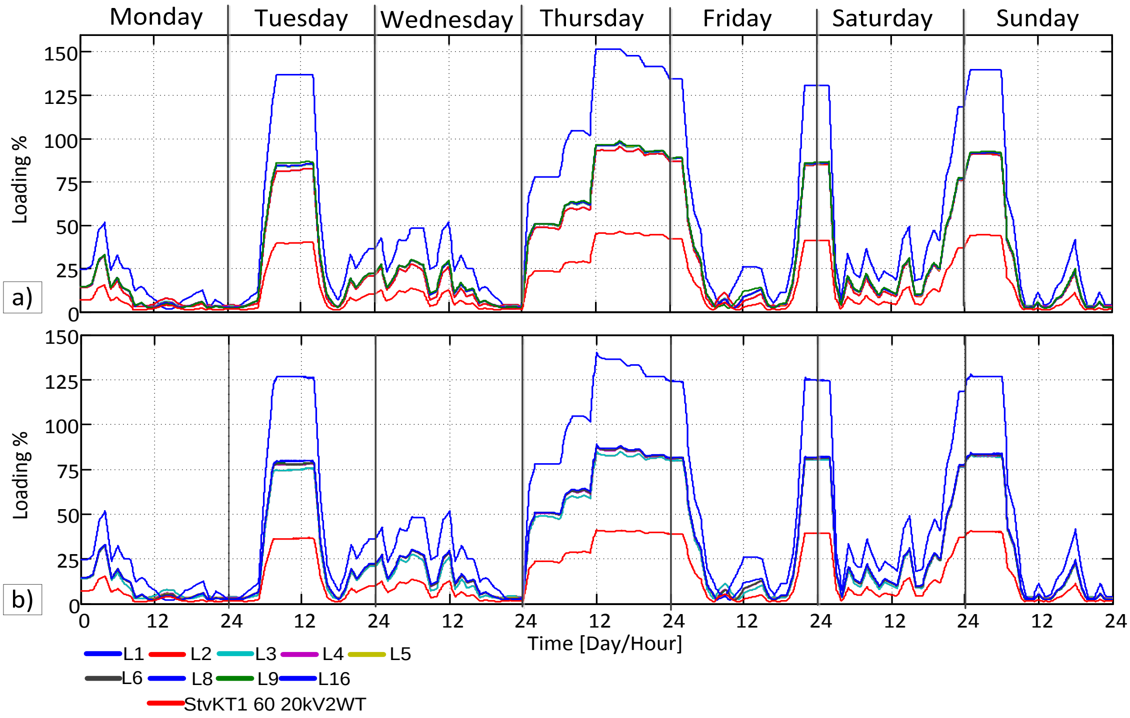


Fig 5.8 Loading of the lines – long term analysis

a) Base case b) With alkaline electrolyser used

The figure verifies the founding of Chapter 4 regarding the steady state analysis that the alkaline electrolyser successfully decreases the line loadings. The effect is most noticeable at the higher loadings of the lines when the excess generation of power is at its peak. At these points the loadings for some of the lines are decreased up to 8% using the alkaline electrolyser. However, it should be noted that one of the lines (line 16) is still operating at loading over 100% and should be considered for changing.

Another point that should be taken into consideration is that the alkaline electrolyser is generating hydrogen from the excess power. Given this worst case scenario with peak excess power generation, the electrolyser is able to generate up to 2.7 tons of hydrogen over the duration of one week. Given this data, the storage size can now be defined.

5.4 Sizing of the hydrogen storage tank

From the dynamical analysis of the alkaline electrolyser, the production ratios for the hydrogen gas have been defined. Based on the obtained data the size for the hydrogen storage will be defined.

The power generation profile used is defined with very high wind penetration and high level of excess power generation from the wind turbines. The generated power from the wind turbines can be observed in Fig 5.3. As it can be seen from the illustration, the power output from the wind turbines is kept high during the whole week in order to produce the maximum amount of hydrogen from the electrolyser.

The data obtained shows hydrogen accumulation from the system of up to 2.7 tons during the one week time frame. Considering this, the minimum amount of hydrogen that the storage should be able to store should be up to 2.7 tons of compressed hydrogen gas.

However, taking into account the very high generation profile used for this scenario, the actual generation rates expected will be lower. Nonetheless, the information given about the maximum storage size in [33] and [34] suggests using a smaller tank, not exceeding a capacity of 2 tons of pressurized hydrogen. Based on this, it was decided that the hydrogen storage should be able to accumulate 2 tons of hydrogen at most. Therefore, the storage chosen for the hydrogen system will store 2 tons of hydrogen gas when full.

Given the technical requirements for hydrogen gas storage in [35], the tank should always have a minimum amount of hydrogen stored. The value for the minimum amount of hydrogen is set to 0.1 tons. The upper limitation is already defined at 2 tons. However, in a situation where extra hydrogen (above the 2 tons) is generated, it will be extracted via the gas grid. It is assumed that the hydrogen storage is connected to the local gas grid and it is possible to remove the excess hydrogen via it when the storage limit is reached. Thus, all of the excess hydrogen will be extracted from the storage and can be sold or used over the gas grid.

5.5 Impact assessment of the fuel cell

In order to define the main role for the fuel cell in the hydrogen system, its purpose should first be made clear. The steady state analysis did not define the role of the fuel cell as data for the stored hydrogen in the system is required. This data can be obtained only after conducting the long-term dynamical analysis on the grid with the alkaline electrolyser (section 5.3).

During the steady state analysis in Chapter 4.3, no undervoltages were defined for the grid. Hence, voltage deviation control will not be implemented as main control for the fuel cell, given that such issues are not present during the study. Yet, it should be noted that the fuel cell is capable to resolve any undervoltage problems in the grid, should they occur. The same voltage control strategy used for the alkaline electrolyser can be implemented for the fuel cell to achieve undervoltage deviation control. The type of control used can be changed by the DSO, should there be any need for this.

Applying the fuel cell for local power management is a viable option for such a generating subsystem. A test scenario was defined in order to test the system while the fuel cell is used for local energy management and backup power generation. Implementing the fuel cell in the network for local energy management can potentially reduce the loading of the lines and provide back-up power generation for the system.

The wind penetration level used for the analysis is unique by having low and high wind speeds during the week. This will allow the hydrogen system to accumulate hydrogen during the high penetration periods and use the fuel cell for utilizing the gas if required. The power output from the wind turbines can be seen in Fig 5.9.

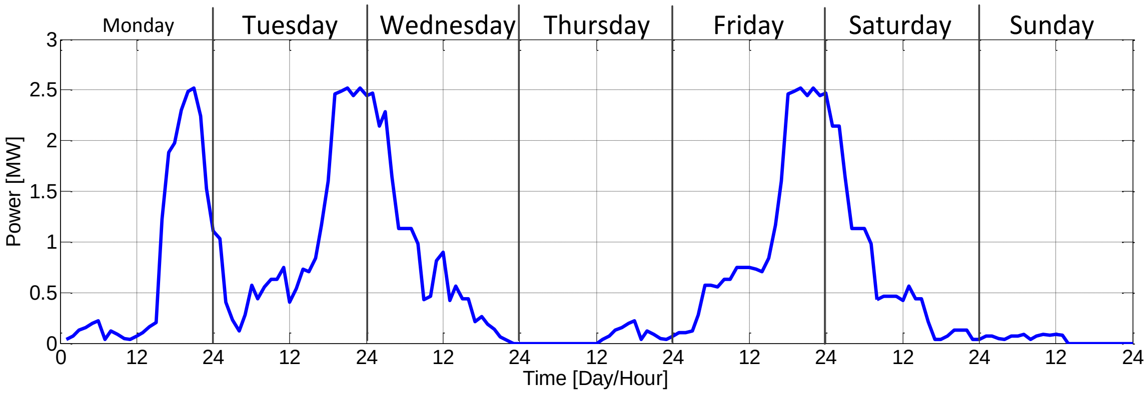


Fig 5.9 High/Low Wind turbine generation profile

The main points for this operating scenario are summarized in Table 5-1

Table 5-1
High feeder loading with fuel cell implemented

External grid	The external grid is connected to the system and is balancing the power flow in the whole network.
CHP	The CHP plant is generating zero power in to the system.
Wind turbines	The power generated from the wind turbines is set to follow the pattern show in Fig 5.9. This wind patter is unique by having high excess wind power generation during the first half of the week and almost zero generation in the end of the week.
Feeder loadings	The consumption of the network is set to its maximum loading data available. First week of January have been used as having the highest feeder consumption.
Alkaline electrolyser	The electrolyser is set to voltage control reducing any overvoltages in the system and generating hydrogen to the storage.
Fuel cell	The fuel cell is connected to the system and is rated at the same power as the electrolyser 0,8MW. The control is set to power balancing. The fuel cell will cover for any inner power generation shortages in the network. The main target will be to draw as less energy as possible from the external grid.

The obtained power flow data, bus voltages and hydrogen generation for such an operation scenario can be seen in Fig 5.10.

