Coordination Control of a Novel Topology of Wind Farm Combined with Hydrogen Storage System and Combustion Turbine

Master Thesis Report

Group WPS4-951

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Preface

The presented project is a long master thesis based on project "Modeling and Controlling of Modern Wind Farms with Hydrogen Energy Storage Systems". The project was carried out from 15th September 2015 to 23th May 2016. The project is conducted in Department of Energy in Aalborg University in Denmark.

The title of this report "Coordination Control of a Novel Topology of Wind Farm Combined with Hydrogen Storage System and Combustion Turbine" is a summary of the whole project. This project is to propose a novel topology of wind farm which can give constant output electrical power as conventional power plant.

As master thesis, this project is selected to present the overall knowledge that related to the education program "Wind Power System" (Electrical Engineering).

The project is studied and finished by the author alone under guidance from the thesis supervisor: Weihao Hu. The author would like to express the gratitude and appreciate to Weihao Hu for the guidance and support during the whole project work. The author would also thank the Aalborg University for the support during the study program.

A journal paper and two conference papers are published during this project. They are listed below:

(1) Shihua Xuan, Weihao Hu, Zhe Chen, "Coordination control of a novel configuration of wind farm combined with hydrogen storage system and combustion turbine", *Energies*, [Status: 1st invision]

(2) Shihua Xuan, Weihao Hu, Chi Su, Zhe Chen, "Modeling of Wind Farm Combined with PEM Electrolyzer and Combustion Turbine" *2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference* [Status: Under review]

(3) Shihua Xuan Weihao Hu, Jiakun Fang, Zhe Cheng "Voltage Fluctuation Mitigation of Wind Farms by Using PEM Electrolyzer" *2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference* [Status: Under review]

Summary

This project proposes a novel topology of a wind farm. The proposed topology consists of a wind farm, a proton membrane exchange (PEM) electrolyzer and a combustion turbine driven generator. A coordination strategy is also proposed in this report to coordinate the equipment in this topology. The objective of this proposed topology is to give constant electric output power. The coordination strategy also makes the system able to follow the order from transmission system operator (TSO). Thus, from the grid aspect, the proposed system is a conventional power plant.

The simulation of the system is built to verify and test the function and the performance of the proposed system. Several case study under different conditions or requirements are studied in this report.

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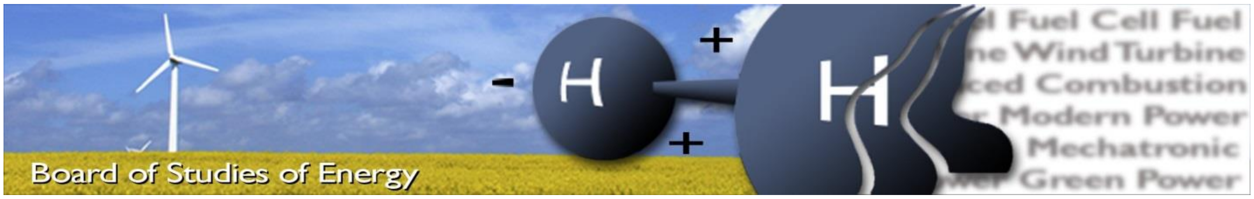

Title:	Coordination Control of a Novel Topology of Wind Farm Combined with Hydrogen Storage System and Combustion Turbine
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Synopsis:

The project aims to propose a novel topology that can supply constant electric power. The proposed topology also has the ability to follow the TSO order.

The control strategy, which coordinates the proposed topology to give constant electric power production, is also developed in this project.

The simulation is built and tested to verify the function and performance of the proposed system.

The simulation software is MATLAB/Simulink.

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.

Contents

1. Introduction

This chapter presents the general information of this project. The background of this project is introduced in 1.1. Some simple introduction of the key components is shown in 1.2. Based on the background and the key components of this project, the motivation of this project is proposed in 1.3. After the motivation of this project, the state of art is introduced in 1.4. In the last part of this chapter, the organization of this report is presented in 1.5.

1.1 Background

With the developing of human civilization, the energy requirement is keeping growing from year to year. When the resource of traditional energy, like coal and petroleum, become less and less, human beings are trying to seek a new energy solution. Wind power as a renewable energy source has been used by human being since a long time ago. In the early time, the sailing is designed for sailing and the mill is designed for crushing grain. The wind power is used to generate electricity since early 20th century. Recently, wind power generation technology is developed very fast, the capacity and the size of wind turbines grew a lot from 1990s to 2010s. The capacity of the wind farms also developed very fast. Now, the wind power generation technology is well developed. Big offshore or onshore wind farms are built to generate electricity.

The potential of the wind power generation technology is still big. According to the European Wind Energy Association (EWEA), the capacity of the wind power installation is still expected to rise by 41% to 85% from the end of 2013 until the end of 2020. EWEA's scenarios of wind power capacity growth of some countries of European Union are shown in table 1.

Table 1 - EU wind power installations, actual (end 2013) and new EWEA 2020 low, mid and high scenarios in MW [1]

Country	2013 actual installations (MW)		Low 2020 scenario (MW)		Central 2020 scenario (MW)		High 2020 scenario (MW)	
	Offshore	Total	Offshore	Total	Offshore	Total	Offshore	Total
Germany	520	34.250	5.000	45.000	6.500	51.500	7.500	57.500
UK	3.681	10.531	8.500	18.500	9.500	21.000	11.000	24.000
France	0	8.254	1.000	14.000	1.500	20.000	1.500	21.500
Poland	0	3.390	0	7.000	0	10.000	500	12.500
Denmark	1.271	4.771	2.300	5.900	2.800	6.500	3.000	7.000
Ireland	25	2.037	25	3.525	25	4.025	200	4.700
Czech R	0	269	0	500	0	1.000	0	1.200
Slovakia	0	3	0	150	0	300	0	350
EU 28	6.560	117.288	19.543	165.583	23.493	192.453	27.768	216.978

The wind power installations will keep increasing as shown in table 1. Thus, the ratio of wind power generation will increase in next few years. With the increase of the wind power installation, the ratio of the wind power generation in the power system will be increased. The wind power industry has a big potential to be developed. A bright future can be seen in wind power industry.

The modern wind farm has two different types: on shore wind farm and offshore wind farm. The onshore wind farm is proposed and developed since early 1900s. The offshore wind farm is introduced into industry since 1991, when the first offshore wind farm is built in Vindeby in Denmark. For onshore wind turbines, the construction is easier compared with offshore wind farms, but the good wind resources still make people interested in offshore wind farm technology. Figure 1.1 shows the positions, capacities and the construction years of the wind farms in Denmark. It can be seen the offshore wind farms developed very fast in recent years.

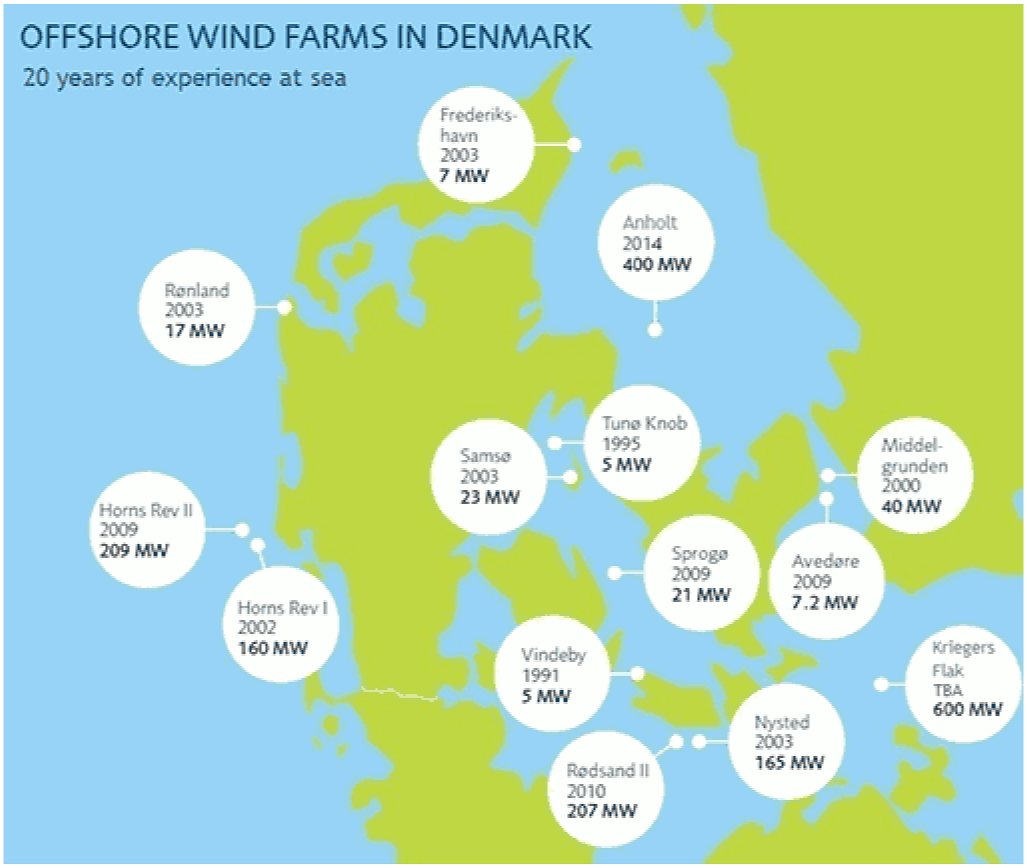

Figure 1.1 Wind farms in Denmark [2]

Wind power shows bright future, but also brings new challenges at the same time. The wind conditions are usually hard to be predicted precisely. Thus, the output power of wind farm is not stable due to the fluctuation of wind speed. The wind speed varies every second during one day. The load of power system also always varies. But the variation of wind speed does not match the variation of load, which is because the random wind speed does not “cooperate” with load variation. Figure 1.2 shows the wind speed variation of wind and load during one year. It can be seen that situation, which low wind energy meets the high load requirement, happens a lot during on year. To solve this problem, energy storage system for wind farms is proposed.

The energy storage system applied in industry now is mostly fly wheels or super capacitor banks. Flywheel converts the electric energy into kinetic energy when the energy production from wind farm is more than the load requirement, and at the alternative situation, it converts the kinetic energy into electricity. The super capacitor banks or battery storage system put the exceed energy from wind farm into storage and release it when necessary.

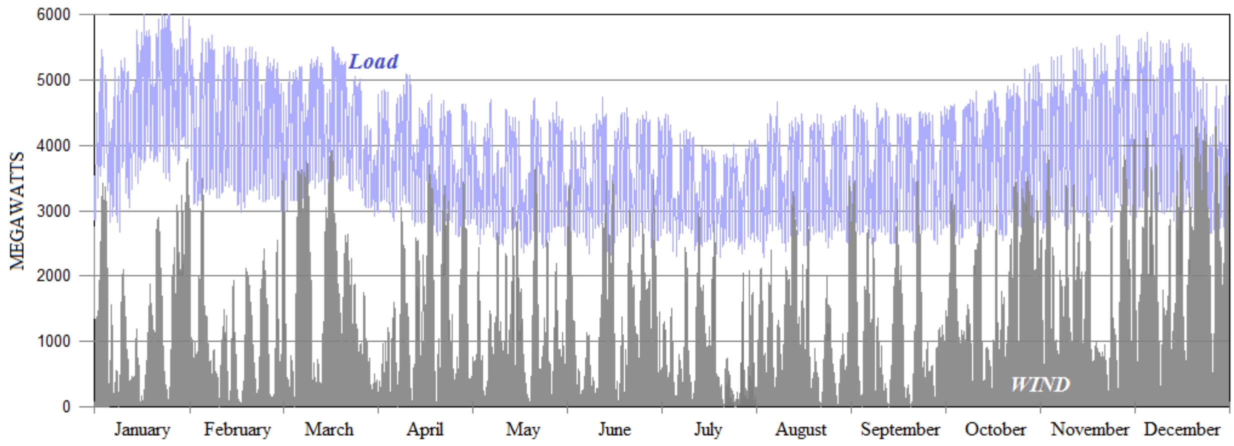

Figure 1.2 Total wind power generation and load variation in Denmark during 2013 [3]

Table 2. Wind energy abandon situation in China [4]

Province	Electricity lost due to abandon wind energy (100GWh)		Wind energy abandon rate(%)	
	Year 2012	Year 20113	Year 2012	Year 20113
Jilin	20.32	15.72	32.23	21.79
Gansu	30.24	31.02	24.32	20.65
Mengdong	52.36	33.09	34.30	19.54
Hebei	17.65	28.00	12.48	16.59
Heilongjiang	10.50	11.51	17.40	14.61
Mengxi	60.99	29.90	26.03	12.17
Xinjiang	2.15	4.31	4.29	5.23
Liaoning	11.29	5.28	12.54	5.00
Yunnan	1.70	1.69	5.98	3.68
Ningxia	0.47	0.43	1.22	0.78
Shanxi	0.16	0.00	0.57	0.00
Average in China	208.22	162.31	17.12	10.74

The energy storage system can only solve the energy fluctuation problem at a certain level. This is because the energy storage systems usually have capacity limitation, which means the energy storage system cannot store or release energy that exceed the capacity of the energy storage system. Thus, when the power production is far more than the load requirement, some wind farms shut down some wind turbines to abandon the wind energy, which is a waste of energy resource. Table 2 shows the situation of abandon wind energy in some district in China. The data in table is from China National Renewable Energy Center. It can be seen that the situation of abandon wind is pretty serious in China. Some district like Mengdong and Jilin has a wind energy abandon rate more than 30%. The wind energy abandon problem is not only a waste of nature energy resource, but also a waste of equipment. The solution of the wind energy abandon problem should be developed.

1.2 Key components in this project

This project involves a lot of equipment. Electolyzer and combustion turbine play important role in this project. Also the electric market is one of the concerns in this project. The information about these key components should be introduced.

1.2.1 Electrolyzer

The electrolyzer is applied in industry to produce hydrogen for a long time. The basic chemistry process in electrolyzer is to electrolysis water to get oxygen and hydrogen. The technology of electrolyer is well developed and wildly used in industry.

The electrolyzers in industry are usually proton exchange membrane (PEM) electrolyzer and alkaline electolyzer. Compare with alkaline electolyzer, the PEM electrolyzer has the advantages of higher current density, higher efficiency and no heavy metal ions. Thus, in the industry production, the PEM electrolyzer is applied more wildly than the alkaline electrolyzer. Figure 1.3 shows a photo of PEM electrolyzer. It can be seen that the electrolyzer applied in industry is usually made up by several small electrolyzers, and each small electrolyzer has their own tanks.

Figure 1.3 PEM electrolyzer [5]

Large equipment that applied for industry hydrogen production is usually made up of several PEM electrolyzer, and each electrolyzer is made up by several electrolyze chamber. The hydrogen is produced in each chamber to improve the efficiency. The hydrogen production from each chamber is separated from the vapor and then collected together. A pump is used to draw all the hydrogen production and compress the hydrogen production into tanks for storage.

1.2.2 Combustion turbine

The combustion turbine burns fuel to convert the chemistry energy into torque to drive machine. Thus, the combustion turbine can be used to drive generator to generate electricity. The combustion turbine is applied for electricity generation in industry for a long time. The technology of using combustion to drive large synchronous generator is well developed. Most of combustion turbines applied for electricity generation use oil as fuel. Some of the combustion turbines use gas like methane as fuel. The hydrogen combustion turbine is researched for a long time, and small-scale hydrogen combustion turbine is already developed.

The combustion turbine could be used to drive large synchronous generator. The generation technology based on synchronous generator is well developed. In the industry production, combustion turbine driven generator is usually used for peak regulation. This is because the combustion turbine do not need big boiler to produce steam to drive combustion turbine, which makes the combustion turbine could respond to the requirement very fast.

Combustion turbine produces torque by burning fuel in the chamber. Burning fuel produces heat and expands the air in the chamber, which further produces the air flow to hit blades. The blades drive the whole turbine to rotate, which further absorb and compress the air in chamber. The fuel burns in the compressed air, which further expands the air flow to drive the turbine. This process gives the turbine ability to provide torque to further drive generator. The energy conversion process is chemistry energy to heat energy, then to the kinetic energy.

The efficiency of this energy conversion process is around 30% to 40%. The most energy loss is in form of heat dissipation. The efficiency of energy utilize could be increased by recycling the heat for the unit that has heat requirement. It is also possible to increase the efficiency to drive multi shaft combustion turbine. The energy utilize efficiency of GT26-1 from ABB could be up to 58.5%.

1.2.3 Electricity market

From the point of economy, electricity is an industry product that can be trade. The electricity is usually generated by power plant and sold to transmission system operator (TSO). The TSO transmit the electricity from power plant to customers. The electricity is sold to customers to make profit. The profit made by TSO is usually used to build equipment that necessary for electricity transmission. When the power plant sells the electricity to TSO, the price varies from time to time. Sometimes the electricity price could be negative, which means the power plant has to pay TSO to give electricity to TSO.

The electricity price is depending on the electricity market. The electricity market is depending on the relationship between supplement and requirement. When the generation is much greater than the load, the TSO sets the electricity price for power plant to be negative to prevent further power input from power plant. When the generation is insufficient, the TSO set the price for power plant to be higher to encourage generation. So the electricity market could balance the generation and load.

The electricity could be sold or traded in form of power (W, KW, MW) or energy (KWh, MWh). The electricity price varies according to the condition of grid or electricity market. Also, the electricity price for different types of customer is different. The electricity price is usually higher for industry customers than household customers.

The TSO in Denmark is Energinet, which is a none-profit company. The Energinet coordinate the electricity in Denmark. The states of the grid and the electricity market data can be found on the Energinet's home page: www.Energinet.dk.

1.3 Motivation

With the proper control strategy, modern wind farms could satisfy most of the requirement of the grid code, but some problems of wind farm still exist so that the wind farms still cannot replace the conventional power plant completely. The technology of wind power generation should be further developed to completely replace the conventional power plant in the future.

One of the major problems for wind farms is that the output power is fluctuating. The fluctuation of power production is caused by the variation of wind speed. For the modern wind farms, energy storage system is applied to solve the problem of output power fluctuation. The energy storage system could release certain energy to compensate the power production during low wind situation. But the energy released by the energy storage system is limited regardless what kind of energy storage system is applied in the wind farm. Besides the fluctuation of wind speed, the tower shadow and wind shear effect also contribute a lot to the oscillation of the output power of wind farms, which cause output power drops regularly when wind turbine rotates. The 3p (three times per revolution) oscillation caused by wind shear and tower shadow effect also influences the voltage at the point of common coupling (PCC). For modern wind farms, the stability and reliability are two of the most important concerns. To replace the conventional power plant, the wind farms have to have very reliable and stable constant output power which is possible to follow the orders form TSO.

The project proposed a new topology to solve the problem above. With the proposed topology and control strategy, the system could work in such a way that the output power of the system is constant like conventional power plants. The output power of the system should also have the ability to adjust the output power according to the TSO order. The output power of the system should be constant regardless of the wind condition.

1.4 State of art

The energy storage system for wind farms has lot of types. The commonly used energy storage systems are flywheel storage and battery storage. The dynamic performance of the wind farm based on flywheel storage system is studied and proposed in [6]. The research based on the battery storage system for the wind farm is conducted in [7]. Besides the mentioned energy storage system, some storage system based on the operation is also possible. A storage system using the rotation energy as a storage system is proposed in [8]. For the wind farms with the energy storage systems, the coordination between the wind farm and the energy storage system is very important and necessary. The coordination strategy varies according to the type of the energy storage system. Methods about coordination between wind farms and the energy storage system are proposed in [8] and [9]. To summarize the function of the energy storage system, the energy storage system could release certain quantity of energy when the situation like low wind meets the high requirement of energy happens. But the energy released by the energy storage system is usually limited by the capacity of the energy storage system.

Besides the instability of wind, the wind turbine output power is fluctuating due to the influence of wind shear effect and tower shadow effect. The fluctuation of output power caused by the reasons above is called 3 times per revolution (3p) oscillation. The 3p oscillation for the wind turbine is studied in [10]. The fluctuating power will further influence the voltage at the point of common coupling (PCC) [11]. A study of 3p flicker mitigation by active power control based on variable speed wind turbine is conducted in [12].

Combustion turbine has been used for electricity generation for a long time. Compare with steam turbine, one of the advantages of the combustion turbine is the faster reaction. The starting process of combustion turbine is also usually faster than steam turbine because the starting process of combustion turbine is simpler. The character of faster respond makes combustion turbine more suitable for peak regulation in power system operation. The steam turbine usually has a corresponding boiler, which makes the structure of the generation system more complicated, which requires more complicated maintenance jobs and operation jobs. Thus, the combustion turbine is more suitable for the situation, in which the equipment is operated automatically. In [13,14], a test about combustion turbine is conducted. In [15], a model of twin-shaft combustion turbine is proposed. Reference [16] proposed a technical assessment about compressed air energy storage, which combine wind farm with combustion turbine. Now, most of the combustion turbine use oil as fuel to drive generator. Some combustion turbine use methane as fuel due to the high heat value of the methane [17]. New prototype of the combustion turbine that uses hydrogen as fuel is developed. [18], [19].

The hydrogen storage system for wind farms draws a lot of attention recent years due to the low emission [20]. The hydrogen storage system shows bright future also because the high heat value of hydrogen. The most widely used way to produce hydrogen in industry now is to electrolysis water. The process of electrolysis water obeys the Faraday's law of electrolysis. The

Proton Exchange Membrane (PEM) electrolyzer is more welcome compared with alkaline electrolyzer in industry because the high efficiency and no heavy metal ions [21]. Usually, when the electrolysis process is involved in the electrical study, the model of electrolyzer is simplified into the Faraday's law of electrolysis, which may cause some important process being neglected. Reference [21] proposed a model of detail PEM electrolyzer. A research about a combination of the photovoltaic with PEM electrolyzer is proposed in [21]. Another PEM model that can be used for electrical analysis is proposed in [22]. Reference [23] proposed the combination of wind farm and hydrogen generation system interconnected with high-voltage DC system. A combination of wind farm, electrolyzer and fuel cell is presented in [24].

The wind turbines in the wind farm usually use induction generator, only recent years the permanent magnet synchronous generator is introduced in the wind turbines. The induction generator has the disadvantage, which requires certain electricity for excitation during the starting process. The disadvantage mentioned above makes the wind farm impossible to finish the black starting process. For conventional power plant, black starting is possible to be achieved. Back starting is still necessary for a generation unit in power system even modern power system is more stable than before. Thus, to make a wind farm achieve black start is necessary. The black start of wind farm is not a new topic. A lot of research is conducted to study the black start of wind farm. Almost all the black start strategy now needs a power source inside the wind farm.

The static synchronous compensator (STATCOM) is applied for reactive power compensation in power system. One of the advantages of STATCOM is that the flexible reactive compensation. For wind farms, especially for the squirrel-cage induction generators, reactive power compensation is usually necessary. STATCOM is a possible solution for the reactive power compensation of wind farms. STATCOM usually consists of a transformer, PWM rectifier and a large capacitor. The dynamic operation of STATCOM is not a new topic. [25] did a research about the reactive power compensation in wind farm based on STATCOM. [26] did a research about STATCOM based on modular multilevel converter.

1.5 Organization of this project

This report is organized as following:

Chapter 1 Introduction presents: the background of the project and brief introduction of electrolyzer, combustion turbine and electricity market. The motivation and state of art are also presented in this chapter.

Chapter 2 Problem formulation presents: the challenge that faced by the project, objective and limitations.

Chapter 3 Proposed topology and configuration propose the novel topology and describe the corresponding components.

Chapter 4 Modeling and simulation implement presents the modeling and testing of each components in the proposed system.

Chapter 5 Proposed control strategy presents the proposed control strategy. The testing of the control strategy is also presented in chapter 5.

Chapter 6 case study presents the different case studies of the proposed system.

Chapter 7 conclusion and future work presents the conclusion of this project and the further future work could be done.

2. Problem formulation

This chapter presents the challenges, objectives and limitations of this project. To formulate the problems of this project, the challenges faced by this project are analyzed and shown in 2.1. After the challenges are presented, the objectives are proposed in 2.2 according to the challenges. Finally, the limitation of this project is presented in 2.3.

2.1 Challenges description

A. Active power production of wind farm

The active power production of the wind farm is not stable. One of the reasons is that the wind speed varies, which cause the output power fluctuation of the wind turbines. Besides of the reason above, the tower shadow effect and wind shear effect also contribute to the oscillation of the output power of wind turbines. The output power of the wind farm should be mitigated. The oscillation caused by the 3p oscillation component should be removed, and the fluctuation caused by the wind speed variation should be compensated by the energy storage system.

B. Wind farm and energy storage system coordination

The function of an energy storage system of a wind farm is to storage the exceed power and release it when necessary. Thus, the cooperation between the wind farm and the energy storage system is important. The ideal energy coordination result is to use energy storage system to absorb the exceed energy or compensate the insufficient energy, so that the output power of the wind farm could be like a conventional power plant. The coordination strategy should be developed to achieve this goal.

C. Capacity limitation of energy storage system

The energy storage system for modern wind farms usually has a capacity limitation. The energy can be stored or released is limited. If the exceed energy is beyond the capacity of the energy storage system, the exceed wind energy has to be abandoned, which is a waste of nature resource. The exceed energy has to be taken into utilization.

D. Wind energy abandon problem

The wind farms sometimes produce more energy than the requirement, or sometimes when the local requirement has big variation, like a big factory is shut down, the installed capacity of wind farms is then greater than the local load requirement. Wind farms are shut down to abandon the wind energy when the above described situation happens. This problem should be solved so that the wind farms can make the most use of nature energy resource. The wind farm should make use of the wind energy as much as it could, no matter what the load condition is.

E. Coordination between gas network and electricity network

The gas network is an energy resource network, which is usually used to transport methane. The Sabatier Reaction makes it possible to produce methane from hydrogen. Electrolyzer has the ability to convert the electricity into hydrogen and oxygen. The hydrogen could be further used to produce methane, which could be coordination between gas network and electricity network.

2.2 Objectives

The objectives of this project are:

- Proposing a new topology and corresponding control strategy, which could make the wind farm work like a conventional power plant from the grid aspect. This means the whole system should have a constant power output, but also have the ability to respond properly to the TSO order. The system should also have the ability to supply reactive power. What is more, the whole proposed system should have the ability to supply power and respond to the TSO order under extreme conditions, such as no wind or all the wind turbines are out of service.
- A control strategy for the proposed topology should be developed. The control strategy should coordinate the wind farm and the energy storage system, and make the wind farm and the energy storage system respond well to TSO order under different conditions.
- An energy storage system which has no limitation of capacity should be developed. This energy storage system should have ability to cooperate with the wind farm and respond well to the give order.
- The proposed topology should have the ability to solve the wind energy abandon problem. The wind farm should absorb wind power as much as possible ignoring the grid conditions.
- The proposed system should have the ability to cooperate the electricity network with the gas network. The exceeding energy production from wind farm could be sent into gas network in form of methane.

2.3 Methodology

Among all the objectives above, the main purpose task of this project is active power coordination. Thus, the objective of active power coordination needs to be described in detail here:

The active power produced by wind turbines is not stable. This is because the variation of the wind speed could cause the fluctuation of the active power produced by the wind turbines. The wind shear effect and tower shadow effect also cause a 3p oscillation component in the active power produced by the wind turbines.

The proposed topology should have the ability to convert the fluctuation power into constant. To pick out the 3p oscillation component in the active power production, the power production from the wind turbines should be measured, and then a band pass (BP) filter should be designed to pick out the 3p oscillation signal from the power measurement. The 3p oscillation signal picked out by the BP filter should be consumed by the PEM electrolyzer, in this way, the 3p oscillation power is picked out. Thus, according to the law of the law of conservation of energy, once the 3p oscillation component is picked out, the reminding power which sent into the grid is smoothed. After the power is smoothed, the fluctuation component in active power, which caused by the wind speed variation should be compared with transmission system operator (TSO). The exceed power signal should be sent into PEM electrolyzer to be consumed. The PEM electrolyzer consumes the power and produce hydrogen and oxygen for later use. The insufficient power signal should be sent into combustion turbine. The combustion turbine should generate the power according to the reference to compensate the insufficient power. Thus, the final output power should be a constant.

It should be mentioned that, to make sure that the reaction of the PEM electrolyzer is correct, a detailed PEM model is built.

2.4 Limitations

The limitations of this project are:

- The combustion turbine has the ability to supply reactive power. Because the main concern of this project is active power coordination, thus, to simplify the model and simulation, the combustion turbine does not supply reactive power. The necessary reactive power for the simulation is supplied by STATCOM.
- Some assumptions are made to simplify the model, which is described in chapter 4.
- Some average model is applied in concern of simulation step and simulation speed, which is described in chapter 4 in detail. To simplify the simulation, some assumptions have been made, which is described in chapter 4 in detail. The experiment will not be conducted to test this project due to the limitation of the equipment.
- The due to the limitation of the subject, the equipment that needed for interconnection of the system and the gas network will not be modeled.
- The capacity of the wind farm, PEM electrolyzer and the combustion turbine are decided to perform the simulation smoothly. The capacities of all the equipment are not optimized in this project.
- The responds of the system under fault conditions are not studied in this project.

3 Proposed topology and configuration

This chapter describes the proposed topology and the equipment that is involved in this topology. The configuration of the whole system is presented in 3.1. The equipment that is involved in the system is presented in 3.2.

3.1 Description of the system

The topology of the system is shown in figure 3.1:

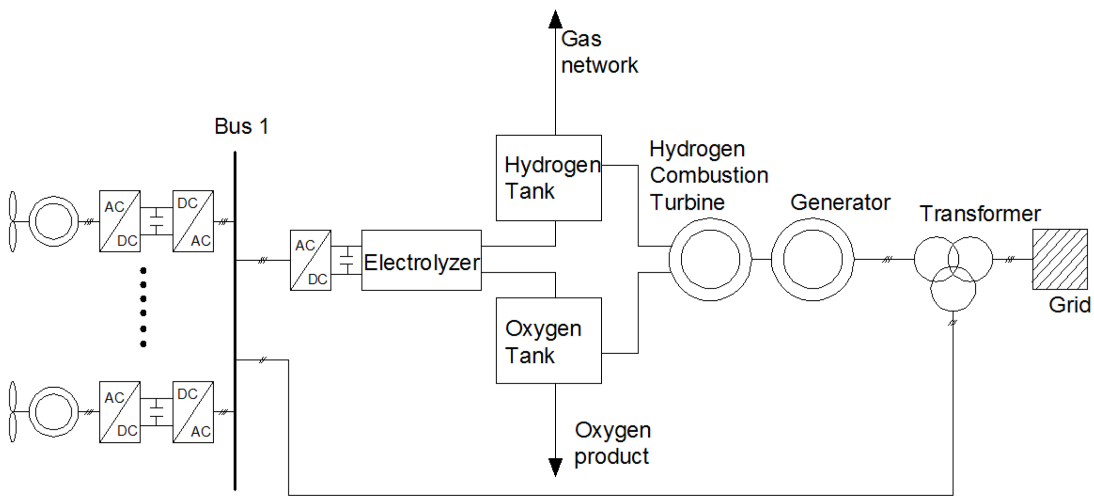

Figure 2.1 The topology of the proposed system

The system is made up of wind turbines, an electrolyzer and corresponding tanks, a combustion turbine and corresponding generator, and a transformer. The wind turbines are all connected a Bus, which is shown as Bus 1 in figure 3.1. The bus 1 is then connected to the grid directly through the transformer. The PEM electrolyzer is also connected to the Bus 1 through a rectifier. The output of the PEM electrolyzer is hydrogen and oxygen, which is outputted into corresponding tanks. The combustion turbine is connected to the tanks through pipes to take gas from the tanks. A generator is driven by the combustion turbine to generate electricity. The electric power generated by the combustion turbine driven generator is sent into grid through the transformer.

The wind power captured by wind turbines is converted into electrical power which contains the fluctuation component caused by variation of wind speed, and the 3p oscillation component caused by wind shear effect and tower shadow effect. A band pass (BP) filter is designed to pick out the 3p oscillation power signal, and then send into rectifier as power reference. Once the rectifier convert the 3p oscillation AC power into DC power, according to the law of conservation of energy, the 3p oscillation component is picked out. Thus, the power which is sent into grid directly from Bus 1 is smoothed. The electolyzer convert the electricity into hydrogen and oxygen production, and then output them into tanks for storage. The hydrogen tank is also connected to gas network. The oxygen production in the oxygen tank could be output directly as industrial oxygen production. The hydrogen combustion turbine takes the hydrogen and oxygen from the tanks as fuel to drive the generator according to the requirement.

To verify the performance of the proposed system, the electrical model of the proposed system is built. The proposed system is connected to the grid. To perform the system properly, the reactive power compensation should be taken into consideration. The combustion turbine in the system has the ability to supply reactive power. Due to the main concern of this project is active power coordination, also to simplify the model and simulation, the combustion turbine is not involved in supplying reactive power. Thus, a STATCOM is connected to the PCC bus to compensate the reactive power for the proposed system. The modeling of the grid is described in chapter 4.7 in detail.

3.2 Description of the component in the system

The key components in the system include an electrolyzer, a combustion turbine driven generator, a wind farm and a STATCOM. Ideally, the combustion turbine in this project has the ability to generate reactive power to satisfy the reactive power requirement in the system. To simplify the project, a STATCOM is included in this system to compensate the reactive power requirement, because the main objective of this project is active power coordination.

3.2.1 Electrolyzer

Compare with alkaline electolyzer, the PEM electrolyzer has the advantages of higher efficiency and no heavy metal ions [13]. Thus, the PEM electrolyzer is applied more widely in industry. This project chooses PEM electolyzer for the system.

The PEM electrolyzer is applied to produce hydrogen by electrolyzing water. The chemistry process in the PEM electrolyzer is to apply current through water, which produces hydrogen and oxygen. The conception of electrolyze water to get oxygen and hydrogen is from the electrochemistry, which is the main method to produce hydrogen in industry. The chemical reaction can be expressed as equation (1):

$$2H_2O \overset{electricity}{=} 2H_2 \uparrow + O_2 \uparrow \quad (1)$$

In this chemical reaction, the positive pole produces oxygen. The corresponding half-reaction equation is shown as equation (2)

$$2H_2O \rightarrow 4H^+ + O_2 + 4e^- \quad (2)$$

The negative pole produces hydrogen. The corresponding half-reaction equation is shown as equation (3) (in alkaline solution):

$$4H^{+} + 4e^{-} \rightarrow 2H_{2} \tag{3}$$

The bound of these two subjects is the Faraday's laws of electrolysis. Electrolyze process obeys the Faraday's laws of electrolysis, which can be simply expressed as the quantity of the production from positive pole is proportional to the current and the time used. The equation is shown as equation (4):

$$M = KIt = KQ \tag{4}$$

In which:
M is the mass of the production
K is electrochemical equivalent
t is the time used during the process
Q is the electric quantity

This project requires an electrolyzer to convert the electricity into hydrogen production for the further utilization. The electolyzer in this project is to consume fluctuating active power, thus, the dynamic performance of this PEM electrolyzer is important. To perform the dynamic reaction, a detailed model of PEM electrolyzer is required.

The PEM electrolyzer model should contain the positive pole model, negative pole model, proton exchange membrane model, tank storage model, and voltage model. The positive pole model is to calculate the oxygen production, the oxygen flow, and vapor pressure for exchange between positive pole and negative pole. The negative pole is to calculate hydrogen production, hydrogen flow, and the vapor pressure for exchange between positive pole and negative pole. The proton exchange model is to calculate the water flow exchange between positive pole and negative pole. The proton exchange membrane model also calculates water activity and water content. The voltage model is to calculate the voltage across the PEM electolyzer. Tank storage model is to calculate gas storage and the pressure in the tank. All the calculation is according to the current flow through the PEM electrolyzer

3.2.2 Combustion turbine

The combustion turbine has been applied for industry electricity generation for a long time. The fuel for combustion turbine could be oil or gas. The fuel is burned to drive the combustion turbine, so that the chemistry energy is converted into kinetic energy. Then the rotating combustion turbine drives the generator to generate electricity. The advantage of combustion turbine could make faster response compared with steam turbine. To adjust the steam turbine, the boiler should also be adjusted. The adjustment of combustion turbine could be achieved by adjusting the fuel for the combustion turbine.

The combustion turbine model in this project is to simulate the process of burning the hydrogen from PEM electrolyzer to drive the generator to generate electricity. The combustion turbine should express this power conversion process precisely. The The model should react properly to the variation of hydrogen quantity which is given to the combustion turbine. The model should also have the ability to generate the electrical power according to the reference.

It should be point out that the output power of combustion turbine is produced by burning the hydrogen in the burning chamber. This means the output power of the combustion turbine is based on the quantity of the hydrogen burned in the chamber. The quantity of hydrogen is a integration of hydrogen flow, which means the quantity of hydrogen cannot sudden change/ Thus, the output power of the combustion turbine can be changed very fast, but cannot be changed suddenly.

3.2.3 Wind farm

A wind farm is usually made up by more than one wind turbines. Generally, the wind turbines absorb wind energy and convert it to electricity. The wind turbines could use PMSG, DFIG or other induction generator to generate electricity. The blades of the wind turbine capture the wind power and convert wind energy into rotation kinetic energy. The rotating blades drive the generator to generate electricity. One of the main concerns of this project is the active power production mitigation of the wind farm. Thus, the wind turbine model should have the ability to give active power production.

The wind turbine model in this project is to calculate the output power according to the wind speed. The wind turbine model should also respond properly to the wind speed fluctuation and the 3p oscillation component in wind speed. The wind turbine model should give the proper output in form of total power quantity signal or three phase electrical signal. The output should respond properly to the input, i.e. wind speed.

The variation of wind speed means the input power for the wind turbines varies. The inertia of wind turbines is usually smaller than the inertia of steam turbine or combustion turbine. Thus, the variation of input power could be reflected on the output power very fast. Which mean when the wind speed varies, the output power of the wind turbines also varies almost at same the time. The active power fluctuation is caused by two main reasons: the fluctuation of wind speed, and the 3p oscillation caused by wind shear and tower shadow effect. Thus, a detailed wind speed model is necessary as a part of wind farm model for the project.

The wind speed model should contain the fluctuating wind speed at hub height, the equivalent wind speed of wind shear effect, the equivalent wind speed of tower shadow effect.

A. Tower shadow effect

The modern wind turbine is usually placed on the top of a tower. The existence of the tower has influence on the aerodynamic performance of wind turbines. When the wind hit the tower, the air flow will be split, as shown in figure 3.2. The disturbance caused by the tower changes the air flow condition in front of the tower. The changed air flow influences the pitches when the pitches passes the area, which further influence the power absorbed by the pitch. The wind energy captured by the pitches has a decrease when the pitch passes the position of tower, which is termed as tower shadow effect. The detailed equations of calculation of tower shadow effect are shown in chapter 4.2. The tower shadow effect causes the drop of the power absorbed by the pitches, which further cause the drop of power production of the wind turbines.