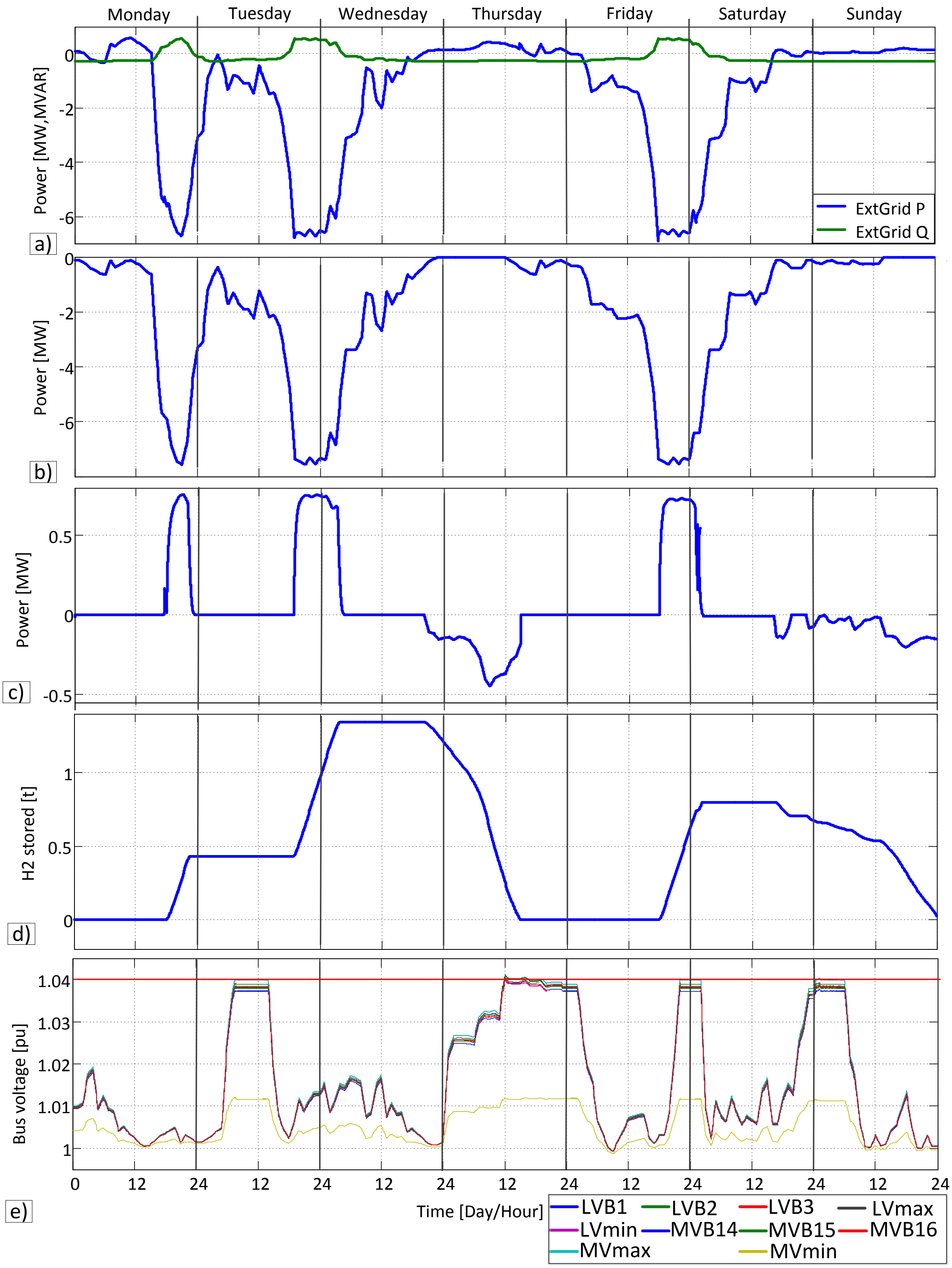


Fig 5.10 Network results – Power flow control
a) External grid power flow (HVBus Fig 4.1) b) Generated power from all WT
c) AE power d) Generated H2 e) Bus voltages

As it can be observed from the plots during the first half of the week when the over-generation is high, the external grid is transferring the excess energy out of the network. The electrolyser sheds the peak generation points and reduces the bus overvoltages to the predefined limits. This can be clearly seen at the following points:

- Monday 17:00-22:00 high excess power generation. The electrolyser is turned on by the hydrogen system to regulate the upper voltage deviations. The voltage at all the buses is kept under 4% limit;
- Tuesday 18:00-02:00 on Wednesday high overgeneration period. The electrolyser is shedding part of the power in order to decrease the bus voltages. The medium voltage buses are kept under 4% while the low voltage ones under 6% deviation;
- Friday 17:00-01:00 on Saturday another high excess power generation period. The electrolyser is started and brings the voltage deviations under the predefined limits.

During the low wind penetration period, the wind turbines are generating practically zero energy in to the grid. At this point the fuel cell system is activated. The fuel cell is generating energy and is supplying active power into the network. It can be seen that the power drawn from the external grid is negligible and at some points is zero. These points can be clearly seen at the following times:

- Wednesday 22:00-13:00 on Thursday no power generated from the wind turbines. The grid is supported mainly form the fuel cell. However at 13:00 on Thursday the hydrogen in the storage is depleted forcing the fuel cell to be turned off;
- Saturday 15:00-24:00 Sunday the fuel cell is supporting the grid consumption mainly by itself. The wind turbines are generating very small amount of power and the grid is feeding zero power to the network.

As a result, the fuel cell is capable to generate enough power for the feeders and successfully support the system and act as a backup power. The only limitations are the maximum output power of the fuel cell and the time frame for which it can support the system is directly related to the hydrogen gas available.

5.6 Conclusions from the long-term dynamic analysis

The long-term dynamic analysis of the network monitored the same grid issues that were found in the steady state analysis. High voltage increase for local buses located in proximity to the wind turbines were monitored during periods of high excess wind power generation.

The proposed hydrogen system was implemented in to the network following voltage control. The main task for the control was to decrease the overvoltages under 4% for medium voltages buses and 6% for the low voltages ones. By using the electrolyser during high wind penetration, the voltage control was successful at shedding part of the excess power in the grid. This measure was successful in reducing the overvoltages for all of the buses under the predefined limits. Additionally, the system was able to decrease the loading of the lines from the reduction of excess power flowing through them.

Afterwards, the impact analysis for the alkaline electrolyser hydrogen production ratios was conducted and based on its results, the hydrogen storage size was defined. The requirements posed on the storage size included the generated hydrogen from the system and technical limitations for the maximum size of the storage. Observing the latter, the size of the storage was defined to be able to accumulate up to 2 tons of hydrogen. At the same time, the minimum amount of hydrogen gas that the storage should maintain is 0.1t due to technical limitations. The upper limitation for the maximum amount of gas stored in it is set at 2 tons. It was decided that the hydrogen gas produced over the 2 ton max capacity is to be extracted via the gas grid connected to it.

The impact assessment for the fuel cell showed that it could be successfully used for local power management in the network. It was shown that the hydrogen system is capable of supporting most of the grid consumption using the fuel cell generation. On the other hand, by implementing the same type of control as for the AE, the fuel cell can also be used for voltage control should any under voltages occur in the system. Thus, the only limitation imposed on the fuel cell is the amount of hydrogen gas available in the storage.

These results allow us to conclude that the hydrogen system is capable of providing technical support for the gird. It can be used for voltage deviation control and local power management in the network. Moreover, the hydrogen system also reduces the line loading and losses of the system through increased balance between supply and demand in the network.

6 Electricity market analysis of the hydrogen system

Chapters 4 and 5 defined the technical problems in the network under study and showed how they can be solved using the hydrogen system. Given the flexibility of the hydrogen system in its supply/demand, it can also provide additional economic benefit. Following the price fluctuations at the energy market, the proposed system can be used for accumulating revenue from high/low market prices of electricity. The fluctuations of the electricity prices are mainly caused by the high correlation between the wind power generated in the system and the overall system demand. Given the high wind power penetration of the local network under study, it can provide high economic benefit by utilising the price variability following the wind penetration. This chapter will focus on how the hydrogen system can be used for accumulating additional benefit by taking advantage of the electricity price fluctuations.

First, a short introduction describing the energy market of Denmark is given. The market structure, its working principles and the electricity price setting for the NordPool market are presented. Bearing in mind these factors, the highlights for the main points of the market that can introduce economic benefit from the proposed system are given.

The second part of the chapter explains the implemented control strategy of hydrogen system designed to follow the changes in market prices. The breakpoints for the prices at the market are given and it is defined how they are used in the control. The main inputs and outputs for the market price control are explained.

Lastly, the chapter shows the long-term behaviour of the system while following the market price control signals. Different scenarios for the system are analysed in order to assess its overall behaviour.

6.1 The energy market – NordPool Spot

As previously mentioned, Denmark is one of the members of NordPool electricity exchange market. The NordPool market is one the leading power markets for energy exchange. Twelve country members, over 380 individual companies included and 501 Twh traded in 2014 make NordPool the biggest electricity market in Europe. NordPool Spot provides a platform for dynamical energy exchange between the system operators, energy producers, distributors as well as large end users. The main resource traded in this electricity market is the supply and demand of electrical power [7].

The energy traded at NordPool market is operated at 3 different sub-markets, which are namely:

- Elspot – this is the day-ahead market for energy exchange. The volume of energy to be traded and the prices for each hour are set one day prior to the actual energy exchange.
- Elbas – the intraday market for energy exchange. It is also referred to as the last hour balancing market. The prices for the volumes to be traded are agreed on one hour before the actual deal. This is a regulating power market that has to handle any unexpected power imbalances that may occur after the Elspot market is closed.
- Regulating power market – the power market that focuses on the imbalances that the previous two markets were not able to resolve. This market is operated by the TSOs of their countries and bids for the supply/demand are placed 45 minutes before the actual trade. The main aim of this market is to analyse the excessive use of the reserves in the system and to restore their availability to the system.

In order to examine how the proposed hydrogen system can benefit its owner or operator from the energy market, the day ahead market was chosen for the research. Thus, the hydrogen system will be operated based on the prices of the Elspot market. This platform was chosen based on the planning opportunities it provides to the buyer/seller of energy. Given the innovative nature of the proposed system, an analysis providing longer time for defining the operating hours of the system must be conducted first, while its behaviour can be subsequently assessed on the more dynamical Elbas and RPM markets. Therefore, the scope of this study will focus only on the Elspot market prices.

Elspot is the main area for trading power in the Nordic and Baltic regions. The prices for the Elspot market are defined by the members and their planning of the supply/demand of power they offer beforehand. The byers estimate how much energy they need in order to meet the next day demand and the price they are willing to pay for it. Alternatively, the sellers (wind parks, hydroelectric plants, photovoltaics or any other power generating plant owners) assess how much energy they can deliver and at what price hour by hour [7].

The bids for power on Elspot start at 8:00 AM each day and continue until 12:00 AM. During this period the buyers/sellers are allowed to place, change or remove their offers. After the market closes at 12:00 AM, NordPool Spot evaluates the placed offers and sets the prices for the following day on an hour-by-hour basis. The process regarding the price setting is shown in Fig 6.1. When the two curves for selling and buying power meet, the price is set for this hour [7].

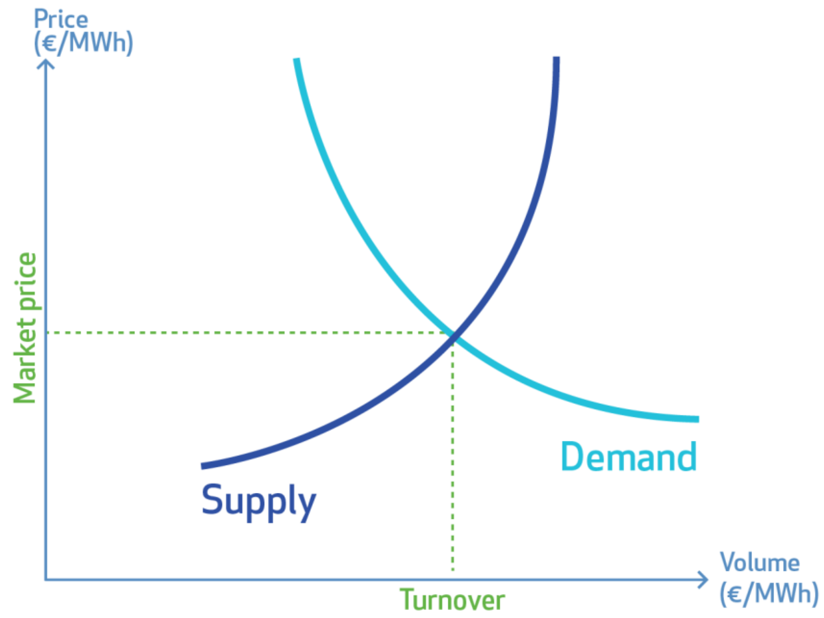


Fig 6.1 Elspot price setting [7]

Given the flexibility of the proposed hydrogen system, it can be used by adjusting it supply/demand to follow the market prices in order to bring additional economic benefit to its owner. By following the prices of the Elspot market, it can be used to adapt its supply or demand and thus take advantage of the market prices. The economic strategy for such energy market is simple - buy at low price and sell at high. When transferred to the NordPool market, this logic corresponds to generating at high demand periods when the price is high and consuming at low demand and high excess power generation when the price is low. By implementing this logic into our hydrogen system for market price control strategy, it can be used to follow these main points:

- At low/negative market price, use the alkaline electrolyser and generate cheap hydrogen gas from the system. The generated gas can be either used by the fuel cell or sold on the gas market
- At high market price, use the fuel cell and generate energy in to the system when the prices are at their peak.

It is noteworthy to specify that the minimum allowable price for “buying” electrical power at NordPool is set at -500 €/MWh (negative prices are possible due to periods of very high wind penetration) and the maximum price for selling is fixed at 3000 €/MWh [7]. Theoretically up to 3500 €/MWh of income can be generated from the Elspot – NordPool market for 1MWh of power.

6.2 Market price control strategy for the hydrogen system

As to follow the electricity price signals of the energy market, two different types of market price control will be implemented for the hydrogen system. The market price controls to be implemented for the system are based on the operation principle implemented for the system. The two implemented controls are defined as:

- On/off market price control – This type of control will monitor the system prices and will turn on the hydrogen system only for the most beneficial periods. The control output will be based on 3 price levels – high, low and normal. Based on the monitored price, the hydrogen system will output either its maximum rated power for AE/FC or will remain turned off.
- Continuous marker price control - This type of control will operate the system continuously. Unlike the on/off market price control, this control operates the system during the chosen time frame without shutting it down. The control will follow the system prices and scale the hydrogen system consumption/generation based on them.

In order to implement the electricity price strategy for both market price controls, the price signals which are most beneficial for the used type of control have to be defined first. The NordPool Spot market provides data of the hourly Elspot prices for the last 2 years. The data used in this research is in regard to western Denmark since the network under study is located there. Hence all of the data used in this study is referred only for the region of western Denmark (DK1). Based on the obtained data from NordPool, three consecutive days in 2014 were chosen with their hour-by-hour prices. The chosen days with their hourly prices, user consumption and wind generation can be seen in Fig 6.2.

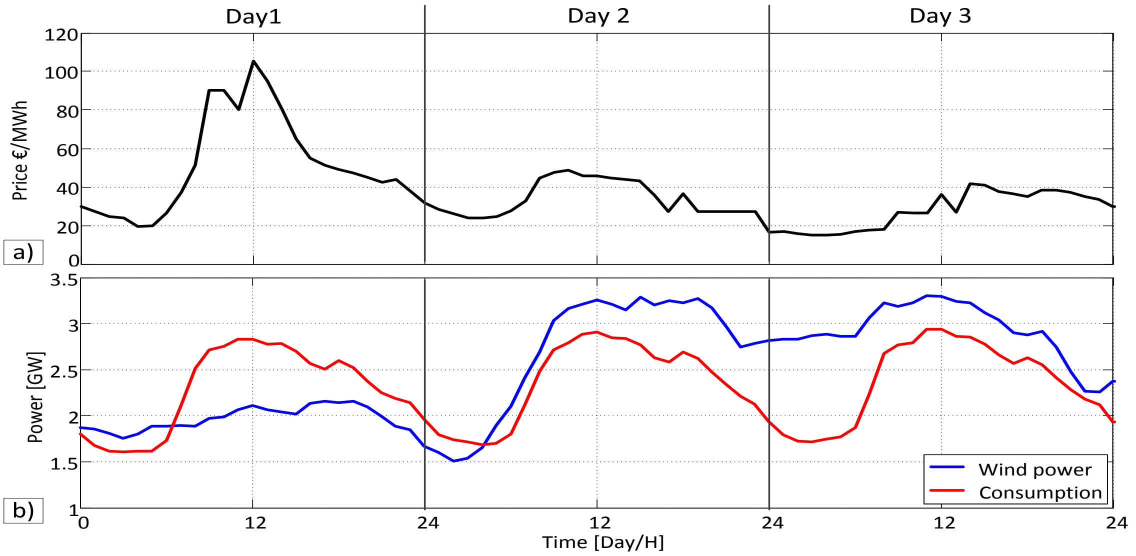


Fig 6.2 Nordpool Spot data for 2014 western Denmark
a)Hourly electricity prices from Elspot market b)Consumption and wind power generation

The chosen days have high electricity price fluctuation. During the first day, the prices increase up to 105 €/MWh and reach its peak price. At Day 3, the price reaches its bottom at 15 €/MWh. This high price difference is convenient for demonstrating how the hydrogen system can be operated during periods with high/low price periods.

Another point that should be emphasized for the chosen days relates to the wind power generation and its partial correlation to the electricity price. Even though the wind power and spot price correlation is not obvious in most cases, given that it is affected by additional factors, it still should be accounted for. The chosen days present a good example for this correlation. By comparing the data for the consumption and wind generated power in DK1 with the spot price, the following trends can be defined:

- When the wind power is low while the consumption is high, the spot price for energy is high. This can be clearly seen at Day 1 in the interval between 08:00 and 22:00 o'clock.
- While the consumption of the system is low and the wind generation is high, the spot price tends to be low. This is visible at Day 2 from 22:00 to Day 3 10:00. During this period, the difference between demand and wind generation is forcing the electricity price to drop.
- When the difference between consumption and wind generation is small the price is kept close to its average price for the spot market (31.67 €/MWh for 2014 as per the NordPool data).

Based on the above observations, it can be assumed that the correlation between wind power and spot electricity price is high. To emphasize this connection, different papers [36] [37] [38] back it up with a more in-depth analysis on the relations between the overall energy system, wind generation and spot prices.

6.2.1 On/off market price control

The logic behind this control is based on defining 3 price levels for the system to follow. Based on the defined prices, the control will output signal to the hydrogen system either to use one of its sub-system (AE or FC) at full power or to remain idle in the gird. The price levels chosen for this control are high price, low price and normal price. Each of them is defined for the system as:

- High electricity price

$$C_{high} = C_{average} * K_{high} = 37{,}63 * 1{,}3 = 48{,}9\ €/\mathrm{MWh} \qquad (6.1)$$

Where $C_{average}$ is the average electricity price during the 3 day period chosen for the study and "K_{high}" is the coefficient for defining high price for the study. The selected value for "K_{high}" to be implemented in the market price control is chosen to be 1.3 (30% increase of the average value) higher than the average price monitored in the system. This value is chosen arbitrary in order to show how the system will behave using such control strategy. The DSO or the owner of the hydrogen system can choose to define their own breakpoints for high price level, based on deeper financial analysis of the market.

- Low price – The minimal price for the system to follow. The minimum price level takes into account the hydrogen system efficiency defined in Chapter 3.3. The minimum price is defined as:

$$C_{low} = C_{high} * \eta_{H2} = 48{,}9 * 0{,}368 = 18€/\mathrm{MWh} \tag{6.2}$$

Where η_{H2} is the hydrogen system efficiency.

- Normal price level – Everything in between high and low price levels:

$$C_{low} \leq C_{normal} \leq C_{high} \tag{6.3}$$

Fig 6.3 shows the best hours for operating the hydrogen system following the 3 price levels defined for this control.