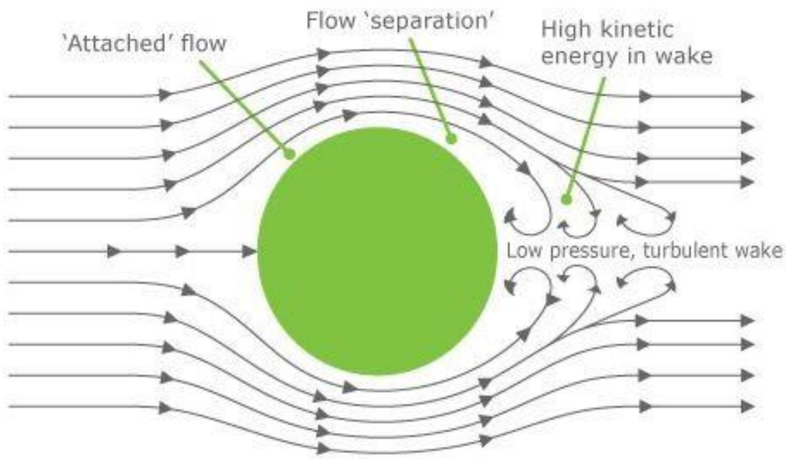

Figure 3.2 Tower shadow effect [27]

B. Wind shear effect

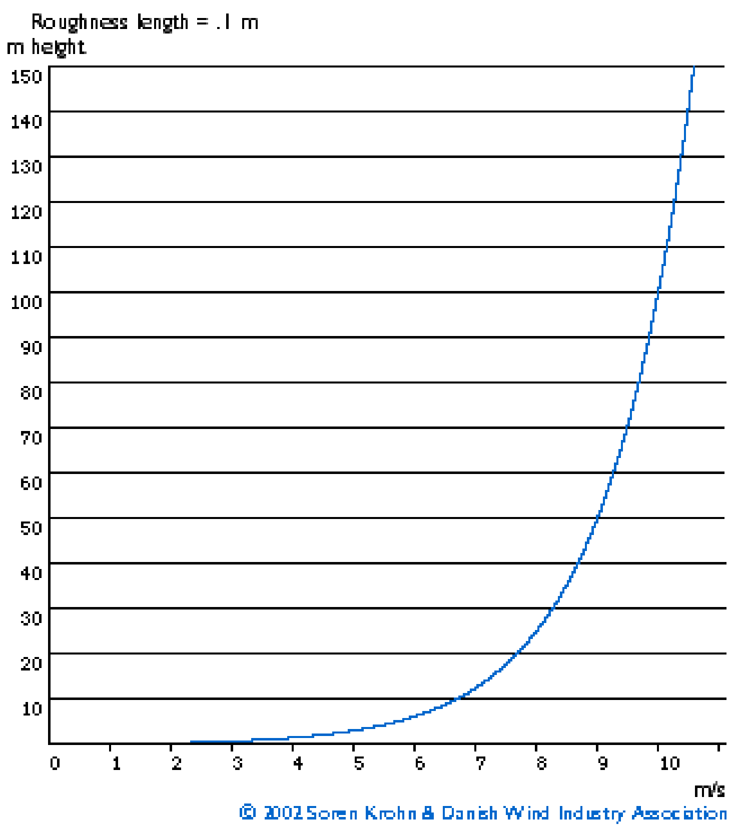

Figure 3.3 Wind shear effect

Generally, wind speed is different at different height. The wind speed usually increases with the increase of height from ground, which is shown in figure 3.3. The increase of the wind speed with the increase of height is terms as wind shear effect. The wind energy is a function of wind speed. The height of each pitch varies when the wind turbine rotates, which causes the variation of the energy that absorbed by the pitch varies. The output power of wind turbines is based on the power absorbed by the pitches, thus, when the power absorbed by the pitches varies, the output power of wind turbine varies. The detailed equations of the equivalent wind speed influenced by wind shear effect are presented in chapter 4.2

C 3 times per revaluation

The number of pitches of a wind turbine is related to the torque that the turbine can provide. The curves in figure 3.4 show the relation between tip-speed ratio and rotor torque coefficient for different types of wind turbines. It can be seen that when the number of pitch increases, the peak point of the curve increases, the corresponding tip-speed ratio for the peak point decreases. This means when a wind turbine has more pitches, this wind turbine can give more torque, but at the same time, the wind speed that needed give the top torque is slower.

The modern onshore wind farms usually use three-pitch wind turbines to capture the wind energy, which is due to the concern of torque coefficient, resonance and other factors. The three-pitch wind turbines is tested and applied in industry for a long time. For 3 pitch wind turbines, the pitches pass the position of tower three times per revolution, which means the power production that caused by the tower shadow effect appear three times per revolution. For the same reason, the power production oscillation caused by wind shear effect also appears three times per revolution.

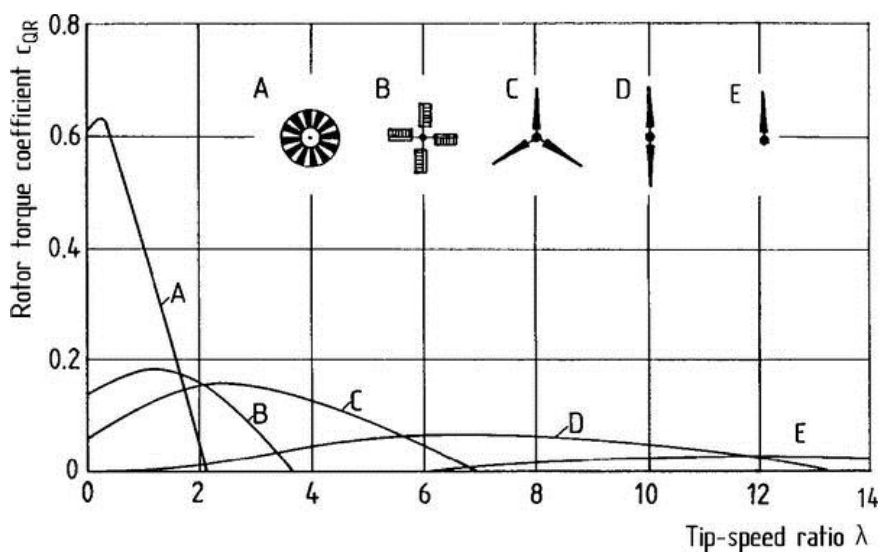

Figure 3.4 Tip-speed ratio vs rotor torque coefficient for different types of wind turbine [29]

The wind speed model which contains all the components that described above should be built to perform the active power fluctuation. The modeling of the wind speed model is introduced in chapter 4.2

3.2.4 STATCOM

As a device used for power system reactive power compensation, STATCOM is widely used for reactive power compensation. Compared with some other compensation devices, STATCOM has some advantages such as: less harmonic component, faster reaction, and flexible reactive power compensation. Usually, a STATCOM consists of a convertor, a DC side energy storage power source, and inductor [25]. The connection from the STATCOM to the grid could be described like in figure 3.5.

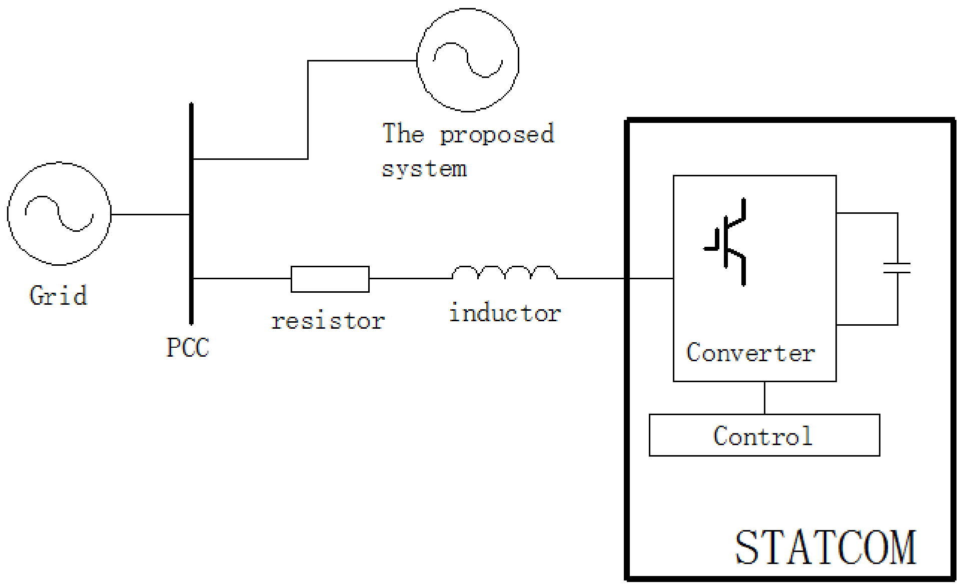

Figure 3.5 The connection of STATCOM

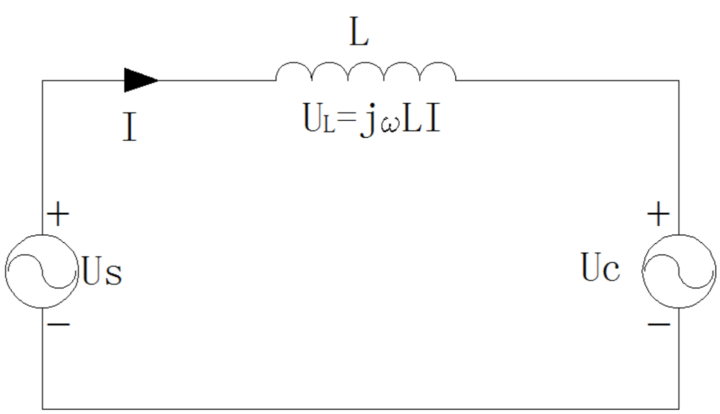

Figure 3.6 The equivalent circuit of Figure 3.5 without resistor

If neglect the losses(all the resistor is zero), the equivalent circuit of figure 3.5 could be described like figure 3.6. In the figure 3.6, $U_s$is the voltage of the grid side, U_c is the voltage of the converter side, U_L is the voltage drop of the inductor. As shown in figure 3.6, the positive direction of the current is defined as the current flow from the grid to the converter. Consider all the variables as vector, equation 5 could be obtained.

$$\dot{I} = \frac{\dot{U}_s - \dot{U}_c}{j\omega L} \tag{5}$$

It could be seen from the equation 5 that the direction of the current could be controlled by changing the converter side voltage. When $U_s > U_c$, the current is lagging converter side voltage 90 degrees, as shown in figure 3.7, the STATCOM now works like an inductor.

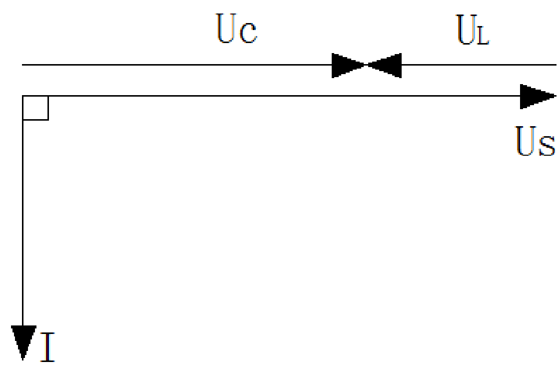

Figure 3.7 The current and voltage vectors of Figure 3.6 when $U_s > U_c$

When $U_s < U_c$, the current is leading converter side voltage 90 degrees, as shown in figure 3.8, the STATCOM is working like a capacitor.

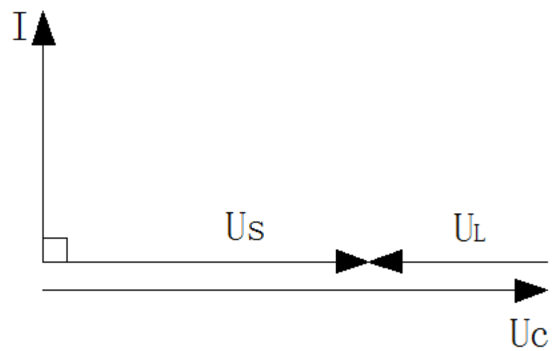

Figure 3.8 The current and voltage vectors of Figure 3.6 when $U_s < U_c$

In practical, the losses must be considered. When take the losses in consideration, assume all the losses is presented by a resistor, the equivalent circuit is described as in figure 3.9. Because of the existence of the resistor, the angle between U_s and I is no longer 90 degree. As shown in figure 3.10, when the current is lagging U_s by a degree less than 90 degree, the STATCOM is working like an inductor. When the current is leading U_s by a degree less than 90 degree, the STATCOM is working like a capacitor, as shown in figure 3.11. As expressed before, either working as an inductor or a capacitor could be adjust by change the U_C. By changing the amplitude or the phase of U_C, the amplitude and the phase of current could be changed.

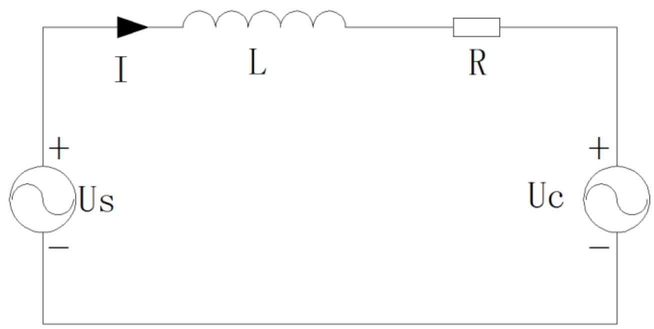

Figure 3.9 The equivalent circuit of Figure 3.5 with resistor

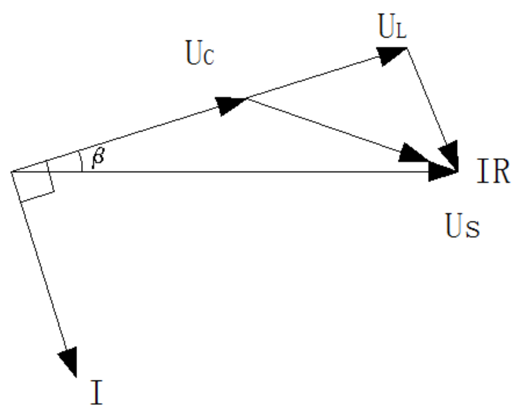

Figure 3.10 The current and voltage vectors of Figure 3.9 when $U_s > U_c$

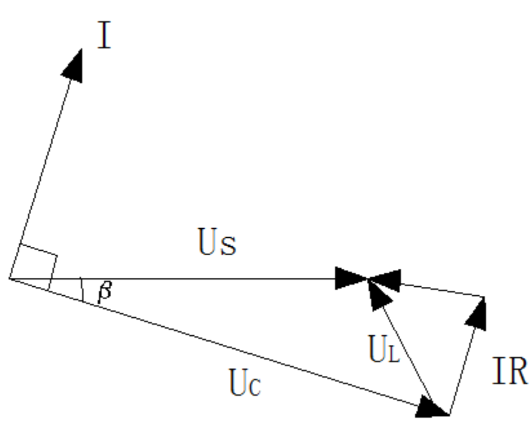

Figure 3.11 The current and voltage vectors of Figure 3.9 when $U_s < U_c$

The STATCOM model is not main concern of this project. The requirement of STATCOM for this project is only to compensate the reactive power so that the wind farm model could work properly. The model of STATCOM should have the function mentioned above. Detailed model of the STATCOM is not necessary. The model of STATCOM should compensate the reactive power properly according to the requirement.

4. Modeling of the proposed system

This chapter presents the modeling of the proposed system. All the related equations for modeling different equipment are presented in this chapter. For the equipment build by mathematical model, a test of the performance of the model is also conducted and presented after the modeling.

4.1 Modeling of PEM electrolyzer

The model of PEM electrolyzer is proposed in [21] and applied in this project. The PEM electrolyzer model in this project is built in a detailed way to perform the dynamic performance of the PEM electrlyzer. The PEM electrolyzer model in this project includes positive pole model, negative pole model, proton exchange membrane model, voltage responds model, tanks model. A electrical model of the PEM electrolyzer is also built to perform the electrical modeling of the whole system

4.1.1 Calculation of hydrogen production speed

The electric charge of each electron is elementary charge. The quantity of charge carried by each mole of electron can be calculated by equation (6)

$$q = e_0 N_a \tag{6}$$

in which:

q is the charge quantity carried by each mole of electron (C/mol)

e_0 is the charge carried by each electron (C)

N_a is the Avogadro's constant (mol^{-1})

And according to equation (3), for every mole of hydrogen, 2 mole of electron is needed. Thus, to produce every mole of hydrogen, 2 × q Kulum (C) charge is needed. The quantity of electric charge also can be expressed as equation (7)

$$Q=It \tag{7}$$

in which

Q is quantity of electric charge

I is current

t is time

The quantity of hydrogen can be expressed as equation (8)

$$N = \frac{Q}{2q} \tag{8}$$

Therefore, from equation (6) (7) (8) the production velocity of hydrogen (H_{2g}) can be expressed as equation (9), in which, F is Faraday's constant.

$$H_{2g} = \frac{N}{t} = \frac{\frac{Q}{2q}}{t} = \frac{\frac{It}{2eN_a}}{t} = \frac{It}{2eN_a t} = \frac{I}{2eN_a} = \frac{I}{2F} \tag{9}$$

4.1.2 Modeling of positive pole of the PEM electrolyzer

The positive pole model calculates the pressure of O_2 at positive pole for the voltage model, the O_2 flow from positive pole for the storage model, the pressure of H_2O at positive pole for the membrane model.

The positive pole of the electrolyzer produces O_2 andH^+. The H^+ combines with H_2O form H_3O^+ which comes to negative poles [21]

The dynamic equations that describe the positive poles is shown as equation (10):

$$\begin{cases} N_{O_2} = \int F_{O_{2ai}} - F_{O_{2ao}} + O_{2g}\,dt \\ N_{H_2O_a} = \int F_{H_2O_{ai}} - F_{H_2O_{ao}} - F_{H_2Oeod} - F_{H_2Od}\,dt \end{cases} \tag{10}$$

In which:

N_{O_2} is the quantity of oxygen
$F_{O_{2ai}}$is the input mole velocity of oxygen at positive pole, which is zero
$F_{O_{2ao}}$is the output mole velocity of oxygen at positive pole
$O_{2g}$is the oxygen production in mole velocity
$N_{H_2O_a}$ is the quantity of water at positive pole
$F_{O_{2ao}}$is the input mole velocity of water at positive pole
$F_{H_2O_{ao}}$ is the output mole velocity of water at positive pole
F_{H_2Oeod} is the electro-endosmosis velocity of water
F_{H_2Od} is the diffusion velocity of water

According to the Faraday's laws of electrolysis, the production speed of oxygen is shown as equation (11). It should be noticed that the production speed expressed by equation (11) is the total production speed from all the cells in the electrolyzer.

$$O_{2g} = \frac{nI}{4F}\eta \tag{11}$$

In which:

n is the number of electrolyzer capsules that connected in series .

I is the current flow through the series electrolyzer .
F is the Faraday's constant.
η is the efficiency of the electrolyzer, which is usually bigger than 99%.

The production of oxygen causes pressure in the chamber. The pressure of the oxygen in the chamber can be calculated by ideal gas equation. The oxygen pressure can be calculated as equation (12).

$$P_{O_2} = \frac{N_{O_2}RT}{V_a} \tag{12}$$

In which

R is the gas constant
T is the temperature
V_a is the volume of the chamber of positive pole

In the electrolyzer, the existent of water vapor cannot be avoided. The steam will also cause the pressure. The pressure of steam can be calculated by equation (13):

$$P_{H_2O_a} = \frac{N_{H_2O_a}RT}{V_a} \tag{13}$$

Thus, the total pressure at positive pole, which is caused by oxygen and the vapor, is shown as equation (14):

$$P_a = P_{O_2} + P_{H_2O_a} \tag{14}$$

Thus, the percentage of the oxygen can be expressed by pressure. The percentage of oxygen at the positive pole is shown as equation (15):

$$y_{O_2} = \frac{P_{O_2}}{P_a} \tag{15}$$

The relationship between pressure and flow can be simplified into linear [21]. The relation is expressed as equation (16):

$$F_{ao} = k_{ao}(P_a - P_{ao}) \tag{16}$$

In which, the k_{ao} is Pipe flow coefficient. The output of the positive pole is assumed to be connected to a pump to take out the oxygen production, thus, the P_{ao} in equation (16) is assumed to be 0. At the same time, it should be noticed that the flow from positive pole is a mix of oxygen and water vapor, so the flow can be also expressed as equation (17):

$$F_{ao} = F_{O_{2ao}} + F_{H_2O_{ao}} \tag{17}$$

From the equation (15) and equation (17), it can be obtained the flow of oxygen and water vapor at positive pole can be expressed as equation (18):

$$\begin{cases} F_{O_{2ao}} = y_{O_2} F_{ao} \\ F_{H_2O_{ac}} = (1 - y_{O_2}) F_{ao} \end{cases} \tag{18}$$

4.1.3 Modeling of negative pole of the PEM electrolyzer

The negative pole model calculates the pressure of H_2 at negative pole for the voltage model, the H_2 flow from negative pole for the storage model, the pressure of H_2O at negative pole for the membrane model.

The negative pole of electrolyzer produces H_2 from H_3O^+, at the same time, some water come from positive pole to negative pole due to concentration difference. The dynamic equations that describe the negative poles is shown as equation (19):

$$\begin{cases} N_{H_2} = \int F_{H_{2cl}} - F_{H_{2co}} + H_{2g}\, dt \\ N_{H_2O_c} = \int F_{H_2O_{ci}} - F_{H_2O_{co}} + F_{H_2Oeod} + F_{H_2Od}\, dt \end{cases} \tag{19}$$

In which:

N_{H_2} is the quantity of hydrogen

$F_{H_{2cl}}$ is the input mole velocity of hydrogen at negative pole, which is zero due to no input of hydrogen

$F_{H_{2co}}$ is the output mole of hydrogen velocity at negative pole

H_{2g} is the hydrogen production in mole velocity

$N_{H_2O_c}$ is the quantity of water at negative pole

$F_{H_2O_{ci}}$ is the input mole velocity of water at negative pole

$F_{H_2O_{co}}$ is the output mole velocity of water at negative pole

F_{H_2Oeod} is the electro-endosmosis velocity of water

F_{H_2Od} is the diffusion velocity of water

According to the Faraday's laws of electrolysis, the production speed of hydrogen can be calculated as equation (20). It should be point out that the equation (9) only shows the hydrogen production speed in single chamber of electrolyzer, while the equation (20) shows the total hydrogen production speed.

$$H_{2g} = \frac{nI}{2F}\eta \tag{20}$$

The pressure of the Hydrogen can be calculated by ideal gas equation as equation 21.

$$P_{H_2} = \frac{N_{H_2}RT}{V_c} \tag{21}$$

The pressure of vapor at negative pole can be calculated by equation (22).

$$P_{H_2O_c} = \frac{N_{H_2O_c}RT}{V_c} \tag{22}$$

The total pressure at negative pole is shown as equation (23).

$$P_c = P_{H_2} + P_{H_2O_c} \tag{23}$$

The percentage of the hydrogen at the negative pole is shown as equation (24):

$$y_{H_2} = \frac{P_{H_2}}{P_c} \tag{24}$$

The relationship between pressure and flow can be simplified into linear [21]. The relation is expressed as equation (25):

$$F_{co} = k_{co}(P_c - P_{co}) \tag{25}$$

In which, the k_{ao} is Pipe flow coefficient. At the same time, it should be noticed that the flow from negative pole is a mix of hydrogen and water vapor, so the flow can be also expressed as equation (26):

$$F_{co} = F_{O_{2co}} + F_{H_2O_{co}} \tag{26}$$

From the equation (24) and equation (26), it can be obtained the flow of hydrogen and water vapor at negative pole can be expressed as equation (27):

$$\begin{cases} F_{H_{2co}} = y_{H_2}F_{co} \\ F_{H_2O_{co}} = (1 - y_{H_2})F_{co} \end{cases} \tag{27}$$

4.1.4 Modeling of proton exchange membrane

Proton Exchange Membrane model is mainly used to study the water transmission phenomenon. The water transmission in the proton membrane is mainly due to electro-endosmosis and diffusion phenomenon.

The water transmission caused by electro-endosmosis phenomenon can be described as equation (28):

$$\begin{cases} F_{H_2Oeod} = n_d \frac{i}{F} M_{H_2O} A n \\ n_d = 0.0029\lambda_m{}^2 + 0.005\lambda_m - 3.4 * 10^{-19} \\ \lambda_m = \sqrt{\lambda_a{}^2 + \lambda_c{}^2} \end{cases} \tag{28}$$

In which:

M_{H_2O} is the molar mass of water

A is the arean of the electrolytic cell

n_d is the electric traction coefficient

λ_a and λ_c is the water content for positive pole and negative pole. They can be calculated as equation (29):

$$\begin{cases} \lambda = 0.43 + 17.81a - 39.85a^2 + 36a^3 & 0 < a \le 1 \\ \lambda = 14 + 1.4(a - 1) & 1 < a \le 3 \\ a = \frac{P}{P_0} \end{cases} \tag{29}$$

In the equations above, a is the water activity, P is the pressure of vapour, and P_0 is the pressure of standard pure vapour which is calculated by Goff-Grattch equation, which is described by equation (30)

$$\log_{10} e_w = -7.90298\left(\frac{T_{st}}{T} - 1\right) + 5.02808 \log_{10}\left(\frac{T_{st}}{T}\right) - 1.3816 \times 10^{-7}\left(10^{11.344\left(1-\frac{T_{st}}{T}\right)} - 1\right) + 8.1328 \times 10^{-3}\left(10^{-3.49149\left(\frac{T_{st}}{T}-1\right)} - 1\right) + \log_{10} 1013.25 \tag{30}$$

The water transmission caused by diffusion could be described by Fick's law of diffusion, which is shown as equation (31)

$$F_{H_2Od} = D_w \frac{C_{wc} - C_{wa}}{t_m} M_{H_2O} An \quad (31)$$

In which, t_m is the thickness of the membrane, C_{wc}, and C_{wa} is the concentration of water at the surface of membrane. other parameters could be calculated by the following equations (32) and (33):

$$D_w = D_\lambda \times e^{2416 \times (\frac{1}{303} - \frac{1}{T_{el}})} \quad (32)$$

$$\begin{cases} D_\lambda = 10^{-10} & \lambda_m < 2 \\ D_\lambda = 10^{-10} \times (1 + 2 \times (\lambda_m - 2)) & 2 \leq \lambda_m < 3 \\ D_\lambda = 10^{-10} \times (3 - 1.67 \times (\lambda_m - 3)) & 3 \leq \lambda_m < 4.5 \\ D_\lambda = 1.25 \times 10^{-10} & \lambda_m \geq 4.5 \end{cases} \quad (33)$$

4.1.5 Modeling of voltage responds of PEM electrolyzer

The voltage model is to describe the relation between the current and voltage. The voltage model includes the open circuit voltage of the electrolyzer, activation polarization voltage, ohm polarization voltage, which is described by equation (34)

$$V_{el} = E + V_{el.act} + V_{el.ohm} \quad (34)$$

The open circuit voltage E could be described by equation (35):

$$\begin{cases} E = E_0 + \frac{RT_{el}}{2F} \ln(\frac{P_{H_2} P_{\frac{1}{2}O_2}}{a_{H_2O}}) \\ E_0 = \frac{\Delta G_f}{2F} \end{cases} \quad (35)$$

In which

ΔG_f is the Gibbs free energy
F is the Faraday's constant
R is the gas constant
T_{el} is the temperature
a_{H_2O} is the water activity, which is 1 here

The activation polarization voltage can be expressed as equation (36)

$$V_{el.act} = \frac{RT_{el}}{2\alpha F} \ln(\frac{i}{i_0}) \quad (36)$$

The ohm polarization volatage can be expressed as equation (37)

$$\begin{cases} V_{el.ohm} = iR_{el.ohm} \\ R_{el.ohm} = \dfrac{t_m}{\sigma_m} \\ \sigma_m = (0.00514\lambda_m - 0.00326) \times e^{1268(\frac{1}{303} - \frac{1}{T_{el}})} \end{cases} \tag{37}$$

In equation (36) and equation (37):

α is the passing coefficient
i_0 is the exchange current density
$R_{el.ohm}$ is the resistor of the membrane

4.1.6 Modeling of tanks for PEM electrolyzer

The storage model in this paper is to describe the relation between pressure and quantity of the gas stored in the tank. The dynamic equation is shown as equation (38)

$$P = z\frac{N_{H_2}RT_b}{M_{H_2}V_b} \tag{38}$$

In which:

P is the pressure of the tank
z is the compress constant
N_{H_2} is the input mole speed of hydrogen (mol/s)
R is the gas constant
T_b is the temperature of the tank
M_{H_2} is the mole mass of hydrogen
V_b is the volume of the tank

The energy consumption of equipment that necessary for the hydrogen storage is neglected. The volume of hydrogen tank is twice bigger than the volume of oxygen tank due to the production ratio.

4.1.7 Electrical model of the PEM electrolyzer

The mathematical model is built to calculate the hydrogen and oxygen production, gas flow, gas pressure, voltage, and the power consumption. The function of PEM electrolyzer for the whole system is to consume the electricity energy according to the reference, therefore, from the grid aspect, the PEM electrolyzer is a dynamic load. To verify the performance of the electrolyzer in power from electrical aspect, a model of dynamic load model is built to consume the electrical energy during the electrical modeling.

The Simulink library provide dynamic model that can follow the given reference. The electrical power signal that needs to be consumed is sent into this model. The constitution of the reference of power signal is described in chapter 2 in detail.

4.1.8 Dynamic simulation of elctrolyzer

The overall connection of the different model of the PEM electrolyzer is shown in figure 4.1. The positive pole model uses the current and water supplement to calculate the oxygen production, oxygen pressure at the positive pole and the oxygen flow from positive pole. The positive pole model also calculates the vapor pressure for proton exchange membrane model, which is to calculate the water flow exchange between positive pole and negative pole. The negative pole is to calculate hydrogen production, hydrogen pressure and hydrogen flow according to the current. The vapor pressure for calculation of exchange between positive pole and negative pole is also calculated in negative pole model. The proton exchange model is to calculate the water flow exchange between positive pole and negative pole. The voltage model take the hydrogen and oxygen pressure at corresponding pole to calculate the voltage across the PEM electolyzer. Tank storage model takes the hydrogen and oxygen flow to calculate gas storage and the pressure in the tank.

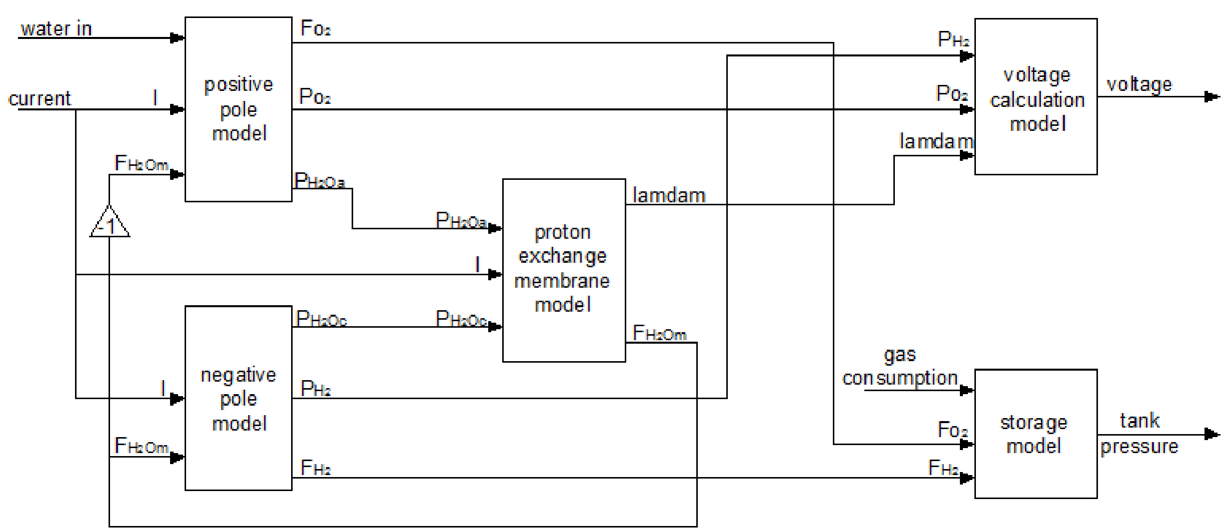

Figure 4.1 The signal connection between different models in PEM electrolyzer

The dynamic simulation of the PEM electrolyzer is to test the performance of the electrolyzer. The electrolyzer model is given a current signal with step variation. The respond of the PEM electrolyzer, which including the hydrogen production speed and hydrogen production flow variation is observed. Besides, the voltage responds and pressure responds of the hydrogen tanks are also observed.

It should be point out that the hydrogen production speed responds to the current, thus, the current, as the input signal of PEM electrolyzer, is assumed to be as shown in figure 4.2 to test the performance of PEM electrolyzer. The respond of the hydrogen production speed is shown in figure 4.3.The hydrogen production flow from negative pole is shown in figure 4.4. The hydrogen flow is a function of the hydrogen production speed, vaper flow, the internal pressure and so on. It can be seen that the hydrogen flow respond to the hydrogen production speed, which is in a manner of gas flow respond to pressure variation. This is because the hydrogen production speed influences the pressure in the chamber. The pressure in the chamber is function of hydrogen quantity. The hydrogen quantity is dynamic balance of production and output flow. The hydrogen quantity cannot change suddenly, which mean the pressure of hydrogen cannot change suddenly. Thus, the hydrogen flow cannot change suddenly.

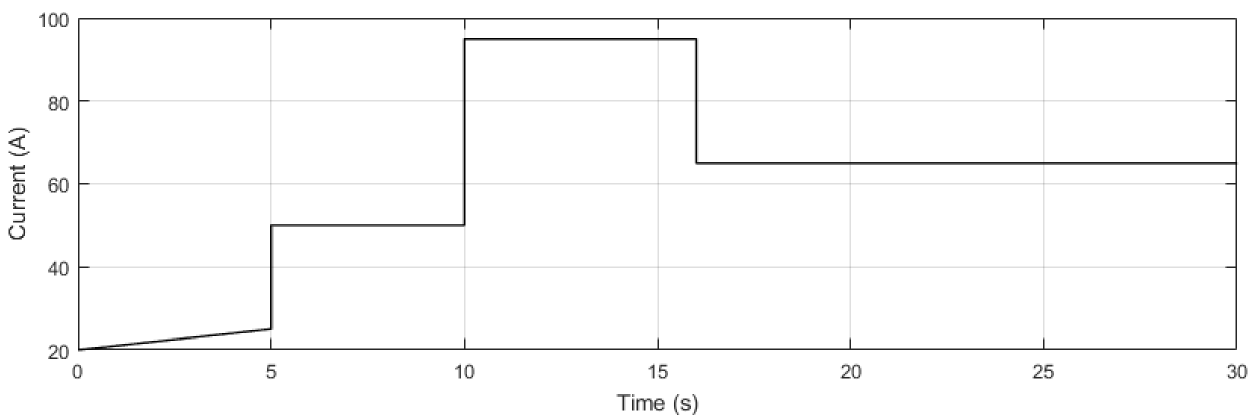

Figure 4.2 The current signal for PEM electrolyzer testing

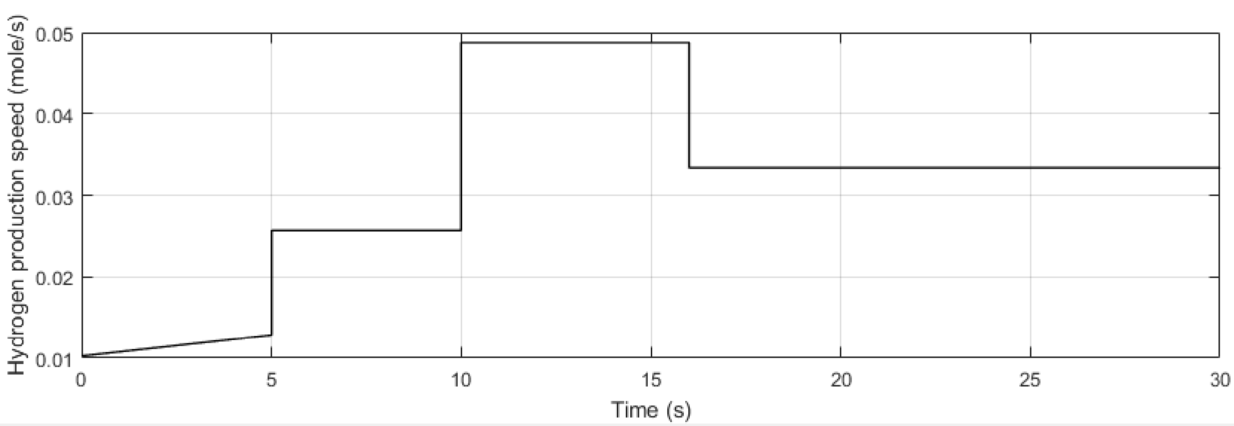

Figure 4.3 The corresponding hydrogen production speed refer to current signal

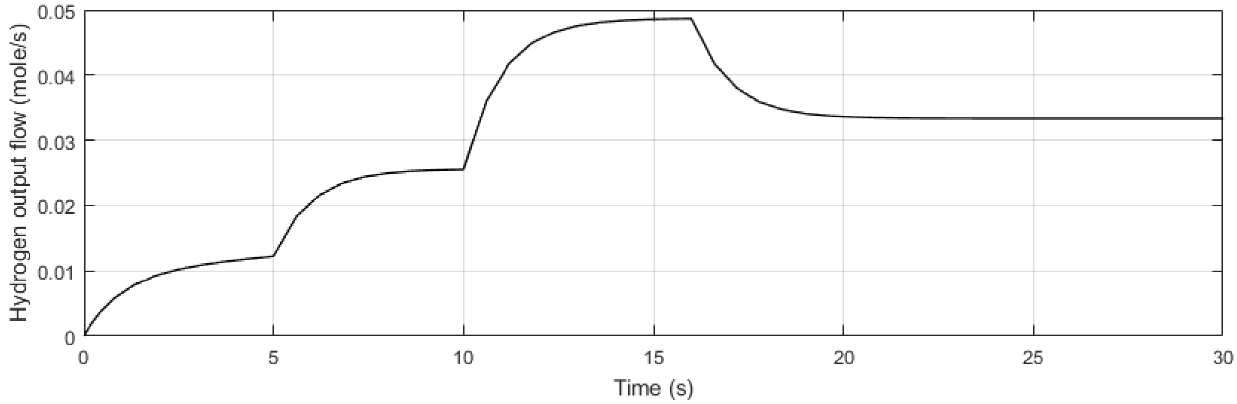

Figure 4.4 The hydrogen production flow

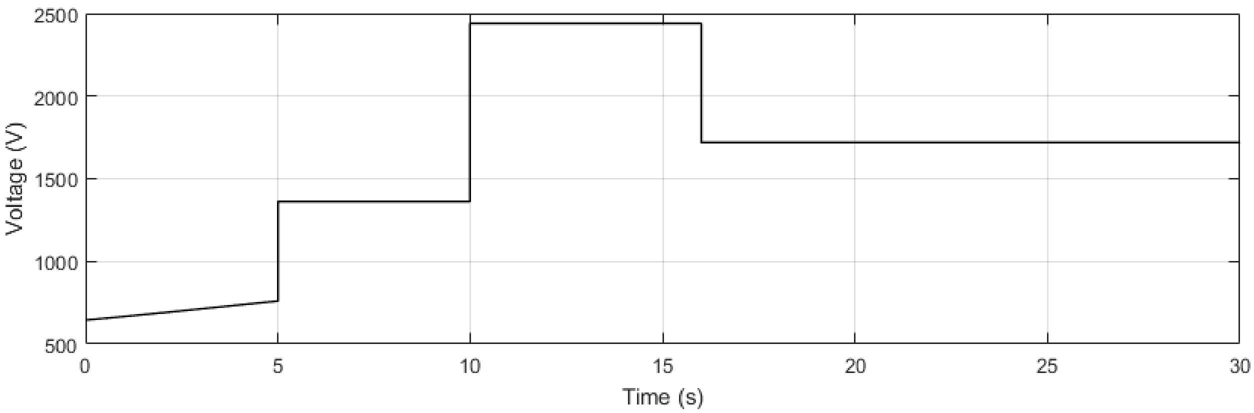

Figure 4.5 The voltage across PEM electrolyzer

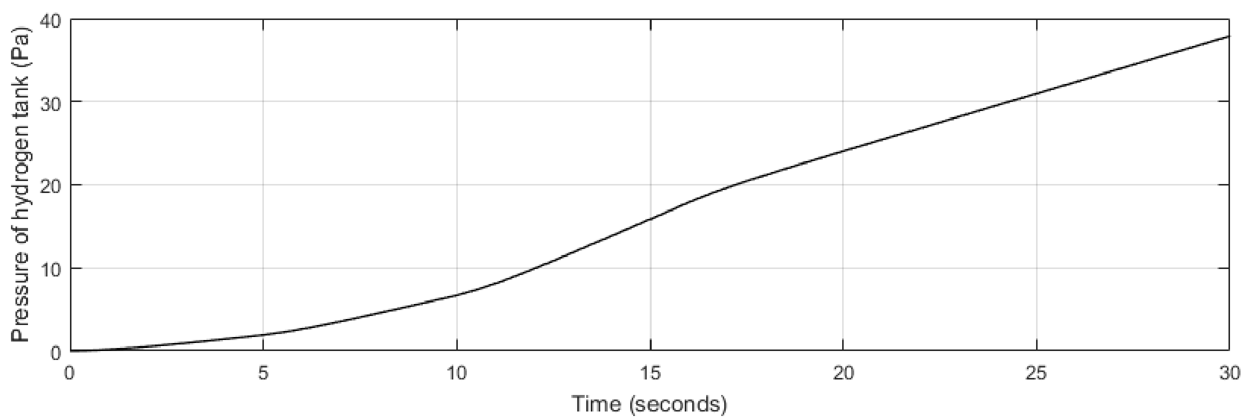

Figure 4.6 The pressure of the hydrogen tank

The voltage responds is shown in figure 4.5. It can be seen that the voltage varies according to the current, but the changing rate is different. The pressure variation in hydrogen tank is shown in figure 4.6. It can be seen that the pressure keep increasing with different changing rate. The variation of increasing rate is due to the change of the variation of hydrogen flow.