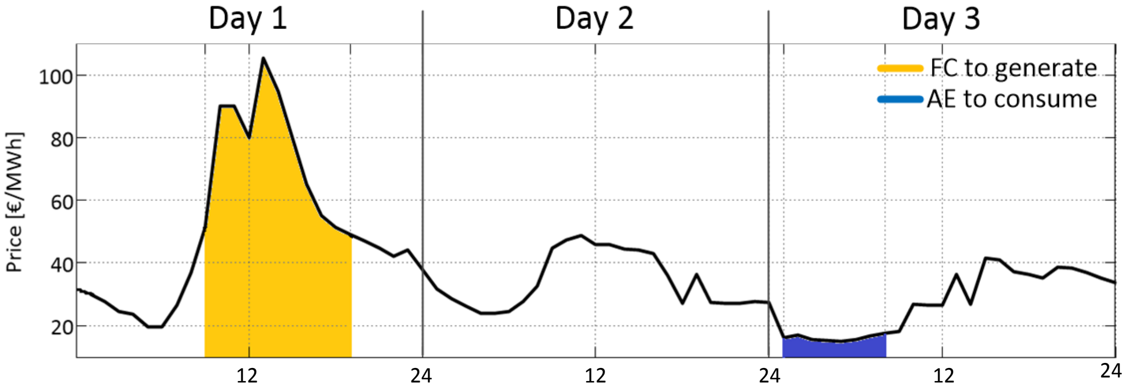


Fig 6.3 Electricity price – best selling/bying hours for on/off market price control

The best hour for using the fuel cell to generate is shown in yellow on the graph, while the lowest price hours for consumption using the alkaline electrolyser are shown in blue. Based on the defined levels for high and low price, the best hours for consuming and selling are the following:

- Day 1: 09:00-19:00 – Best hours to generate energy in to the system using the fuel cell in order to benefit from the high market price.
- Day 3: 01:00-08:00 – Best hours to consume electricity from the grid using the alkaline electrolyser to produce hydrogen gas at minimum price.

Everything in between this hours is assumed to be at normal price level and the system will remain not operational following the on/off market price control.

Based on the three chosen price levels for the on/off market price control, the implemented control block diagram for the system can be seen in the following Fig 6.4.

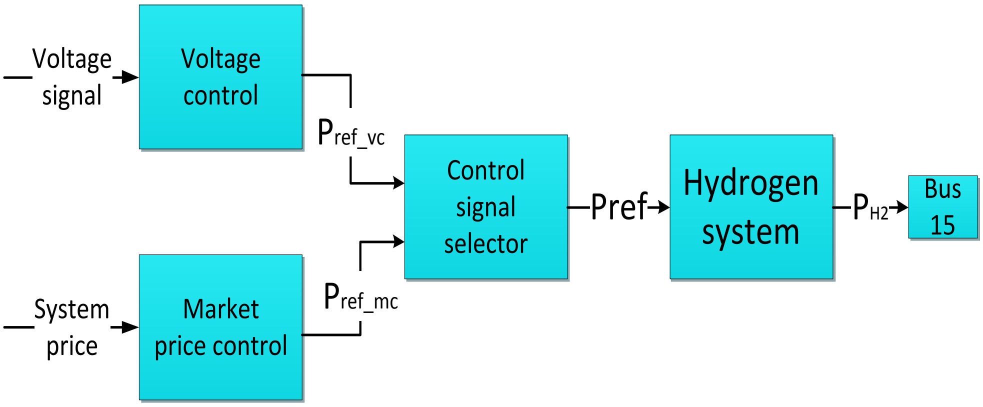


Fig 6.4 Market price and voltage control strategy block diagram

The market price control block in the system follows the system price of the market and compares it with the 3 predefined price levels (high, low and normal). Based on the electricity price monitored, the control block will send a signal to the system to use one of its sub-systems (AE or FC) or to stand idle. The 3 reference levels for the system are defined as:

$$\begin{gathered} C_{system} \geq C_{high} \rightarrow P_{ref\_mc} = P_{FC}^{Max} \\ C_{system} \leq C_{low} \rightarrow P_{ref\_mc} = P_{AE}^{Max} \\ C_{low} \leq C_{normal} \leq C_{high} \rightarrow P_{ref\_mc} = 0 \end{gathered} \qquad (6.4)$$

Where C_{system} is the monitored price at the moment, Pref_mc the set point for power given from the on/off market price control to the hydrogen system, P_{AE}^{Max} and P_{FC}^{Max} the maximum output power for electrolyser and the fuel cell.

The corresponding market price breakpoints are defined as:

- ➢ High price in the system

$$C_{system} \geq C_{high} \rightarrow P_{ref} = P_{FC}^{Max} \qquad (6.5)$$

At this set point the control will try to generate as much power as possible to the grid in order to benefit from the high price.

- Low price in the system

$$C_{system} \leq C_{low} \rightarrow P_{ref} = P_{AE}^{Max} \tag{6.6}$$

When the system detects low price, it will set the power reference signal to be the maximum input power for the electrolyser. This will allow the hydrogen system to generate cheap hydrogen gas by taking advantage of the low system price.

- Normal price level

$$C_{low} \leq C_{normal} \leq C_{high} \rightarrow P_{ref} = 0 \tag{6.7}$$

When the system monitors normal price levels the market price control sets the power of the hydrogen system to zero. During this period the systems will neither consume, nor generate power to the grid as the price is not beneficial for it based on the predefined price levels.

Subsequently the market price control signal is sent to the block "control signal selector". This block separates the signals from the two controls implemented – voltage and market price control. The block functionality is defined by the following equation:

$$P_{Ref} = \begin{cases} P_{ref_{vc}}, & V_{bus} \geq 1.04 \\ \\ P_{ref\_mc}, & 0.96 < V_{bus} < 1.04 \end{cases} \tag{6.8}$$

Where "P_{ref_vc}" is the set point given from the voltage control and "V_{bus}" the monitored values for all of the bus voltages.

6.2.1 Continuous market price control

This type of control will operate the hydrogen system continuously through the chosen time frame. The system will be fully operational during the 3 chosen days and based on the control signal, it will scale its output power following the price signals. Unlike the on/off market price control, this control will vary the hydrogen system power following the system prices trying to achieve revenue without shutting the system down. The main price breakpoints used for the control logic are based on the average electricity price during the chosen 3 days.

The average price calculated for the chosen days is set at 37.63 €/MWh. Everything higher than the average price will be considered as beneficial for the hydrogen system to generate using the fuel cell. On the other hand, everything below the average price is perceived as profitable for using the alkaline electrolyser to produce cheap hydrogen. The same block diagram presented in Fig 6.4 is used for the control implementation. The only difference relates to how the control signal for the hydrogen system is defined. The set point for the hydrogen system power is chosen on the highest and lowest price observed for the selected time frame. The power set point “P_{ref_mc}”, given from the continuous market price control, is defined as:

$$P_{ref\_mc} = \begin{cases} \dfrac{C_{system}}{C_{highest}}, & \left(C_{system} - C_{average}\right) > 0 \\ \\ \dfrac{C_{system}}{C_{lowest}}, & \left(C_{system} - C_{average}\right) < 0 \end{cases} \tag{6.9}$$

Where “$C_{average}$” is the average price, “$C_{highest}$” and “C_{lowest}” the highest and lowest prices during the 3 day time frame.

Following this control, the hydrogen system will output the fuel cell peak generation when the highest price is monitored. Alternatively, when the system monitors the lowest price in the system, it will use the AE at its peak-rated power. For the prices that lie in between the highest and lowest, the control will scale the hydrogen power output according to the price monitored. If operated together with voltage control, the logic for the power set point reference remains the same as the one shown in (6.8). The working hours for each of the sub-system (AE and FC) operating under this type of control can be seen in the following Fig 6.5.

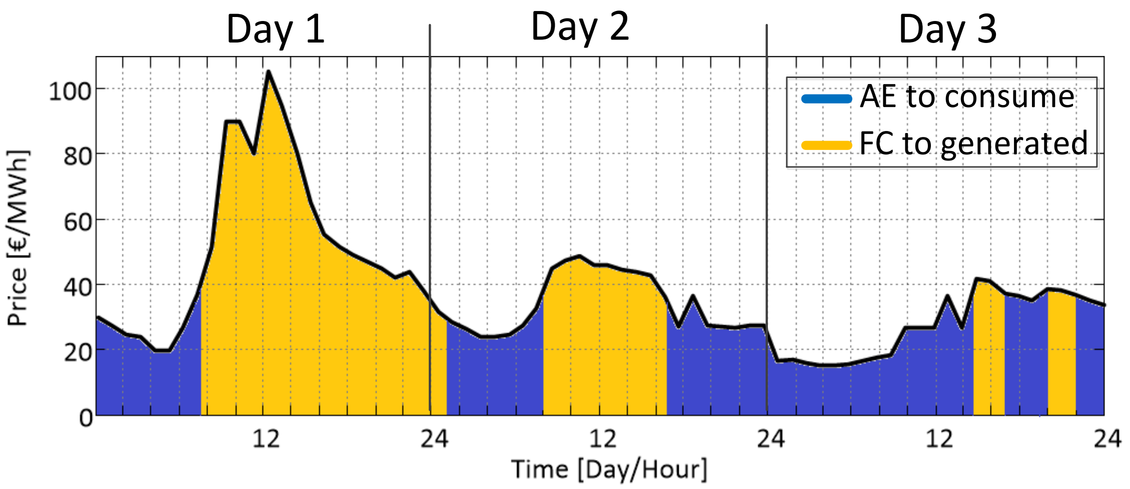


Fig 6.5 Operating schedule for the hydrogen system - continues market price control

The plot shows the operating hours for the fuel cell in yellow and in blue for the alkaline electrolyser. As it can be seen, according to the used logic for the implemented control, the hydrogen system is operational continuously during the whole period.

6.3 NordPool Spot market and hydrogen system analysis

To evaluate the long term behaviour of the hydrogen system under the NordPool Spot energy market, 4 different study scenarios were chosen for the analysis. Each of the scenarios is intended to assess the system under different operating conditions that might be observed during the grid operation. The scenarios were chosen based on the grid problems already defined in Chapter 4 and they include any limitations for the system that may occur while operating under the market price control.

- Scenario 6.1 – High local wind with market price control. For this operating scenario the local wind penetration for the network is higher than the global wind pattern data shown in Fig 6.2. Considering the distributed wind power generation across Denmark, it is possible to have areas with higher wind penetration than the majority of the other areas. Given the latter, it is assumed that the geographical area for the network under study has higher wind penetration than the majority of the other wind turbines located in western Denmark. The hydrogen system control is set to operate only in on/off market price control. The voltage deviation control will be turned off in this scenario. This will allow analysing the behaviour of the system operated without any grid support, targeting only maximum profit from the electricity market. The scenario will assess the possibility of applying only market price control for the system and the issues related to it.

- Scenario 6.2 – High local wind with on/off market price and voltage control implemented. This operating scenario is identical to Scenario 6.1, however, the voltage deviation control for the system is turned on. The system will operate using the voltage deviation control and on/off market price control simultaneously. The main point is to analyse the hydrogen system while it acts as a technical support for the system and generates additional profit from the energy market following the market price control.

- Scenario 6.3 – High local wind with continuous market price and voltage control. This operating scenario will assess the system behaviour operating continuously during the 3 chosen days for the study. The scenario main point is to show the full extent of the systems flexibility in following predefined power set points for demand/supply based on the market prices. Unlike the on/off control implemented, here the power set points for the hydrogen system will be continuously adjusted and scaled following the market price for electricity. Any limitations and issues for such control will be defined and analysed based on the results obtained.

The wind profile used for the Scenario 6.1, 6.2 and 6.3 is shown in the following Fig 6.6.

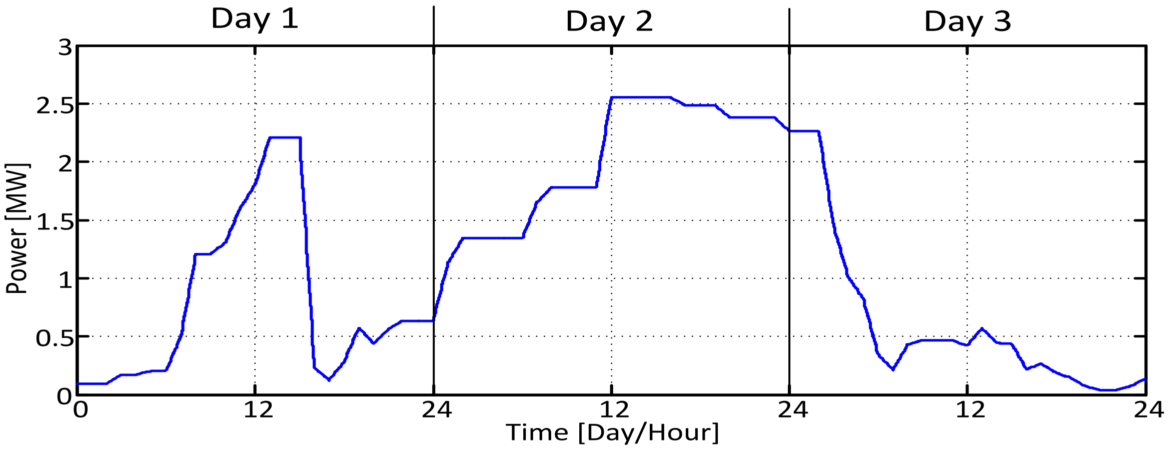


Fig 6.6 High local wind generation for 1 wind turbine

- ➢ Scenario 6.4 – Real data wind penetration. For this operating scenario the wind generation profile is based on actual wind penetration values measured for the chosen days. The hydrogen system will be operated using both types of control voltage and on/off market price. This scenario assesses how the network and the hydrogen system would have behaved under the same operational conditions measured in 2014. The wind profiles used for the Scenario 3 are shown in the following Fig 6.7.

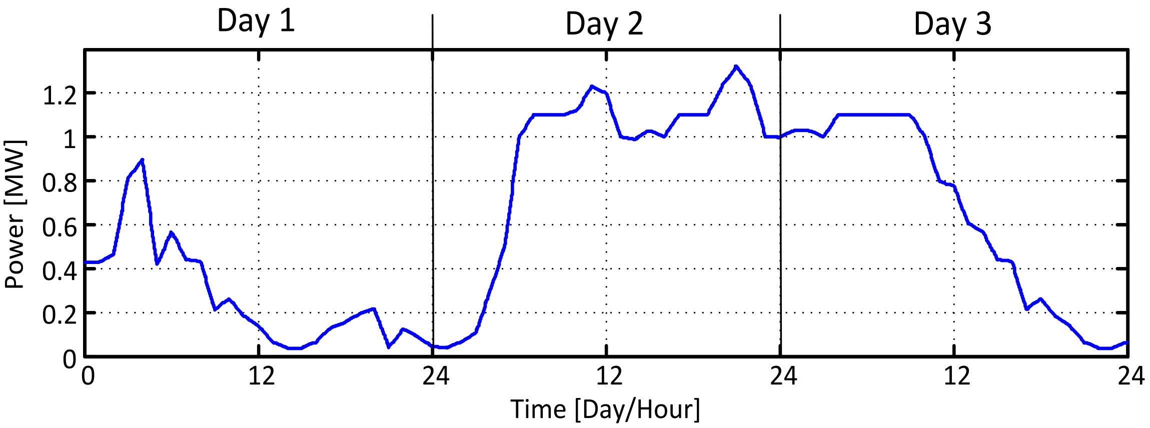


Fig 6.7 Equivalent wind generation for 1 wind turbine

The main points for the 4 operating scenarios used for the NordPool Spot market study are summarized in the following Table 6-1

Table 6-1
Summary scenarios used – market price control

	Wind profile used	Hydrogen system control used	CHP generation in the grid	Initial state of charge for the storage	Network feeder loading
Scenario 6.1	High local wind	On/off market price control	0	100%	Low loading
Scenario 6.2	High local wind	On/off market price control, Voltage control	0	100%	Low loading
Scenario 6.3	High local wind	Continues market price, Voltage control	0	100%	Low loading
Scenario 6.4	Real data wind	On/off market price control, Voltage control	0	100%	Low loading

The CHP generation in the network is set to zero in order to emphasize the effect of the wind generation on the local grid and hydrogen system performance. It is assumed that the hydrogen storage is full with hydrogen at the beginning of the Day 1 for each of the scenarios.

6.3.1 Scenario 6.1 – High local wind with on/off market price control

The results obtained for this operating scenario using the settings defined in Table 6-1 are presented in the following Fig 6.8.

As it can be observed from the plots, the generated wind power has high peak periods overlapping with the hours for selling/consuming power from the gird. The hydrogen system starts following the market price control at 09:00 during Day 1 in order to generate electricity at a high price. However, at 16:00 the fuel cell is turned off as the hydrogen gas in the storage reaches the minimum allowed value of 0,1 tons. The stored amount of gas is insufficient in order to cope with the full demand of high price generation during Day 1. This shortage of hydrogen gas decreases the maximum achievable profit from the system during Day 1. This can nevertheless be considered as one of the limitations for the hydrogen system. The hydrogen gas available to the fuel cell is only the stored amount in the hydrogen tank. Direct infeed of hydrogen through the gas grid to the fuel cell is not covered in the scope of this study and hence is not an option for the system.

During Day 3 the alkaline electrolyser is successful in following the control signal for low price. The system is operating through the full low price cycle and generates up to 1 ton (50%) of hydrogen in to the storage.

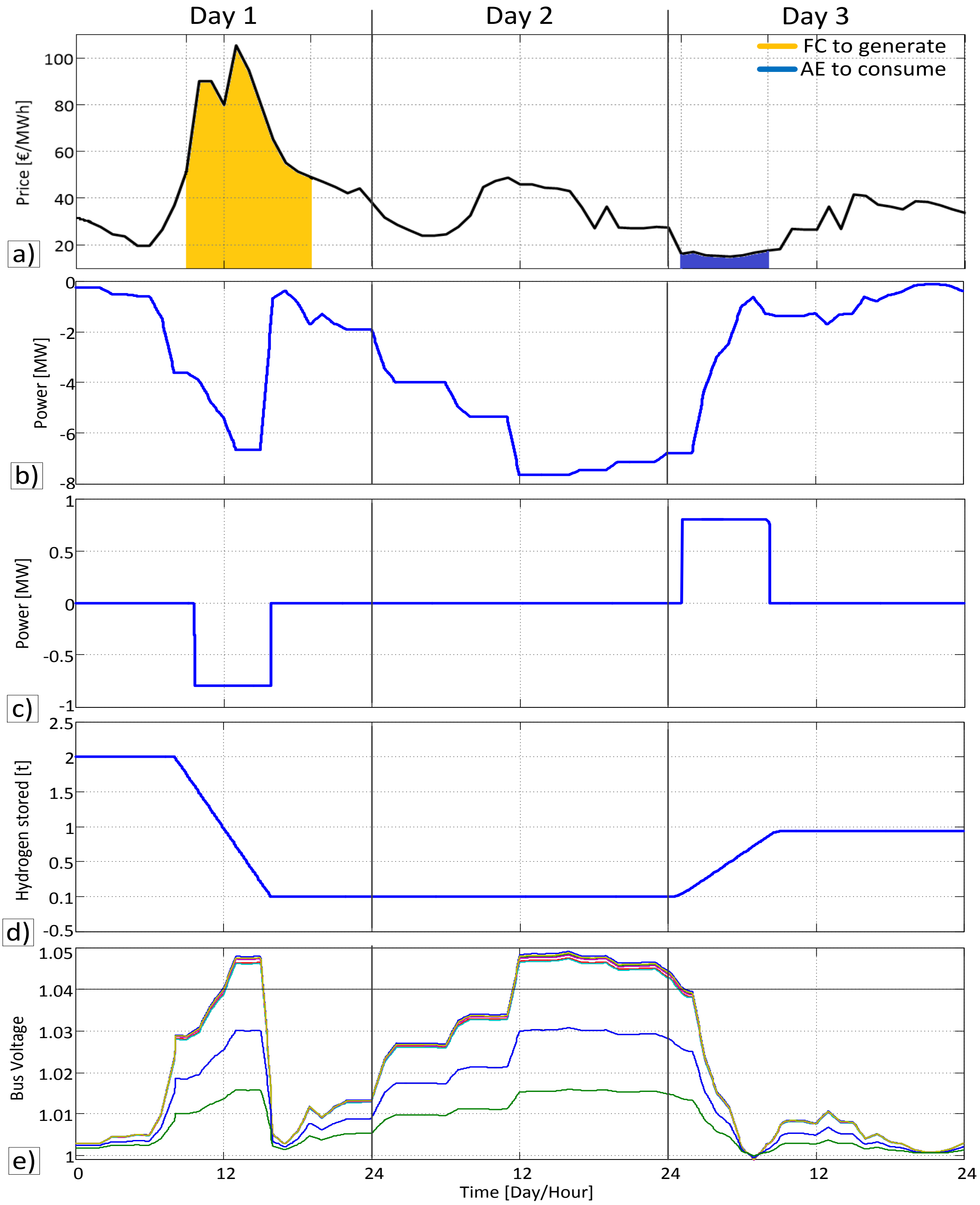


Fig 6.8 Network results – market price control Scenario 6.1
a) Electricity price b) Power generated in the local network c) Hydrogen system power output d) Stored hydrogen gas e) Bus voltages