From all the simulation above, it can be concluded that the PEM electrolyzer responds properly to the variation of current. The whole model of the PEM electolyzer can be used for further modeling and calculation.

In this project, the current to the PEM electrolyzer is decided by the power that needs to be consumed. To determine the current so that the production of the current and the corresponding voltage is exact the power that need to be consumed, the PEM electrolyzer is operated with an increasing current. The power of the PEM electrolyzer is recorded with corresponding current and made into a look-up table in Simulink. The look-up table gives the corresponding current under certain power, so that the PEM electrolyzer can consume the required power with the current. The table is shown in Appendix 2.

4.2 Modeling wind farm

The wind farm model in this project includes two main parts: wind turbine model and wind speed model. The wind turbine model is built to show the power conversion from wind power to electrical power. The wind speed model is built to perform the wind speed fluctuation and the oscillation caused by the 3p components.

4.2.1 Modeling of wind turbines

Wind farms can be made up by different types of wind turbines. The wind turbines can be divided into two big categories: synchronous generator wind turbine and asynchronous generator wind turbine. The synchronous generator applied in wind power generation is usually permanent magnet synchronous generator (PMSG). The asynchronous generator for small capacity wind turbine is usually squirrel-cage induction generator due to the brush less character. Double fed induction generator (DFIG) is a relatively new technology for wind turbines based on induction generator.

Due to the limitation of capacity of individual wind turbine, the wind farm is usually made up by several wind turbines. The wind turbines in a wind farm are usually connected to a common bus, and then connected into grid through a substation. For offshore wind farms, the underwater cable is usually applied to connect wind turbines to the substation. Wind power generation is highly rely on power electronics, which makes the wind power generation more complicated than conventional power plant. From the point of grid, the wind farms usually cannot be treated as conventional power plant due to the power generation of the wind farm is highly depends on the wind conditions.

The wind turbine model applied in this project is to present the power conversion from wind power to electrical power. The power production of a wind turbine is usually a responds of wind speed, which means, the production of the wind turbines changes when the wind speed changes. The wind turbine model should present this character of the wind turbine, which means the power production signal of wind turbines model should be a respond of variation of wind speed signal.

There are two kinds of wind turbine model applied in this project: an electrical model to present the electrical characters, and an average model to present the relations between power production and wind speed. The average model is also used to simulate the wind condition which the wind speed is above 12 m/s. To simplify the model, the structures like tower, shield and hear dissipation system, which makes no contributions to the power conversion are neglected. The pulse width modulation (PWM) needs a very high frequency to model, which requires a very small step size to simulate. To accelerate the simulation speed, an average model which obeys the law of conservation of energy is applied.

The Simulink library provides the wind turbine model which could respond the variation of wind speed. The output of the model is three phase AC electricity port. For the electrical model applied in the power system, the induction type of the wind turbine from the Simulink library is applied. The pitch control of this wind turbine is enabled and the maxim pitch angle is set as 45 degree. To accelerate the simulation process, the inertia of the pitch control is neglected. The operation wind speed range for the wind turbine is between 4 m/s to 12m/s. The rated operation wind speed for the turbine is 9 m/s, thus, when wind speed is above 9 m/s, the pitch control system start to operate to limit the output power. The operation characters are shown in figure 4.7. The main function of the electrical model is to verify the performance in the electrical system model. The limitation of the electrical model is that the operation wind speed range is only up to 12 m/s, thus, the average model is need to present the performance of the system with wind speed above 12m/s. It should be mentioned that the pitch control of the wind turbine is disabled to perform the proper responds to 3p oscillation component.

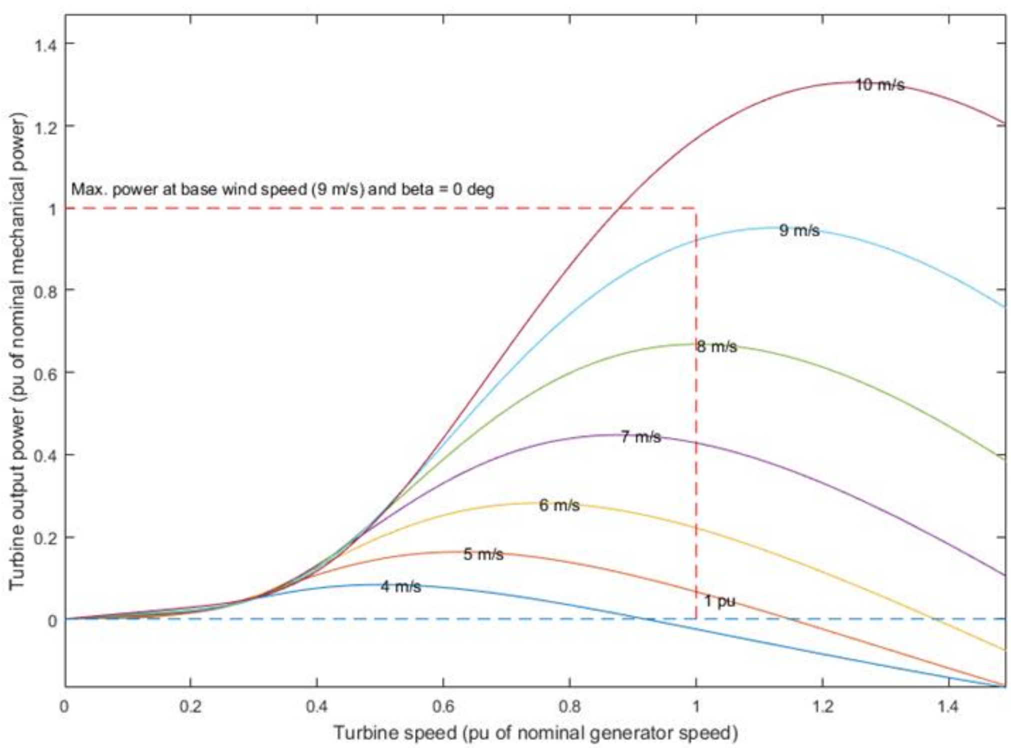

Figure 4.7 the operation characters of wind turbine [28]

Table 3. Parameters of average model of wind turbine

Parameters	Data
Cut-in Wind Speed	4m/s
Cut-out Wind Speed	25m/s
Rated Wind Speed	11.4m/s
Rotor Diameter	178.3m
Rated Power	10MW

The average model of this project is a look-up table. The look-up table gives the power as output according to the wind speed as input. The data of this look-up table is based on the 10MW prototype from DTU (Denmark Technical University), which is shown as Table 3. Detailed wind speed- power relation is shown as Table 4. When the wind speed is below 4 m/s, the wind turbine cannot be start. When the wind speed is above 25 m/s, the wind turbine is cut off due to the protection. This average model presents the relationship between the wind speed and the output power of the wind turbine. The result of mathematical calculation from average model should be verified in the electrical simulation.

Table 4. Operation characters of average model of wind turbine

Wind speed (m/s)	Output power (kw)	Wind speed (m/s)	Output power (kw)
4	280.2	15	10683.7
5	799.1	16	10642
6	1532.7	17	10640
7	2506.1	18	10639.9
8	3730.7	19	10652.8
9	5311.8	20	10646.2
10	7286.5	21	10644
11	9698.3	22	10641.2
12	10639.1	23	10639.5
13	10648.5	24	10643.6
14	10639.3	25	10635.7

To simplify the simulation, all the wind turbines are assumed to receive the same wind variation at same time. And the blades positons for all the wind turbines are all the same. The wind speed at hub height varies as described in chapter 4.2 for all the wind turbines. The 3p oscillation component in the wind speed is the same for all the wind turbines.

4.2.2 Modeling of wind speed

The structure like hub and blades of wind turbine models are neglected in this project, thus, the wind shear effect and tower shadow effect cannot be performed by the wind turbine models with constant wind speed. Therefore, the influence caused by wind shear effect and tower shadow effect should be included in the wind speed model.

The wind speed model for this project is made up of two main parts: the wind speed at hub height, and the 3p oscillation caused by wind shear effect and tower shadow effect.

One of the objectives of this project is to eliminate the 3p oscillation component in the power production. Thus, a detail and accurate model of 3p oscillation is necessary.

One of the concerns of this project is to study the active power fluctuation produced by wind turbines and to eliminate the fluctuation components contained in the active power production. The wind power production from the wind turbines contains the fluctuation caused by variation of wind speed and the oscillation caused by 3 times per revolution (3p). This part of this chapter introduces the model of the 3p oscillates wind speed component that sent into wind turbines.

The inertia of wind turbines is relatively smaller than the steam turbine or combustion turbine applied in conventional power plant. The change of wind condition will influence the performance of the wind turbine a lot. When the output power of the wind turbine needs to be studied in this project, the influence caused by 3p oscillation component in the wind is the main concern.

To simplify the simulation model, the 3p oscillation of the power output caused by the wind speed variation is included in the wind speed model, so that the model of the non-electrical structure, like the tower and the blades of the wind turbines, could be neglected.

Thus, a detailed 3p oscillation wind model must be built to perform the influence caused by the 3p wind speed oscillation.

The wind speed model should include two main parts: 3p oscillation component and the wind speed at hub height.

A Modeling of 3p oscillation

The 3p oscillation model is introduced in [10], and applied in this project.

The wind speed varies with the height from the ground. Generally, the wind speed increases with the increase of the height. This is termed wind shear. The kinetic energy carried by the wind is related to the wind speed (assume the air density is constant). So, the wind energy contained in the wind varies with the height. If the variation of the density of the air is neglected, generally, the wind energy increases with the increase of the height from the ground. When the wind turbine rotates, the position of the blades varies during one turn, which means the blades of the wind turbines is under different wind condition. Thus, the wind shear influence the power captured by the blades, which will further influence the power production of the wind turbines. For most modern wind turbines that have three blades, the torque oscillates three times during each rotation.

When the wind blows against to wind turbines, the wind in front of the tower is redirected due to the existence of the tower. Therefore, when the blade passes the tower of the wind turbine, the energy captured by this blade reduces. This effect is termed tower shadow effect. Thus, a drop of energy production of wind turbines could be observed when the blades pass the position of tower. For most of the case, this positon is when the blade is pointing downwards. For three blades wind turbines, the torque oscillates three times during each rotation due to the tower shadow effect.

The wind speed sent into the wind turbines has three components: the wind speed at hub height, the wind shear effect component and the tower shadow effect component. The wind speed at the hub height varies in this project. The equations about the 3p oscillation components are introduced in [10], the conclusions of the final equations are presented below as equation (39) to equation (43).

$$\mathrm{v_{eq}} = \mathrm{v_{eq0}} + \mathrm{v_{eqws}} + \mathrm{v_{eqts}} \tag{39}$$

$$\mathrm{v_{eq0}} = \mathrm{v_H} \tag{40}$$

$$\mathrm{v_{eqws}} = \mathrm{v_H}[\frac{\alpha(\alpha-1)}{8}\left(\frac{R}{H}\right)^2 + \frac{\alpha(\alpha-1)(\alpha-2)}{60}(\frac{R}{H})^3 \cos 3\beta] \tag{41}$$

$$\mathrm{v_{eqts}} = \frac{m\mathrm{v_H}}{3R^2}\sum_{b=1}^{3}[\frac{a^2}{\sin^2\beta_b}\ln(\frac{R^2\sin^2\beta_b}{x^2}+1) - \frac{2a^2R^2}{R^2\sin^2\beta_b + x^2}] \tag{42}$$

$$m = 1 + \frac{\alpha(\alpha-1)}{8}\left(\frac{R}{H}\right)^2 \tag{43}$$

In equation (39) to (43),

$\mathrm{v_H}$ is the wind speed at hub height (m/s).

α is the empirical wind shear exponent.

H is the elevation of rotor hub (m).

β is the azimuthal angle of the reference blade (degree).

β_b is the azimuthal angle of each blade (degree).

a is the tower radius (m)

x is the distance from the blade origin to the tower midline (m).

R is the distance from the blade tip to hub center

The parameters applied in this project are from reference [10], which are: R=20, H=40, α=0.3, a=0.85, and x=2.9.

The position of the blades is one of the important factor when implement equations (1) to (5). To implement the equations correctly, a reference blade is selected which is the red blade in figure 4.8, for which the initial azimuthal angle is 0, which is the position that the blade pointing upwards. The initial azimuthal angles for the other two blades are $120°$ and $-120°$, as shown in figure 4.8. Therefore, during the operation, at any instantaneous second, if the azimuthal angle of the reference blade is β, then the azimuthal angles for the other two blades are $\beta + 120°$ and $\beta - 120°$.

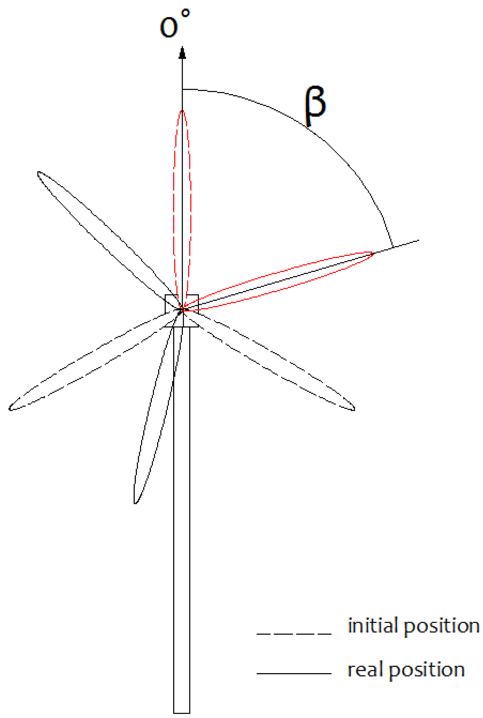

Figure 4.8 The position of the blades

It should be mentioned here that the β in equation (41) is the azimuthal angle for the reference blade. The azimuthal angles for the other two blades do have influence for the wind shear effect, but the expression of the influence is not presented by equation (41), this is because the position of these two blades is canceled due to the mathematical derivation. The detailed derivation is shown in reference [10].

It should be mentioned that the equation (42) is only valid when β_b is between 90° and 270° as above horizontal [10]. When the position of the blades is other than this range, the blades are far away from the tower, the influence caused by tower shadow effect is very limited, thus, the calculation of the equation (42) during this range is meaningless. Therefore, when the position of the blades is out of the range between 90° and 270°, the position is treat as the critical position for tower shadow effect, which is 90° in this project.

B Modeling of wind speed at hub height

The wind speed at the hub height is varies with time, which is shown as figure 4.9. The pure fluctuation could be found in Appendix 3. The figure 4.9 is based on the average wind speed of 8 m/s.

The model of the wind speed at the hub height (v_H) is implemented in the Simulink as a lookup table. The input of the look up table is time, and the output of the look at table is the corresponding fluctuation at that time. This fluctuation is added to the average wind speed, and together, output as the wind speed which varies at the hub height.

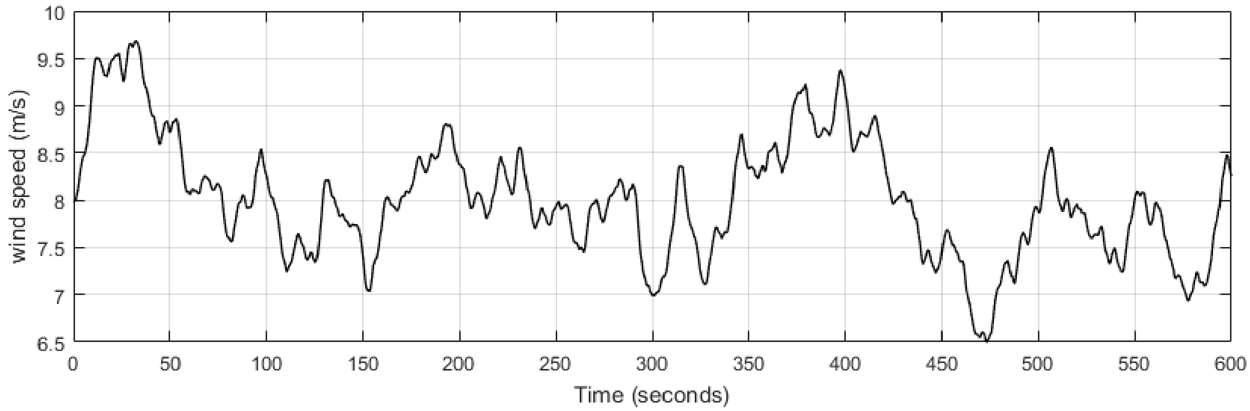

Figure 4.9 The wind speed at hub height

4.2.3 Wind speed model simulation

The equations (39) to (43) are implemented in the simulation using "fcn" function in the Simulink. All the necessary parameters for the calculations are referred to reference [10]. The detailed implementation is shown in Appendix 1.

The signal flow and simulation implement is shown in figure 4.10. The necessary parameters are sent into corresponding block to calculate corresponding equivalent wind speed. The output of each block is the corresponding equivalent wind speed component. The average wind speed at hub height is added a fluctuation component as described before to get the fluctuating wind speed at hub height (v_{eq0}). The necessary parameters are sent into the wind shear calculation to get the wind shear component (v_{eqws}). The equivalent wind speed influenced by each blade is calculated separately and summed together to get the equivalent wind speed component that influenced by tower shadow effect (v_{eqts}). Finally, the wind speed sent into wind turbine is determined as $v_{eq} = v_{eq0} + v_{eqws} + v_{eqts}$.

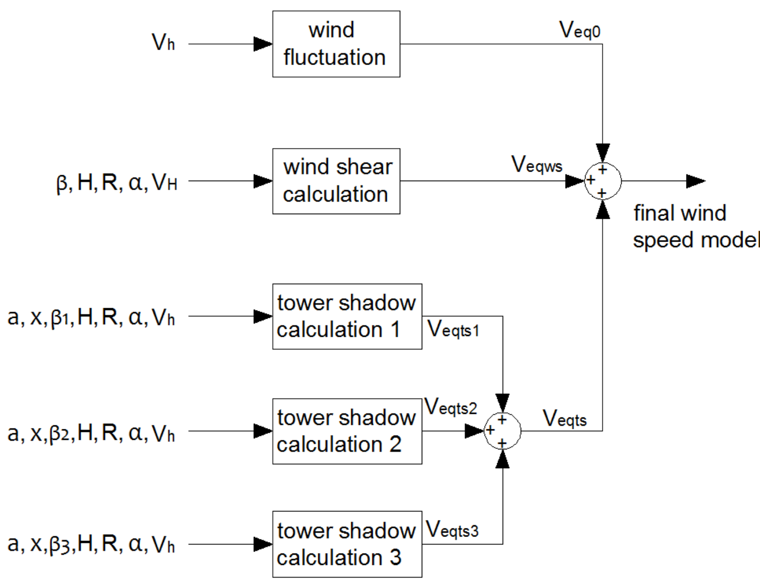

Figure 4.10 The signal flow of wind speed model

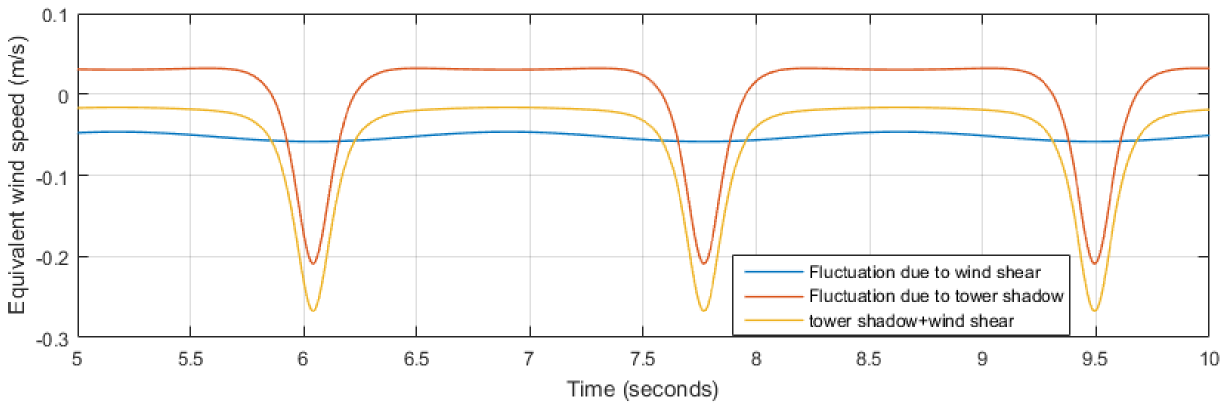

Figure 4.11 The wind shear and tower shadow effect in the wind speed model

The influence caused by the wind shear effect to a constant wind speed of 8 m/s is shown in figure 4.11 by blue curve. The influence caused by the tower shadow effect to a constant wind speed of 8 m/s is shown in figure 4.11 by red curve. The influence caused by the wind shear and the tower shadow effect to a constant wind speed of 8 m/s is shown in figure 4.11 by yellow curve. It can be seen that the tower shadow component has very significant drop due to the position of the blade. It also can be seen that the total wind speed is negative, which mean the wind speed is reduced due to the influence of the wind shear and tower shadow effect.

The final wind speed model is the fluctuating wind speed at hub height with 3p oscillation component caused by wind shear and tower shadow effect. The final wind speed is shown as figure 4.12.

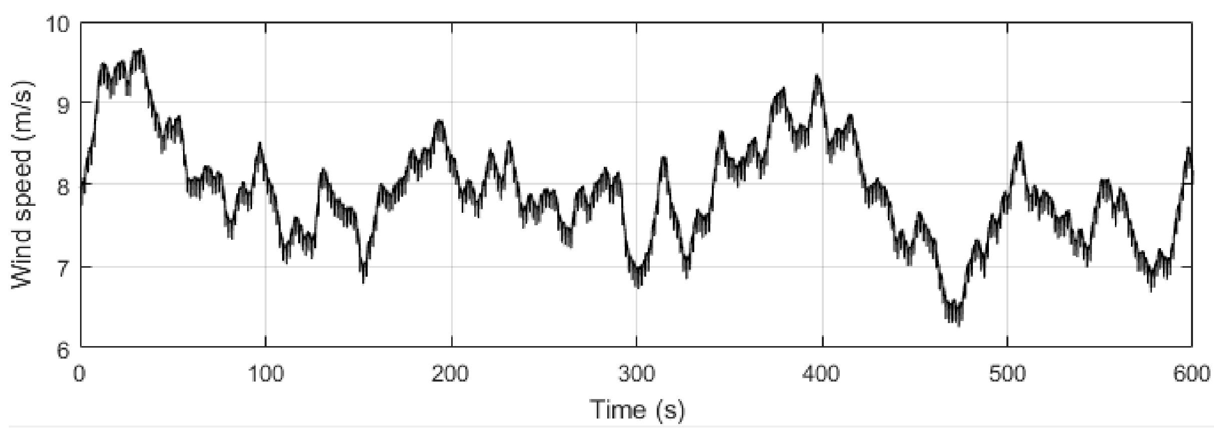

Figure 4.12 The wind speed with 3p oscillation component

4.3 Voltage mitigation

For wind farms, there are a lot of equipment between wind turbines and grid. From the point of electrical study, the equipment between wind turbines and grid can be equivalent into impedance. Usually, when power is transmitted in the cable, the variation of power is represented by the variation of current. Due to the existence of impedance in the transmission path, the variation of the current will influence the voltage at the terminal. Therefore, the fluctuation component contained in the power transmitted in the transmission line will cause a fluctuation component of voltage at the terminal of the cable. Therefore, if the power transmitted is smoothed, the voltage at the terminal could be smoothed.

The equivalent circuit of the system applied in this project could be simplified as figure 4.13. A method that can be used to calculate the voltage at the terminal using the transmitted active power and reactive power is proposed in [12] and applied in this project. For the equivalent circuit shown in figure 4.13 the voltage at the terminal could be expressed by equation (44) and equation (45).

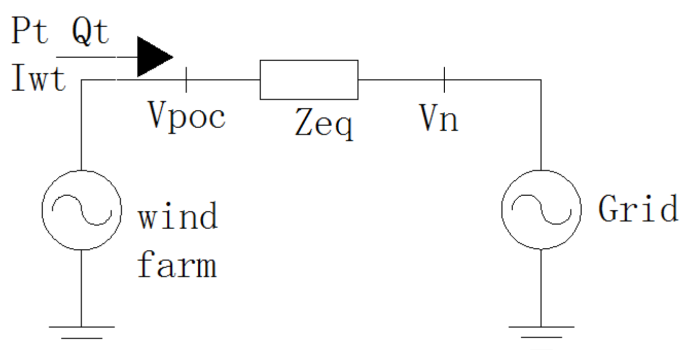

Figure 4.13 The equivalent circuit of proposed system

$$V_{poc} = \sqrt{0.5{V_n}^2 + A} \tag{44}$$

Where:

$$A = P_t R_{eq} + Q_t X_{eq} + \sqrt{0.25{V_n}^4 + (P_t R_{eq} + Q_t X_{eq}){V_n}^2 - (P_t X_{eq} + Q_t R_{eq})^2} \tag{45}$$

The main concern of this project is active power coordination in the proposed system, thus, to simplify the analysis and the calculations, the reactive power Q is assumed to be zero. When the active power has fluctuation component, the fluctuation of voltage will be observed at the terminal. The voltage mitigation is achieved to remove the fluctuation component from the active power. In this project, the active power component is consumed by the electrolyzer. Thus, according to the law of conservation of energy, once the fluctuation component is consumed, the remaining power is smoothed, and then the voltage at the terminal is also smoothed.

The equation (44) and (45) is implemented using “fcn” function in Simulink. The detailed programming could be found in will not be presented due to the limitation of the length of the project. The calculation of the voltage at the terminal uses the active power and the reactive power which measured at the turbines terminal as input. The output of the “fcn” block is the theoretical voltage from the calculation.

4.4 Combustion turbine

The combustion turbine model presents the relationship between the power output and the hydrogen it consumed. The combustion turbine driven generator is applied to compensate the power production of the system. Thus, the combustion turbine in this project must has the ability to follow the given reference power.

To drive the generator, the combustion turbine need to output torque, which can be calculated by equation (46)

$$\tau = \frac{P}{\omega} \tag{46}$$

in which

τ is the output torque of the combustion turbine
P is the output power of the combustion turbine
ω is the rotational speed of the combustion turbine

For synchronous generator, the rotational speed is fixed at steady state, which depends on the number of pole pair of the generator. Therefore, the combustion also has a fix rotational speed. Then, according to equation 46, the torque of the combustion turbine is proportion to the output power. The torque obtained generator is converted into output electrical power, thus, the torque is just an intermediate quantity. To simplify the simulation, an average model of combustion turbine, which based on the law of conservation of energy, is built to express the power conversion.

For the given reference power, the corresponding requirement of the hydrogen and oxygen is calculated by equation 47.

$$F = \frac{P}{H\eta} \tag{47}$$

In which

F is the hydrogen flow velocity (mol/s)
P is the power requirement (w)
H is the hear value of hydrogen (J/mol)
η is the efficiency of the energy transfer

The heat value of hydrogen H in this paper is 2.86×10^5 J/mol. The energy transfer efficiency η is 40% considering the energy convert efficiency of combustion turbine. The hydrogen flow signal is fed into the storage system model.

The Simulink library provides the generator model which can follow the given reference. The power reference for the insufficient power is fed into the generator model. The generator model generates three phase AC electricity which is connected into grid.

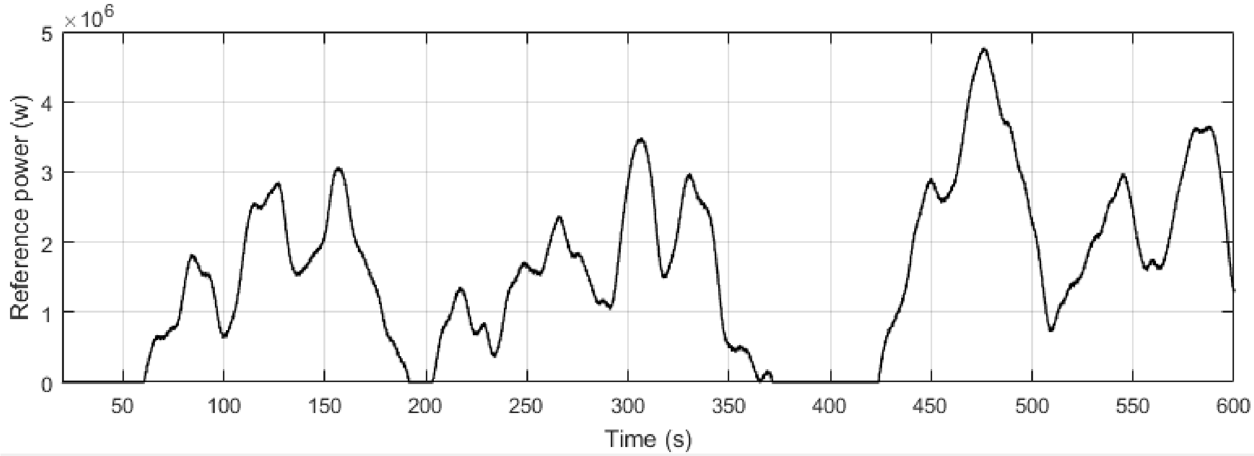

Figure 4.14 The reference power for combustion turbine

It should be point out that the power reference has a limitation of changing rate to prevent sudden change of power reference. This is because the hydrogen combustion turbine is driven by burning hydrogen, and the quantity of hydrogen that burnt is an integration of hydrogen flow. Thus, the quantity of hydrogen cannot be changed suddenly, which means, the reference that given to the generator model should not be changed suddenly. Therefore, a rate changing limitation is implemented before the power reference is sent into the generator model.

The power reference from the logic control is shown in figure 4.14. The combustion turbine should generate the electrical power according to the reference power. The electrical energy generated by the combustion turbine is shown in figure 4.15. It can be seen that the combustion turbine could follow the reference properly.

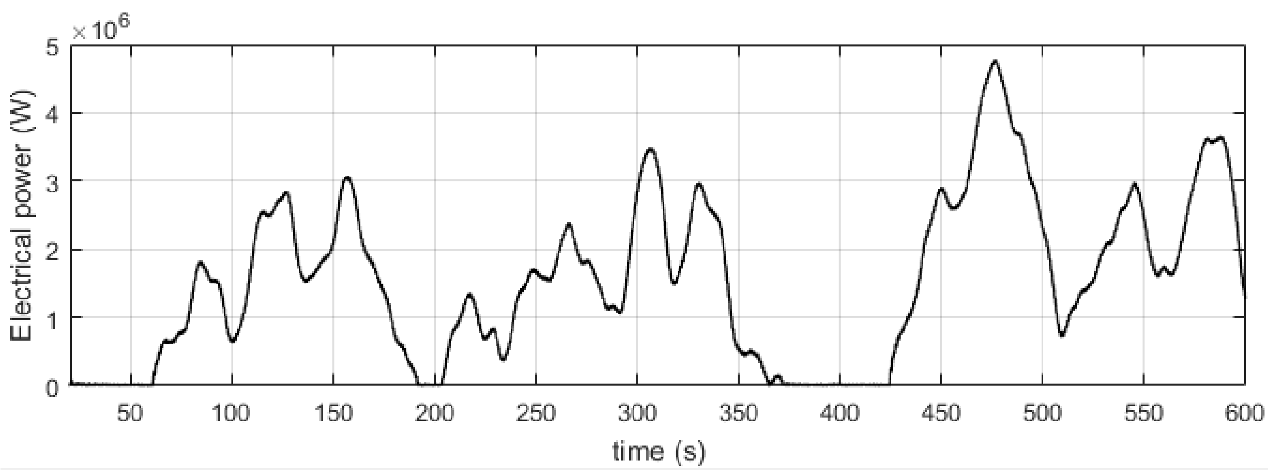

Figure 4.15 The power generation of combustion turbine

4.5 STATCOM

The STATCOM in this project is to compensate the reactive power due to the combustion turbine is not involved in reactive power compensation. The reactive power compensation is not a main concern of this project, thus, detailed STATCOM model is not required.

Simulink library provide standard model of STATCOM. The STATCOM model from the Simulink library is a general model without detailed representations of the power electronics. The model has two control strategies: voltage regulation and Var regulation. With the voltage regulation, the STATCOM will provide reactive power within the capacity to maintain the voltage at the connection point. With the Var regulation strategy, the STATCOM will provide constant reactive power despite the voltage at the connection point.

To perform the simulation properly, the STATCOM in the simulation is selected to be operate under voltage regulation control strategy. The capacity of the STATCOM is set to be 3 MVar. The STATCOM is connected on the 25 KV bus.

4.6 Power system

To verify the calculation result of the project, the electrical model of the topology proposed by this project is built and connected to a simple power system.

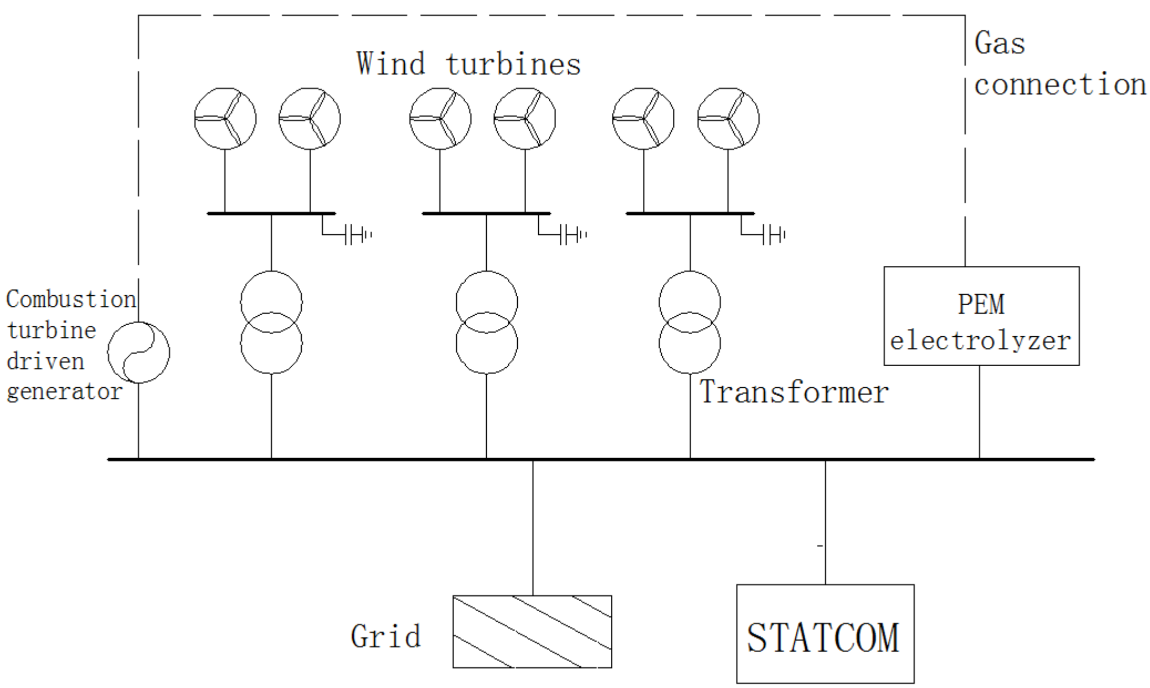

Figure 4.16 The connection of the power system for electrical simulation

The system is shown in figure 4.16. For each group of wind turbines, there are two 1.5 MW wind turbines connected to a 575 V bus. A shunt capacitor is connected to the 575 V bus to compensate the reactive power. A transformer is connected to the 575 V bus to step up the voltage from 575 V to 25 KV. Then the transformer is connected to the 25 KV bus through a 1 Km cable. There are three groups of wind turbines connected to the 25 KV bus, the configuration of each group is identical. The PEM electrolyzer, the combustion turbine, and a STATCOM are connected to the 25 KV bus. The 25 KV bus is connected to infinite grid.

The wind turbines use induction generators, which require some reactive power to operate. The reactive power transmission in power system increases the losses on the transmission line. Thus, the shunt capacitors are connected to the 575 V bus to compensate part of the reactive power locally.

4.7 Price modeling

To connect the system with gas network, the hydrogen production needs to be convert into methane production. The chemistry reaction of this process is Sabatier reaction. The Sabatier reaction is described by equation (48). The catalyst is required for this reaction. This chemistry reaction requires some initial energy to start the reaction, but no energy is required any after the reaction starts.

$$CO_2 + 4H_2 = CH_4 + 2H_2O \qquad (48)$$

Producing methane consumes hydrogen. The hydrogen which consumed to produce methane is a production from PEM electrolyzer, which means the producing of hydrogen consumes electricity. Therefore, producing methane consumes electricity. Thus, the profit made by selling methane is actually a profit made by selling electricity in form of methane. Therefore, the profit made by converting electricity to methane and selling it has a unit of DKK/KWh. The calculation of this profit is described by equation (49).

$$k = \frac{1}{\frac{1}{m} \times a} \times c \qquad (49)$$

In which:

k is the profit made by selling methane which made from electricity (DKK/KWh)
c is the price of methane in DKK/m3
m is the ratio of methane production to hydrogen consumption
a is the electricity consumption for every cube meter hydrogen production KWh/ m3

The price of the electricity and methane could vary according to different condition. The integration of the price respect to time is the profit made by per KWh electricity. The total profit *u* could be expressed as equation (50).

$$u = \sum_{n=1}^{b} c_n \int_{1}^{n} s_n \, dt \tag{50}$$

In which

s is the price during a certain period (DKK/KWh)

b is the total time period of the price variation (hours)

c is the electricity generated at the corresponding time period (KWh)

5 Proposed control strategy

This chapter presents the control strategy for the proposed system. The necessary components for the control strategy are also proposed in this chapter. A simulation is conduction and presented in 5.5 to verify the function of the control strategy.

5.1 Overall coordination method for the whole system

The control strategy for the proposed topology is to coordinate the wind farm, the electrolyzer and the combustion turbine driven generator. The purpose of the coordination is to eliminate all the fluctuation and oscillations in the power production, and make the output power of the whole system constant, like a conventional power plant.