The bus voltages results reveal high overvoltages for some of the buses in the network. The affected buses are the local buses situated near the wind turbines in the network. As defined in Chapter 4, 5 and 6, the buses experiencing overvoltages are at medium voltage B14, B15 and B16, and at low voltage LV1, LV2 and LV3. The overvoltages are occurring as a result of high local wind generation combined with additional generation from the fuel cell connected at B15. This high excess local power generation leads to voltage increase over the predefined limit of 4% for the buses located in close proximity of the wind turbines. This high deviation from the nominal voltage of the buses is unacceptable for the network and actions to bring it down should be undertaken. This results show that the market price control cannot be used only by itself. It is required to combine it with voltage deviation control in order maintain the integrity of the grid and avoid the overvoltages present only using market price control.

6.3.1 Scenario 6.2 – High local wind with market price and voltage control

For this operation scenario, the voltage control for the system is turned on together with the on/off market price control. The voltage control will attempt to decrease the overvoltages observed in Scenario 6.1 under the predefined limit of 4%. At the same time the on/off market price control will try to accumulate additional income from the energy market price. The results for this operating scenario are shown in Fig 6.9.

As it can be observed from the plots, the hydrogen system is following the high price signal and starts the fuel cell at 09:00 on Day 1. However, at 11:00 when the wind generation reaches high levels, the voltage control decreases the power output from the fuel cell. By doing this, the hydrogen system is successful at limiting the overvoltages, which were monitored at Scenario 1 on Day 1. When the high wind generation period is over, the hydrogen system starts following the market price control again and outputs the maximum power of the fuel cell. The fuel cell generates energy until 17:00 when the storage is depleted.

At 11:00 on Day 2, the hydrogen system starts the alkaline electrolyser in order to shed some of the excess wind power generated in to the network. This allows the voltages deviations seen in Scenario 1 to be kept under 4% by the voltage control for this scenario. When the peak wind generation period is over, the control is transferred to the market price control. It generates hydrogen at a low price during the whole low price period. As result, the generated amount of hydrogen is over 100% (2.5 tons). However, given that the maximum amount of the storage is 2 tons, everything above this is extracted from the system via the gas grid.

Thus, it could be concluded that the voltage control for the system is successful at keeping the overvoltages under the predefined limit while operating together with the market price control.

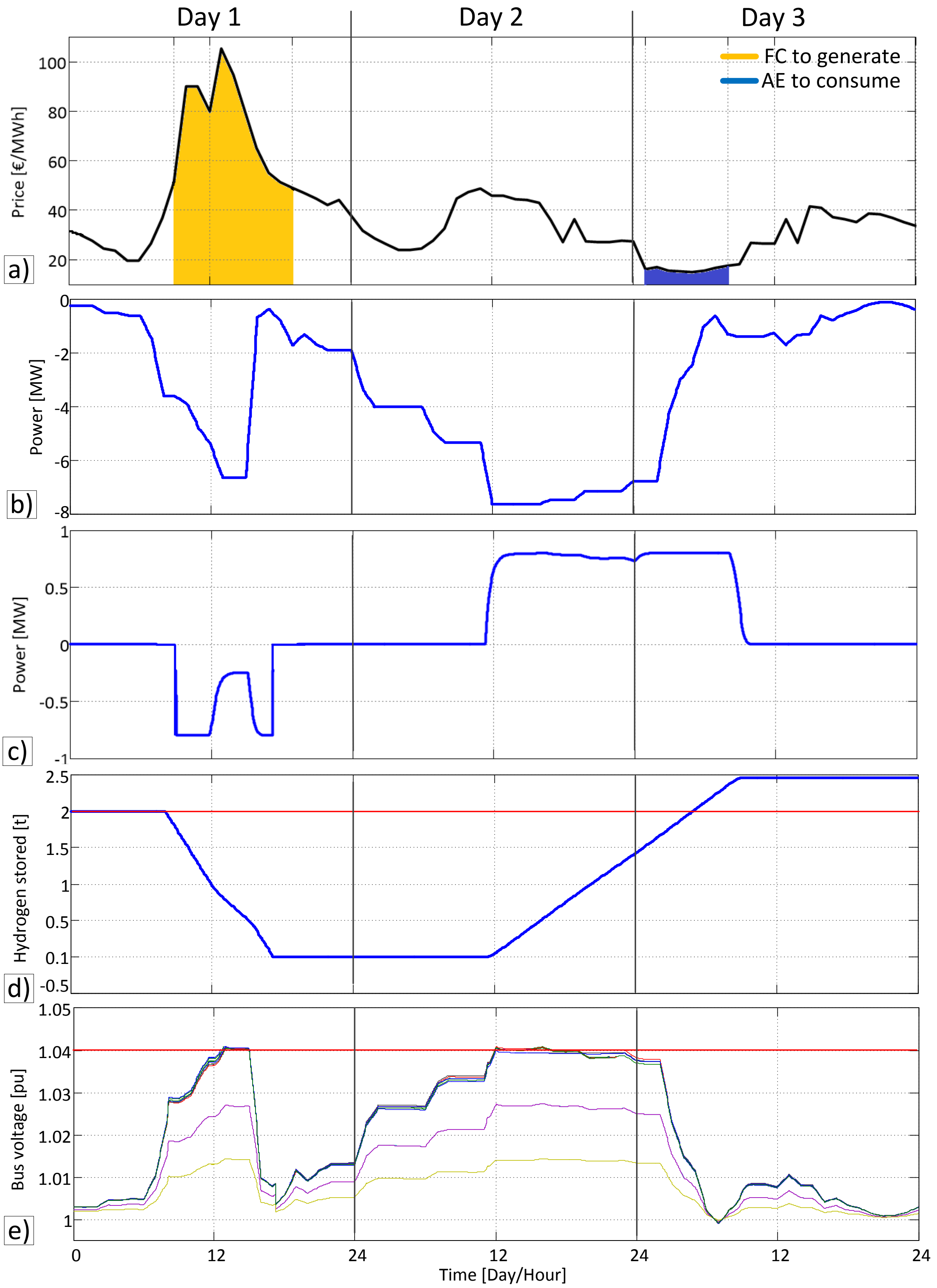


Fig 6.9 Network results – market price control Scenario 6.2

a) Electricity price b) Power generated in the local network c) Hydrogen system power output d) Stored hydrogen gas e) Bus voltages

6.3.3 Scenario 6.3 – High local wind with continuous market price and voltage control

This operating scenario focuses on the long term behaviour of the hydrogen system following the pricing system without being turned off. The main point for this scenario is demonstrating the ability of the proposed system to follow the pricing signals set points and to adjust its power flow based on them. The obtained results from this operating scenario can be seen in the figure to follow Fig 6.10.

From the attained data, it can be seen that the hydrogen system is adjusting its power flow based on the pricing signals received from the control. However, when overvoltages in the system are monitored, the control is switched to the voltage control of the system. This can be seen in Fig 6.10 c) where the power flow of the hydrogen system is shown. The continuous market price control set points are shown in red while the actual power flow of the hydrogen system is illustrated in blue. As the graph makes it visible, the actual power flow of the hydrogen system deviates from the market price control set points. The reason for this is the switching on of the voltage deviation control due to detected overvoltages in the system. Yet, once the excess generation in the system decreases and the overvoltages issue is resolved, the control is switched back to the market price signals.

The hydrogen gas stored in the tank is sufficient in sustaining the consumption of the FC through its operating cycle. The AE generates hydrogen of up to 4 tons in the end of the cycle. However, half of it is extracted via the gas grid due to the storage unit limitation for stored gas. The system proves successful at operating through the full time frame continuously while following market price signals and limiting the voltage deviations. The proposed hydrogen system demonstrated that it is capable of following closely the variability of the market prices deviations and produce/consume power according to them.

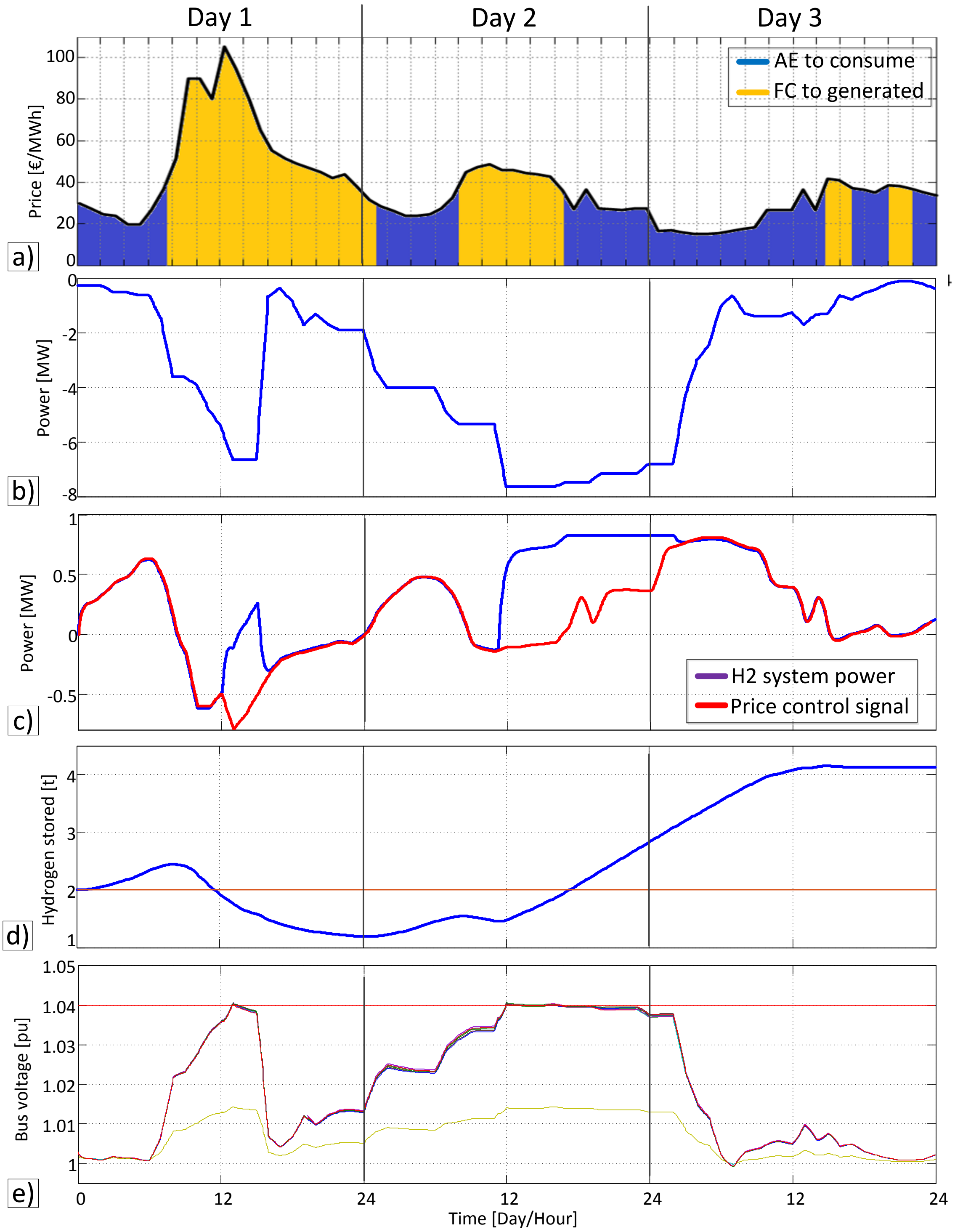


Fig 6.10 Network results – market price control Scenario 6.3
a) Electricity price b) Power generated in the local network c) Hydrogen system power output d) Stored hydrogen gas e) Bus voltages

6.3.4 Scenario 6.3 – Real data wind penetration

For this operating scenario the used data for the wind penetration is based on the real measured data for the days under study. The purpose for this operating scenario is to show how the proposed hydrogen system would have behaved under the exact same conditions for the 3 chosen days of 2014. The result obtained using the setting summarized in Table 6-1 can be seen in the following Fig 6.11.

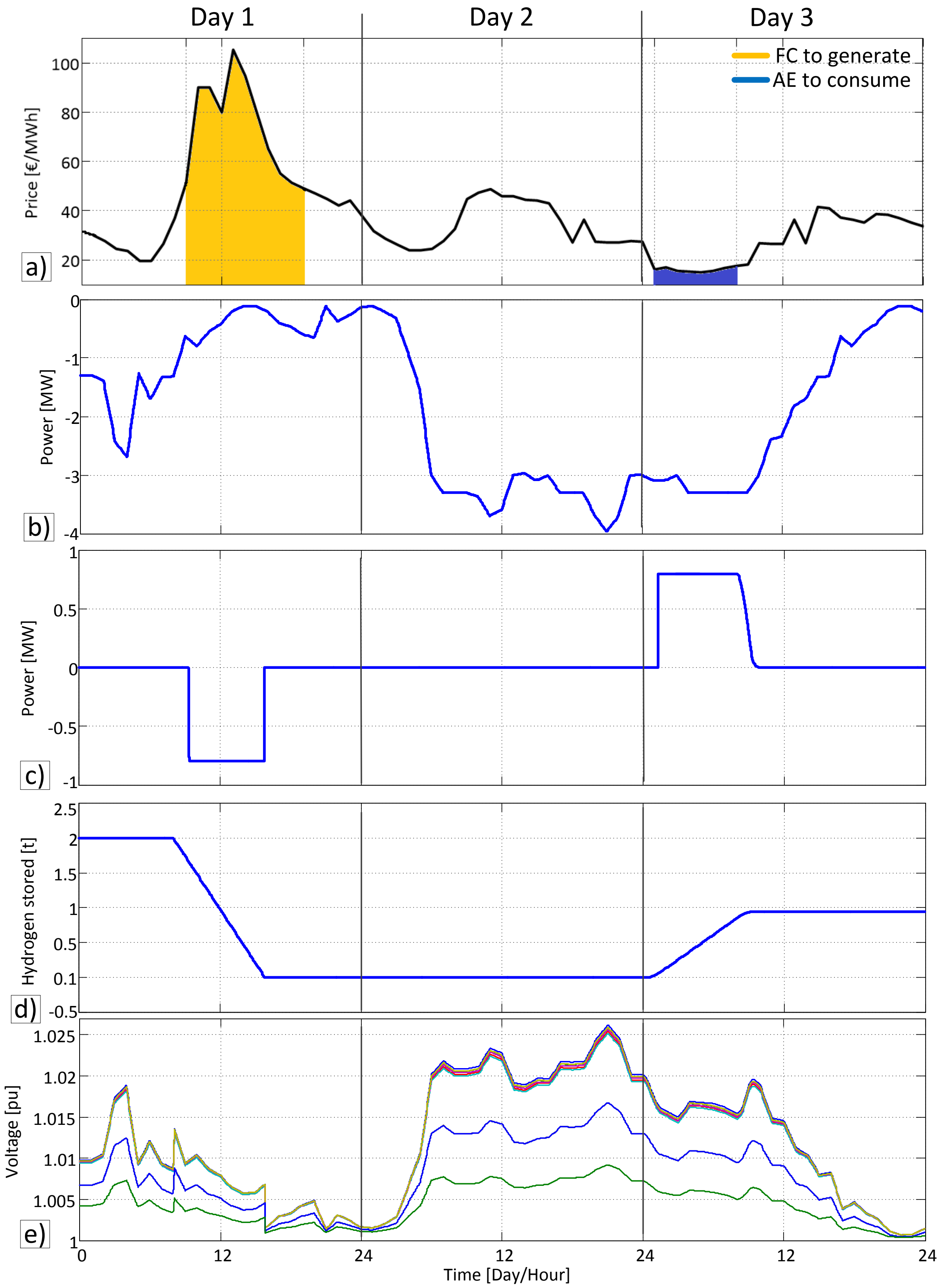


Fig 6.11 Network results – market price control Scenario 6.4
a)Electricity price b)Power generated in the network c)Hydrogen system power output
d) Stored hydrogen gas e)Bus voltages

It can be seen that on Day 1, the fuel cell is following the on/off market price control and starts generating power at a high price. However, at 16:00, as in Scenario 1, the hydrogen gas is depleted. During Day 3 the alkaline electrolyser is started following the low price of the grid. It is operational during the full low price period, generating up to 1 ton of hydrogen. The voltage plot does not show any issues related to overvoltages, given that the wind power generation is kept at medium levels.

This scenario shows that using real data for the 3 days chosen for the study, the proposed hydrogen system would have been successful at generating additional income. The market price control manages to take advantage from the high prices during the first day having only the limitations of the available hydrogen gas. During the third day, the system manages to generate hydrogen gas at low prices from the gird and fill the storage up to 50%.

6.4 Conclusion

The integration of market price control to the hydrogen system showed that it can provide effective demand response and economic efficiency based on the price volatility in NordPool Spot market. The system was able to consume power at low prices, thus generating hydrogen gas at lower resource cost. Given the NordPool Spot market and the correlation between wind power and low prices, it is possible to generate hydrogen gas from excess wind at cheap or even negative prices. This economic strategy may prove itself very beneficial given that the used hydrogen gas can be sold or used by FC. Another benefit stems from the ability to generate gas at negative prices which brings additional revenue from the same process which generates the resource to be used/sold later on.

This fuel cell is able to utilize part of the generated hydrogen in order to generate power at high electricity price periods. It was shown that during the high price periods, the fuel cell can generate power to the grid using the cheap hydrogen produced from the AE. This way the control strategy was able to buy power at low cost while selling it later on at a higher price. The exact monetary benefit of such strategy is not defined here due to the complicated financial analysis it requires, which is not a part of this study’s scope. However, it is certain to say that the system is successful at generating additional income from the NordPool Spot market while using market price control.

The results showed that by combining the market price control with voltage control, the hydrogen system is able to support the grid while accumulating revenue. By using both types of control, the system was able to generate more hydrogen during the 3 days. The extra generated hydrogen, if not used by the fuel cell, can be easily sold on the gas market and add to the overall income from the system.

Given the increasing price and demand for hydrogen gas over the years, the gas can be easily sold when extracted via the grid. Another option is to utilize the hydrogen in the CHP plants. The research of the economic benefits from using such strategy is beyond the scope of this study, however, but it should be accounted for as additional source of income.

Last but not least, the proposed system can provide additional reserve for wind farm owners. It can be used for covering last minute wind penetration fluctuation which is not accounted for in the weather report, thus mitigating the negative financial impact from weather forecast errors.

These results allow us to conclude that the hydrogen system is capable of generating economic gains from the energy market while at the same time supporting the grid. The only limitation imposed on the system found in this work is the stored hydrogen in the tank.