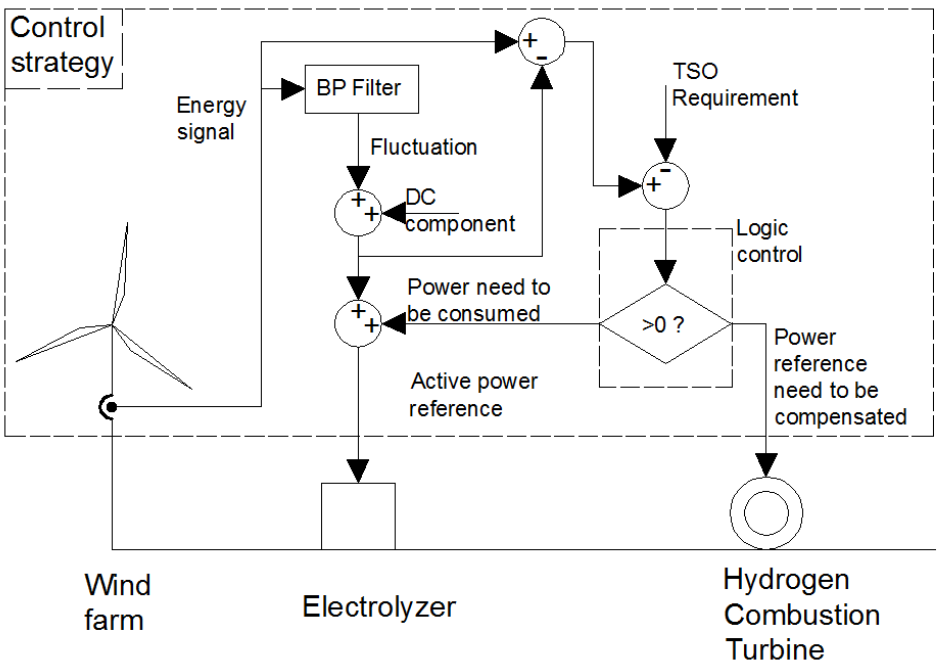

Figure 5.1 The coordination strategy for the proposed system

The coordination strategy is shown in figure 5.1. The power production from the wind farm is measured. The power signal is fed into BP filter designed in chapter 5.4. The BP filter passes the 3p oscillation frequency and block other frequency. The 3p oscillation component, as the output of the BP filter, is sent to further signal process. A DC component is added to this 3p oscillation signal that picked out by the BP filter. The 3p oscillation component together with the DC component is extracted from the power production of the wind farm. The remanding power is compared with TSO requirement. The result of the comparison is sent into logic control. The logic control gives the exceed power reference to electrolyzer to be consumed, or gives the insufficient power reference to hydrogen combustion turbine to be compensated. The logic control is presented in section 5.3. The 3p oscillation component, the DC component and the exceed power signal from the logic control is sent into the PEM electrolyzer together to be consumed. The electrolyzer consumes the power that given to it and convers it to hydrogen and oxygen. The combustion turbine takes the hydrogen and oxygen to drive the generator. The generator compensates the insufficient power. The final energy flow is shown in section 5.3.

5.2 Coordination strategy and signal process description

The power production from wind farm has the 3p oscillation component caused by wind shear effect and tower shadow effect. The power fluctuation caused by variation of wind speed also exists in the power production. To compensate the fluctuation caused by wind speed variation, a dynamic coordination strategy which based on the dynamic measurement should be developed. The 3p oscillation component causes power production drops, which is not a concern of power compensation of combustion turbine. Therefore, to develop the dynamic control strategy for the power compensation, the 3p oscillation component must be eliminate first, and then the smoothed power measurement could be used for the further coordination process.

The wind shear effect and tower shadow effect cause the 3p oscillation component in the power production. The output power of the wind turbines are measured and sent into signal process. The BP filter described before is applied in signal process to pick out the 3p oscillation component in the power production and send the 3p oscillation component into the rectifier that connected to PEM electrolyzer as active power reference. The rectifier convers the AC electrical power into DC electrical power according to the active power reference, which consumes the 3p oscillation component in the wind farm power production. According to the law of conservation of energy, once the 3p oscillation is consumed, the 3p oscillation component in the power production is eliminated. Thus, the remanding power is smoothed. The energy picked out by the rectifier will be further consumed by PEM electrolyzer to produce hydrogen and oxygen for later use. It should be mentioned here that the 3p oscillation signal picked out by the BP filter has negative value. The PEM electrolyzer can only consume power, which means the negative value of the 3p oscillation component cannot be dealt by the PEM electrolyzer. To solve this problem, a DC component is added to the 3p oscillation component to shift the entire 3p oscillation signal above zero. This DC signal is extracted from the power production, which means besides the 3p oscillation component, a part of the power production of the wind farm will be consumed by the PEM electrolyzer.

5.3 Logic control

The variation of wind speed causes the fluctuation in the power production of wind farm. The variation of wind speed is usually random, and very hard to be predicted accurately. Thus, the compensation strategy for the fluctuation caused by variation of wind speed is a dynamic strategy which is based on dynamic measurement. The power production from wind turbines is measured and sent into 3p oscillation mitigation process.

After the 3p oscillation mitigation process, the 3p oscillation component in the power production is eliminated and the remanding power is smoothed. Then, this smoothed power is compared with the order from TSO. The result of the comparison gives two results: the power production is greater than the TSO order, or the power production is less than the TSO order. When the power production is greater than the TSO order, the signal of the exceed power is sent into the rectifier as active power reference. The rectifier converts the power for PEM electrolyzer to be consumed. When the power production is less than the TSO order, the insufficient power signal is sent to the combustion turbine as power reference. The combustion turbine compensates the insufficient power by taking the hydrogen and oxygen from the tanks. The logic control of this part is presented in figure 5.2.

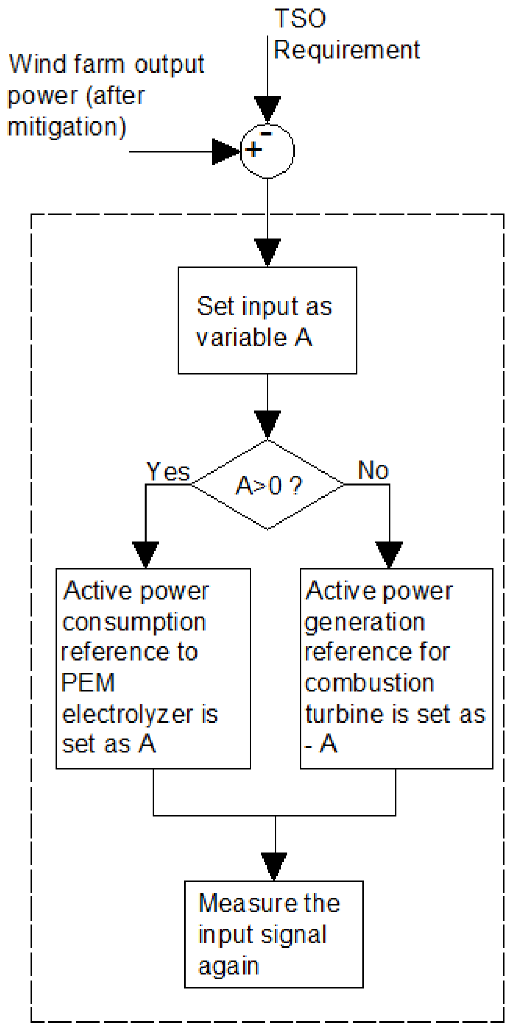

Figure 5.2 The logic control for proposed system

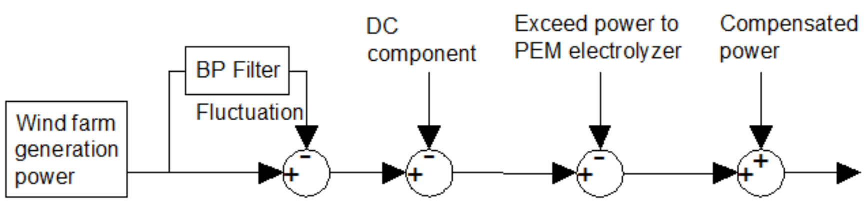

Figure 5.3 The energy flow of the proposed system

The final power which is sent into PEM electrolyzer to be consumed is the 3p oscillation, the DC component and the exceed power production from the wind farm. The final power generated by the combustion turbine driven generator is according to the insufficient power signal. The final power fed into grid is the original wind power minus the 3p oscillation component, minus the DC component, then plus the power compensated by the combustion turbine driven generator. The diagram of energy flow is shown in figure 5.3.

It should be point out here that the PEM electorlyzer model has an input as current. Thus, the power signal for the PEM electrolyzer is sent in a form of current signal. The current that sent into PEM electrolyzer is determined according to the power that needs to be consumed. This means when a power needs to be consumed, a current is determined to consume this exact power with corresponding voltage at this current.

5.4 Band pass filter

The 3p oscillation component caused by the wind shear and tower shadow effect has influence on the power production of wind turbine. The power production of the wind turbines also have 3p oscillation component, one of the objectives of this project is to eliminate the 3p oscillation component in the power production. According to the law of conservation of energy, the total energy of an isolated system remains constant, thus, when the 3p oscillation is picked out and consumed, the power remanding is smoothed.

The power production from wind turbines is measured and sent into signal process. The 3p oscillation component in the power production is picked out and sent into the rectifier which connected to the PEM electrolyzer as an active power reference. The rectifier converts the AC electrical energy into electrical DC energy according to the reference. Thus, the 3p oscillation component in the power production is picked out and consumed by PEM electrolyzer. The remanding power is then smoothed.

A BP filter is required to pick out the 3p oscillation component signal from the measurement. The BP filter is designed in this paper to by-pass the 3p oscillation frequency while block all other frequency at the same time. The transfer function of the BP filter is shown as equation (51)

$$F(s) = \frac{Ks}{s^2 + \left(\frac{\omega_c}{Q}\right)s + {\omega_c}^2} \tag{51}$$

where,
ω_c is the center frequency
K is the gain
Q is quality factor.

Usually, the wind turbines are operated under wind speed between 4m/s and 25 m/s. The wind turbines do not work when wind speed is under 4/s. When the wind speed is above 25 m/s, usually wind turbines are shut down due to protection reason. For the wind turbines applied in this paper, the corresponding rotation speed is between 7.5 rpm and 25 rpm. As explained in chapter 3.2.3 C, for three pitch wind turbines, the rotation frequency for the blades is tripled. The wind turbine applied in this paper has an average pitch rotational speed of 3.64 rad/s, i.e. the $\omega_c = 3.64\, rad/s$. The gain of the filter is designed as $F(j\omega) = KQ/\omega\_c = 1$ to pass all the 3p oscillation frequency, so that the 3p frequency could be selected for the further process. The detailed parameters applied in this project are: Q=80, K=0.0455. The Bode diagram of the filter is shown in Figure 5.4.

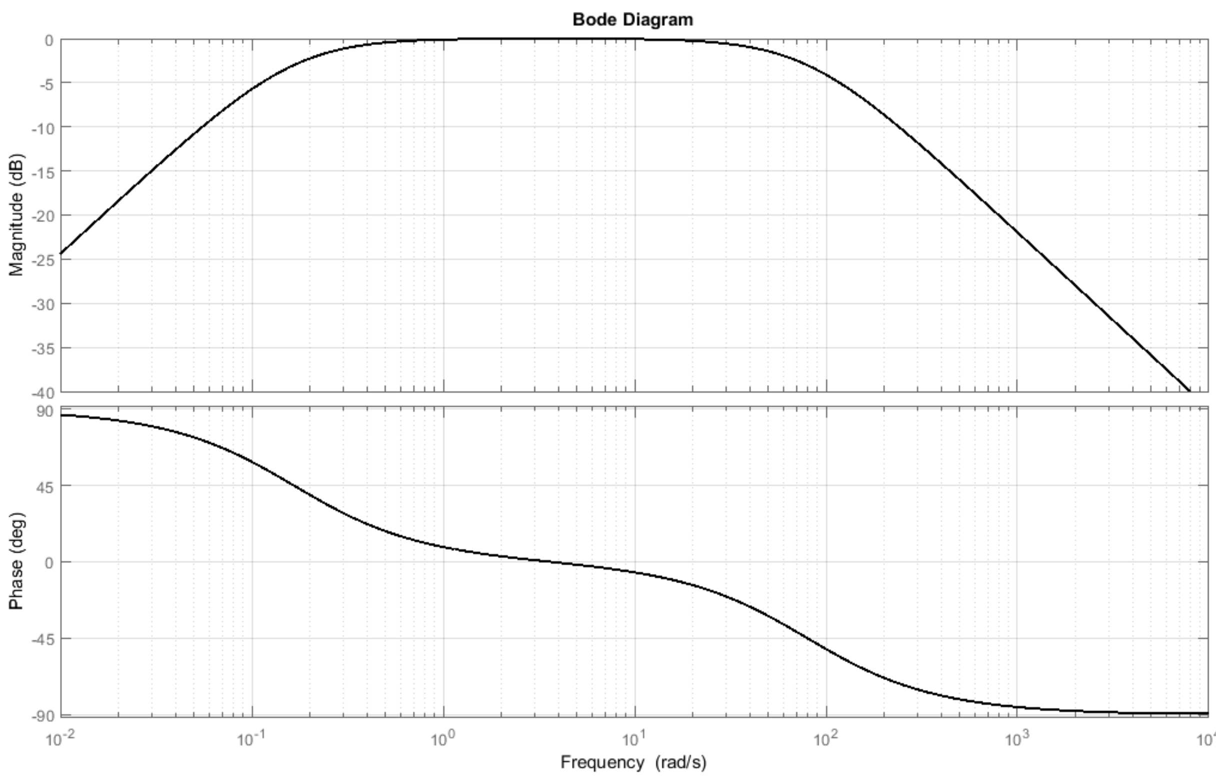

Figure 5.4 The Bode diagram of the BP filter

The function of the BP filter is tested with power production signal. The initial power output of the wind farm is measured and shown in figure 5.5, it can be seen that the 3p oscillation exist in the power production. After the 3p oscillation component is picked out, the power signal remanding is shown in figure 5.6. The 3p fluctuation component signal picked out by the BP filter is shown in figure 5.7. It can be see, that the power production signal after mitigation is significantly smoothed, which means the BP filter works properly. The fluctuation picked out by BP filter has negative value, but the PEM electrolyzer cannot produce any electrical energy, thus, the 3p oscillation signal is not acceptable for PEM electolyze. Due to the reason mentioned above, the signal need further process before sent to corresponding equipment. The detailed process is explained in the case study part of this report.

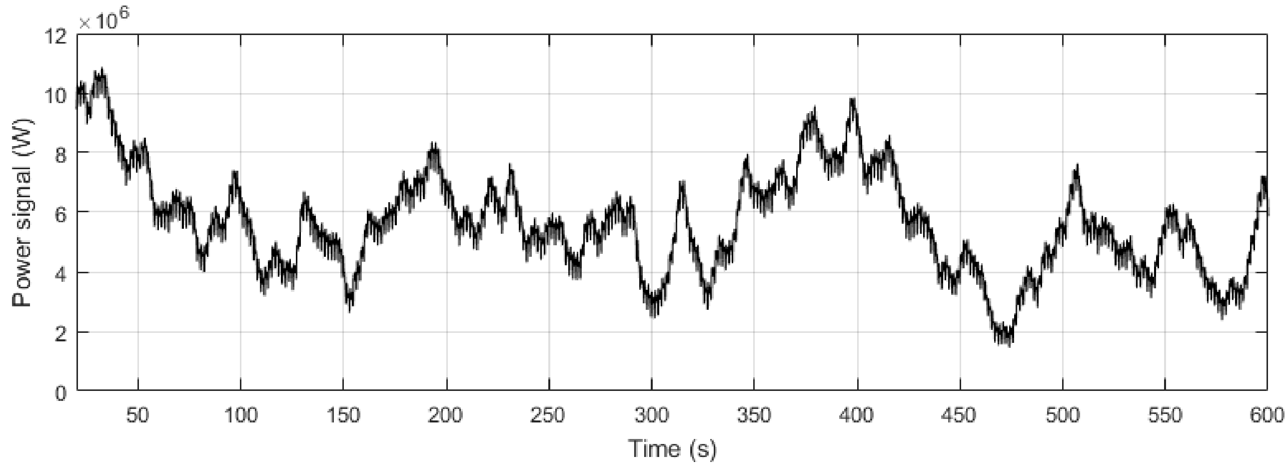

Figure 5.5 The initial power output signal of the wind farm

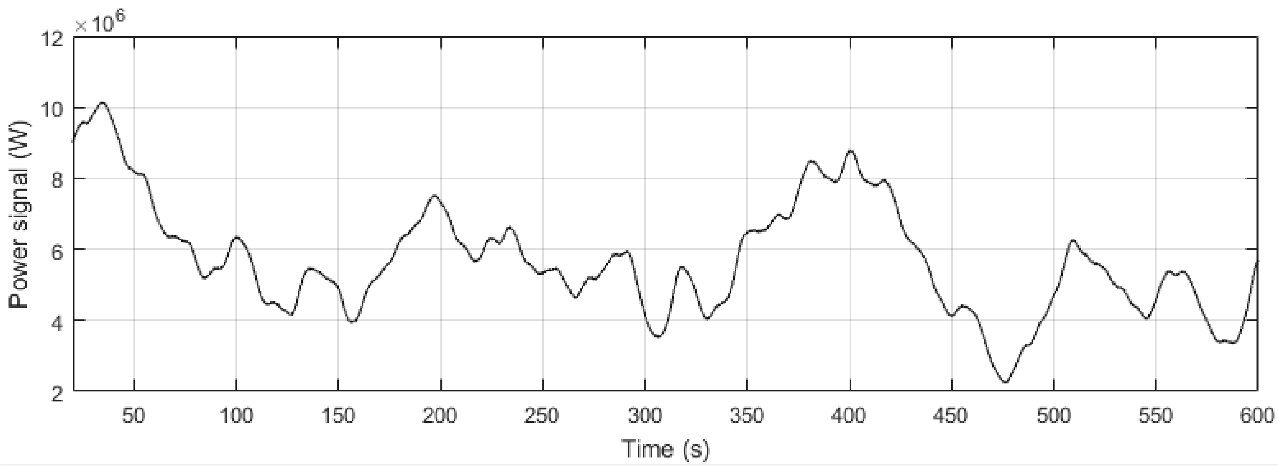

Figure 5.6 The power output signal of the wind farm after mitigation

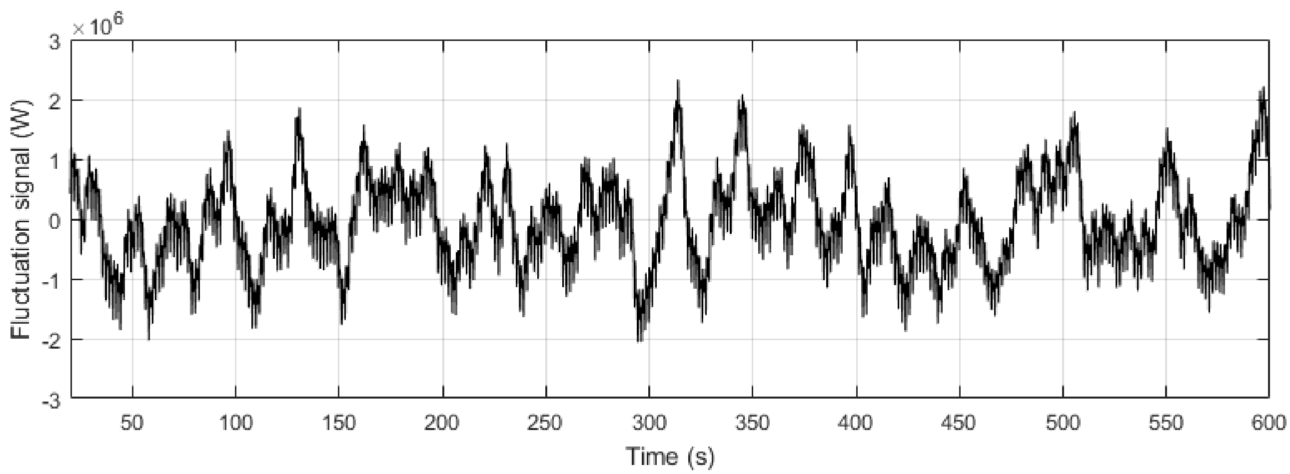

Figure 5.7 The fluctuation power output signal of the wind farm

5.5 Control strategy simulation

The control strategy is first tested using the average model described before. The purpose of the simulation of average model is to ensure the control strategy could work properly with the proposed topology. The difference between the average model and electrical model is that the electrical model has electrical properties, which could verify the function of the model from electrical aspect, while the average model is only to test the signal process.

The wind turbine model in the test is made up by average models described in chapter 4.2. It should be point out that the test of the control strategy is to verify the function of the control strategy and logic control, thus, the signal used for testing do not match the electrical model.

The connection of average model is shown in figure 5.8.