7 Conclusions and future work

This study presented a technical and economic assessment of a hydrogen system integrated in a network with high wind power penetration. Based on the project focus and requirements, the most suitable technologies for the hydrogen system components were chosen. The alkaline electrolyser was chosen as a preferred electrolyser, the polymer membrane was selected as the fuel cell technology and finally a pressurised storage tank was used for the H2 gas. Basis for the selection was essentially in the direction of the commercial availability, system cost and efficiency of the proposed technologies.

Given the chosen technologies, a mathematical model for each of them was developed. Based on the created models, all of the defined elements (AE, FC and storage unit) were connected together forming the proposed hydrogen system.

The developed hydrogen system was implemented and used based on the defined grid issues from high excess wind generation. The main tasks for grid support assigned to the hydrogen system were voltage deviation control and local power management. It was shown that the proposed system is successful at providing voltage deviation control for the buses in the local network. This was achieved by shedding part of the excess wind generated power flowing in the local grid, thus successfully reducing the local bus voltages under the predefined limits. The local power management control implemented for the proposed system proved to be capable of reducing the line loadings. By acting as a backup power source for the network, it also increased its reliability using the local power management control.

The energy market analysis for the hydrogen system showed its capacity for accumulating revenue by following changes in the electricity market prices. It was demonstrated how the system can benefit from the price fluctuations at the electricity market by adapting its demand/supply to the energy system. Based on these findings, it was concluded that the hydrogen system is suitable for providing grid support while taking advantage of the energy market prices for additional revenue.

From the findings of this study it can be conclude that the proposed hydrogen system is a viable future choice for integration in high wind power penetrated systems. The proposed system is capable at providing flexibility in the demand/supply of power in the energy systems. Thus mitigating some of the issues related to excess//shortage of power generation from wind turbines. Voltage regulation control and local power management are one of the main roles for such a system in a power network. Furthermore the system is capable at following the electricity market prices form the energy market. This provides the ability to generate hydrogen at cheap or negative prices from the grid which later on can be utilised benefiting the owner/operator of the proposed system.

The proposed system is a viable choice for DSOs, wind farm owners or private investors targeting revenue from taking advantage from the energy market prices. Distributions system operators can utilise the systems grid support capabilities hence enchanting the energy systems additionally. On the other hand wind farm owners can use the system to mitigate weather forecast errors and the financial losses related to them. Lastly private owners can utilise the system to take maximum advantage from the electricity market price fluctuations. Utilising the systems market price control and generate cheap hydrogen gas which can be sold or used by the fuel cell at more beneficial market prices.

Last but not least the overall cost of such hydrogen system should be defined. The prices are given in Table 7-1 based on the following sources [39] [40] [41].

Table 7-1
System prices

Component	**Capital cost €/kW or €/t**
Alkaline electrolyser	1100
Fuel cell	2500
Pressurised hydrogen storage	800

The future work related to the project should follow some of the limitations and possibilities presented form the proposed system. Some of them are the following:

- Detailed cost-benefit analysis for such a system has to be conducted. This will allow an overall assessment of the system and if its cost beneficial to be integrated now in the energy system given the current manufacturing prices. This type of analysis should focus on the system cost and the financial benefit it can introduce to its owner during its operation time. Assessment for the optimal usage of the extracted extra hydrogen from the proposed system should be included in it. Additionally data which takes into account the hydrogen gas market prices and the possibility to feed it to CHP plants should be obtained. Utilisation in CHPs plants and district heating is a viable option for the hydrogen gas using the Danish gas network. Another option is selling the hydrogen at the gas market given its wide range of use which provides additional platform for benefit. Based on that data and assessment of the obtained revenue accumulated using the mentioned markets and the system cost it will be decided if the proposed system is a viable solution given its cost.

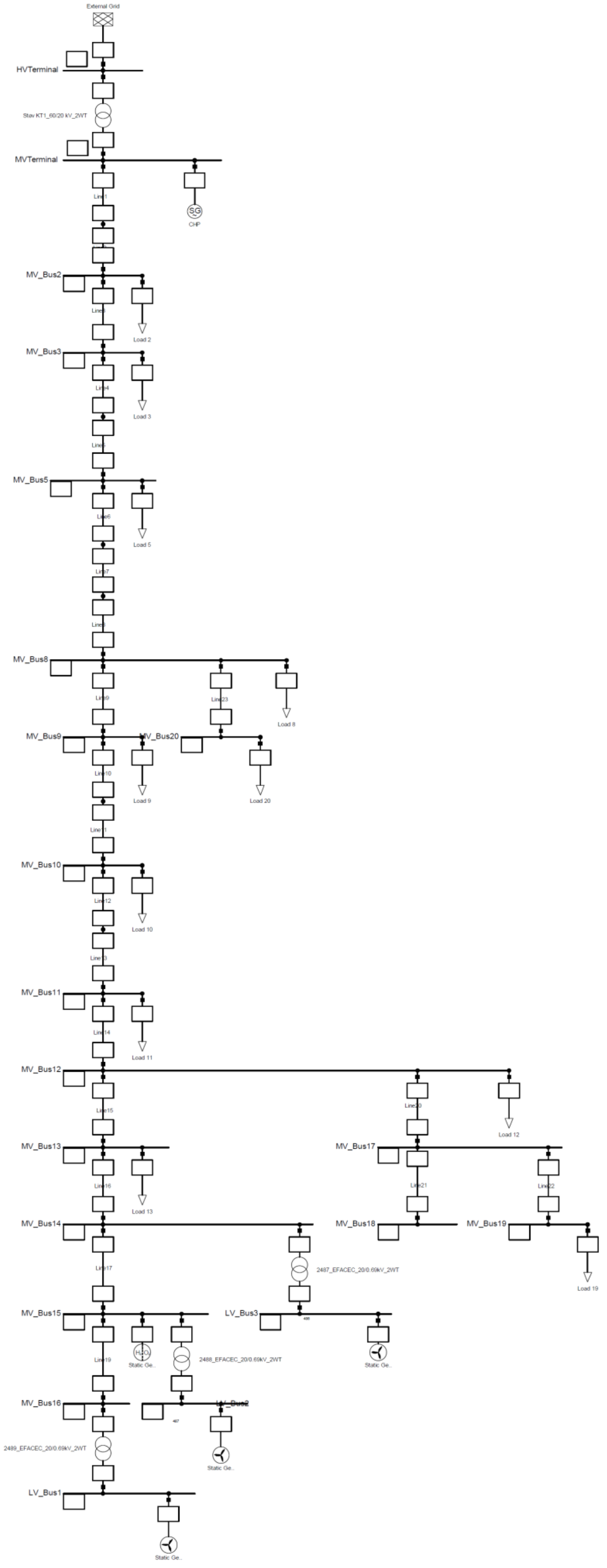
- More explicit and precise model for the hydrogen system that includes thermal management for the system, reactive power control and compressor implementation.
- A more definite electricity market price control strategy. Deeper financial analysis of the NordPool market is required to make an optimal price following strategy for the breakpoints of the market signals. Such analysis would provide data for implementing control strategy for best monetary income by following the electricity market price changes.
- Assessment for the optimal usage of the extracted extra hydrogen from the proposed system. An analysis which takes into account the hydrogen gas market prices and the possibility to feed it to CHP plants. Utilisation in CHPs plants and district heating is a viable option for the hydrogen gas using the Danish gas network. Another option is selling the hydrogen at the gas market given its wide range of use. Data from such analysis can be used to design an optimal gas control strategy which will increase the revenue from utilising the extra gas generated in the system.

Appendix A. Parameters chosen for the hydrogen system modelling

Parameter name	Parameter description	Chosen value	Choice of value based on:
r_1 r_2	Parameters related to the ohmic resistance in the electrolyte [Ω/m^2]	7.331e-5 1.107e-7	Model parameters defined empirically in [24]
s_1 s_2 s_3	Coefficients for overvoltage's of the electrodes [V]	1.586e-1 1.378e-3 -1.606e-5	Model parameters defined empirically in [24]
t_1 t_2 t_3	Coefficients for overvoltage's of the electrodes [$A^{-1}m^2$]	1.599e-2 -1.302 4.213e2	Model parameters defined empirically in [24]
T_e	AE electrolyte temperature [C^0]	80	Constant working temperature used in the project for the AE
F	Faraday constant [C mol^{-1}]	96485	Known value
z	Number of electrons transferred per reaction in AE	2	AE characteristic known value given in multiple references
a_1 a_2 a_3 a_4 a_5	Parameters related to Faraday efficiency	0.995 -9.5788 -0.055 1502.7083 -70.8005	Characteristic parameters related to the Faraday's efficiency in the alkaline electrolyser cell given in [25]
A_{cell}	Electrolyser cell active area [m^2]	0.25	Choise based on a given value for the active area in [25]
T	Fuel cell temperature [K]	333	Constant working temperature used in the project for the FC
p_{H2}	Hydrogen partial pressure inside the FC [atm]	7	Constant working working pressure used in the project for the FC value based on [26]
p_{O2}	Oxygen partial pressure inside the FC [atm]	1	Constant working working pressure used in the project for the FC value based on [26]
ξ_1 ξ_2 ξ_3 ξ_4	Semi-empirical coefficients of the FC model	-0.948 0.00286 7.6e-5 -1.93e-4	FC Model parameters defined empirically in [26]
R_e	Equivalent resistance for the electrons passing through the collecting plates of the FC [Ω]	0.0003	Characteristic value for the fuel cell model defined in [26]

L	Thickness of the fuel cell's membrane [cm]	0.0178	Characteristic value for the fuel cell model defined in [26]
A	Active area of the fuel cell [cm^2]	1.5	Choice based on the size given for the FC area in [20]
β	Adjustable modelling parameter	23	Adjustable modelling parameter for this specific model of FC defined in [26]
B	Semi-empirical coefficients of the FC model	0.15	FC Model parameters defined empirically in [26]
i_{max}	Maximum current density of the cell [A/cm^2]	1	Characteristic value for the fuel cell model defined in [26]
U	Utilization factor for the hydrogen of the FC	0.8	Characteristic value for the fuel cell model defined in [26]

Appendix B. Schematic of the network



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