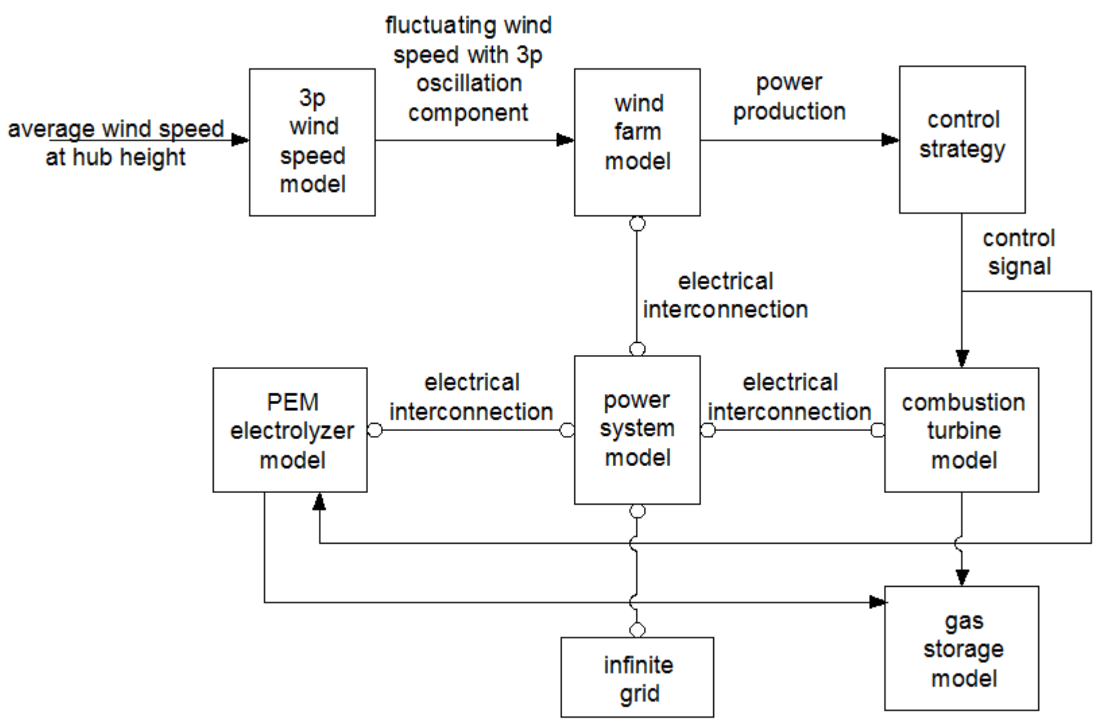

Figure 5.8 The overall connection of the whole system

The average model of wind turbines gives the output power according to the wind speed. The wind speed signal is shown in figure 5.9. The output power signal of the average model is shown in figure 5.10. The output power from wind turbine is sent to 3p oscillation component mitigation process. The 3p oscillation component extracted by the BP filter is shown in figure 5.11 (together with a DC component). The power production after mitigation process is shown in figure 5.12 (after the DC component is extracted).

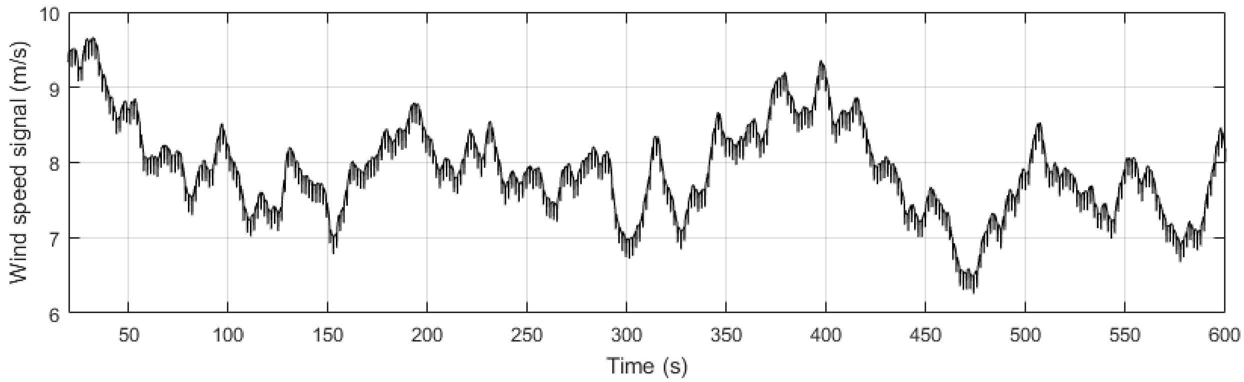

Figure 5.9 The wind speed signal for the whole system

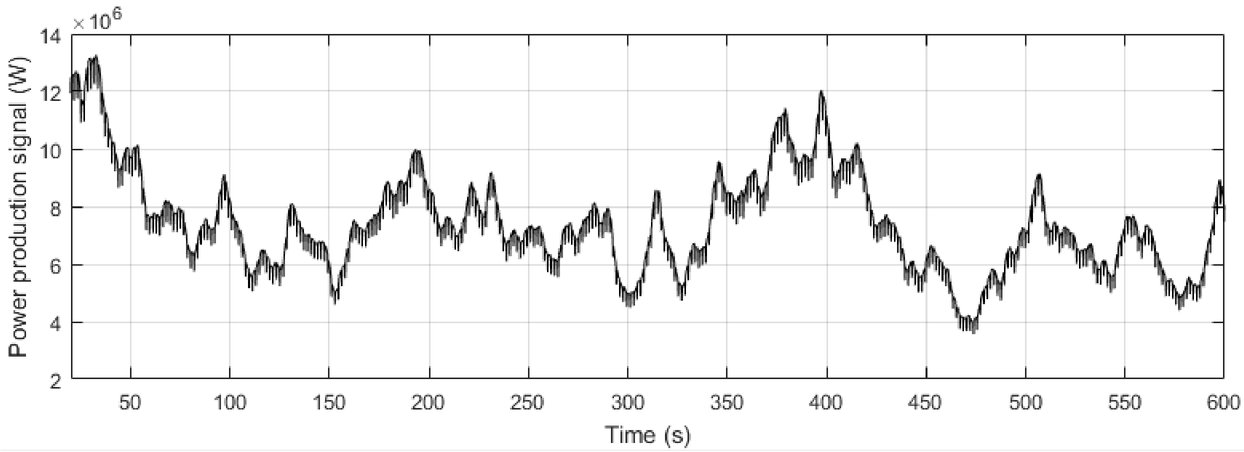

Figure 5.10 The output power signal of the wind farm

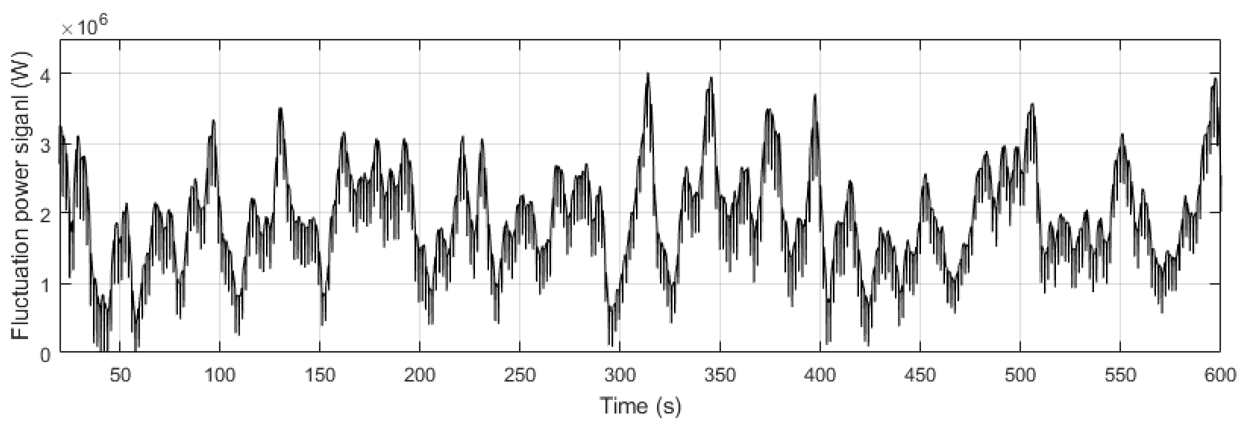

Figure 5.11 The fluctuation power picked out

The TSO order is shown in figure 5.12 by blue curve. After the mitigation process, the smoothed power production signal is sent into logic control together with the TSO order. The logic control is described in chapter 5.3. The output of the logic control is shown in figure 5.13 and figure 5.14. Figure 5.13 shows the exceed power signal that should be sent into PEM electrolyzer. Figure 5.14 shows the insufficient power signal that should be compensated by combustion turbine. The ideal final output power signal, which is signal result of coordination according to the control strategy and logic control, is shown in figure 5.15.

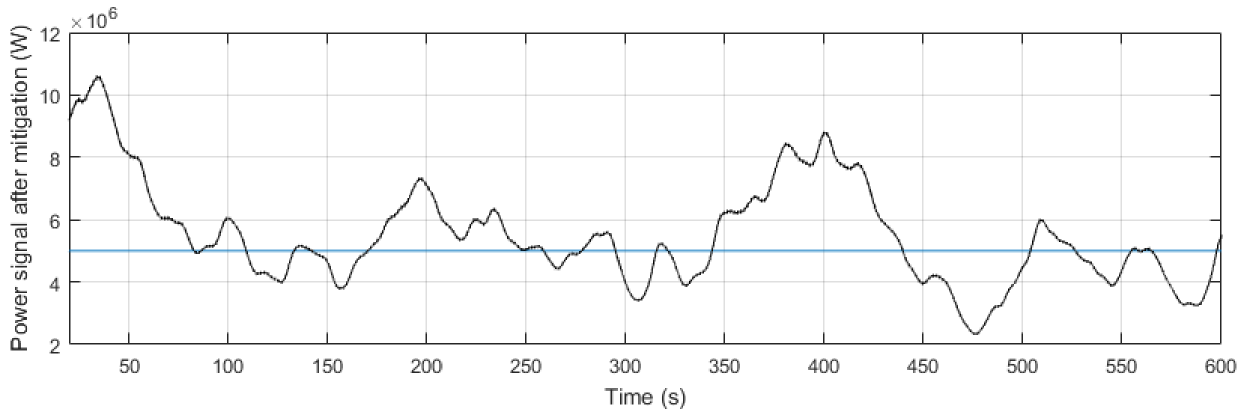

Figure 5.12 The power signal after mitigation with TSO order

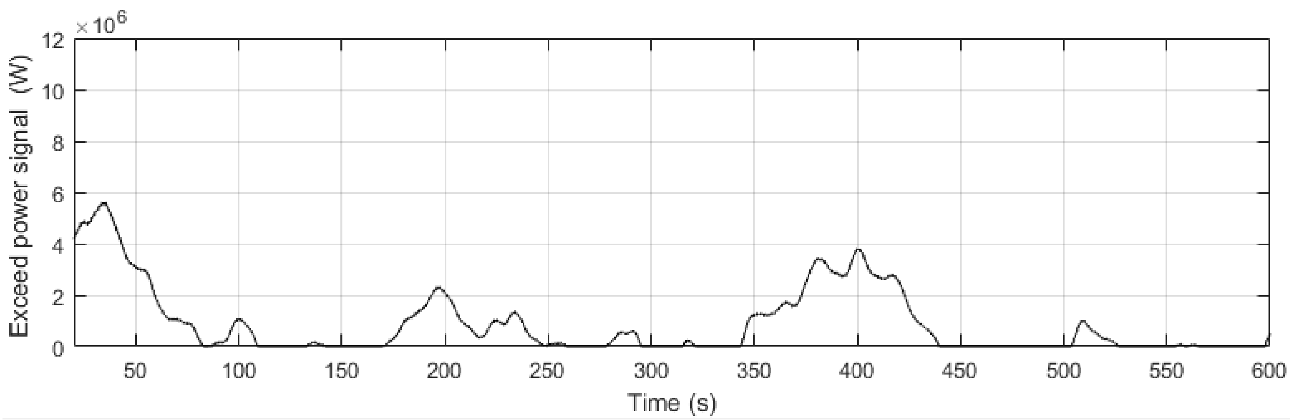

Figure 5.13 The exceed power signal

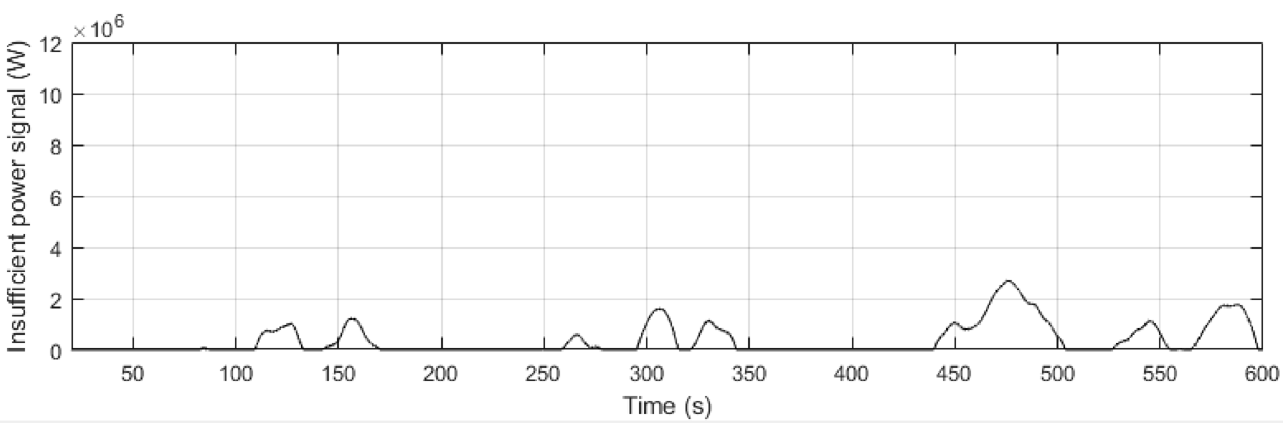

Figure 5.14 The insufficient power signal

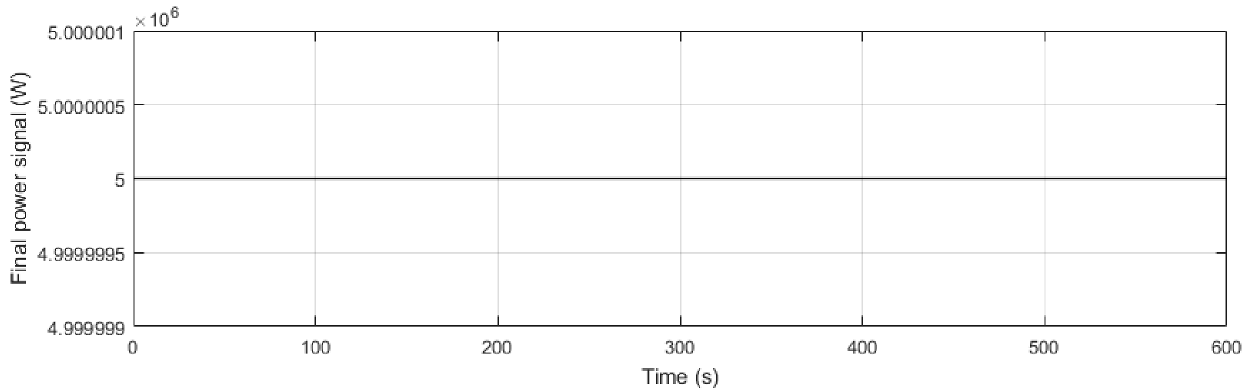

Figure 5.15 The final power signal

It can be seen that the control strategy works properly. The signal could be processed properly to coordinate the whole system to get constant output power.

5.6 Control strategy for extreme cases

The control strategy proposed for extreme case is to coordinate the equipment of the proposed system under extreme conditions. The extreme cases selected for the project are island operation mode, black start mode, and no wind case. The extreme cases are very rare during normal operation in industry, but to improve the reliability of the proposed system, the control strategy under extreme conditions should be taken into consideration.

5.6.1 Island operation mode

One extreme case is when the wind farm is disconnected from the grid, which might happen when there is big fault happens in power system. Under this operation mode, the combustion turbine will be stopped and all the power produced by wind turbines will be sent into PEM electrolyzer to produce hydrogen and oxygen. In this case, the loads for the wind turbines still exist, thus, the wind turbines will not be stopped.

In industry applications, big equipment in power system usually has protection system. The protection system send operation signal to circuit breaker to disconnect the equipment from the grid when necessary. The protection logic is depends on the protection setting. For the proposed system, the control strategy can read the protection signal. Once the proposed system is disconnected by the protection from the grid, the control system of the proposed topology can get the signal and change the control mode into island operation control mode.

Under island operation control mode, the power fluctuation mitigation strategy is disabled. The power reference for the rectifier that connected to PEM electrolyzer is set to be all the power production from wind farm, thus, all the power production from wind farm is consumed by the PEM electrolyzer. The reference power for combustion turbine is set to be zero. The combustion turbine is disconnected from the system and do not generate power any more. The total output power of the whole system to the grid is zero.

5.6.2 Control strategy for other extreme case

The black start case is also an extreme case for the project. For wind farms that made up by induction generators, some reactive power is required to start the wind turbines. When the black start strategy is executed, the combustion turbine takes the hydrogen and oxygen from the tanks and generates electricity to start the wind turbines. During the black start process, the connection between the system and the grid is cut off. After the black start process is finished, the system is connected to the grid.

For the extreme case of no wind or all the wind turbines are out of service, the combustion turbine is operated to satisfy the power requirement. The combustion turbine gets hydrogen and oxygen from the tanks and drives the generator to generate required power. It should be point out that the combustion turbine has capacity limitation, thus, under this extreme control strategy, the system cannot respond to the TSO requirement which is greater than the capacity of the combustion turbine. This control strategy can only be executed when the hydrogen storage could satisfy the requirement of combustion turbine. When the hydrogen storage is below the requirement level, the whole system will be shut down.

6. Case study

Case studies based on the proposed topology and control strategy is presented in this chapter. The simulation is conducted under different condition to verify the responds of the proposed system.

6.1 Operation mode with constant energy requirement

The wind farm is made up by 6 wind turbines. The capacity for each wind turbine is 1.5 MW. The average wind speed is set as 8 m/s. The wind speed model described in chapter 4.2 is built and simulated. The wind speed at the hub height is set as variation around the average wind speed as described in chapter 4.2. The curve of wind speed at hub height is shown in figure 6.1.

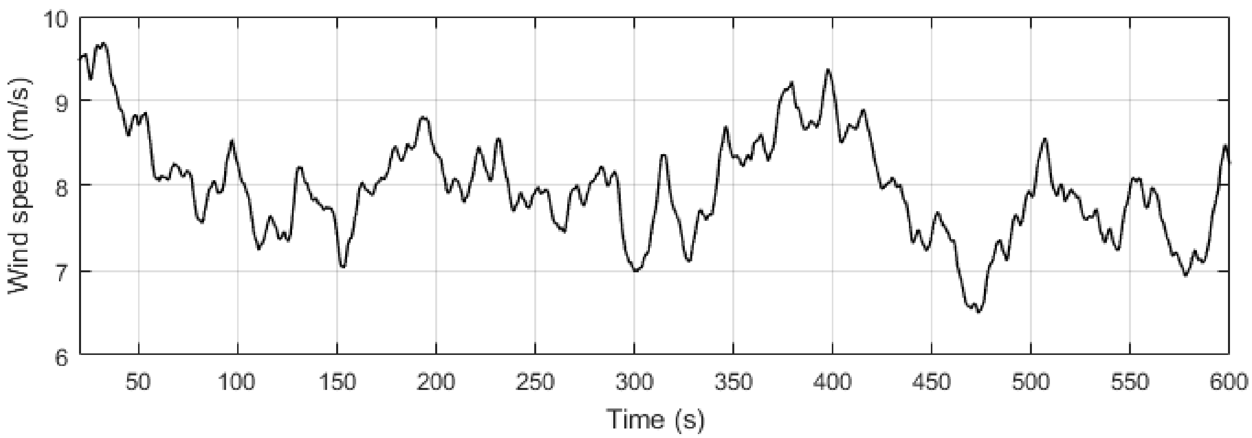

Figure 6.1 The wind speed at hub height

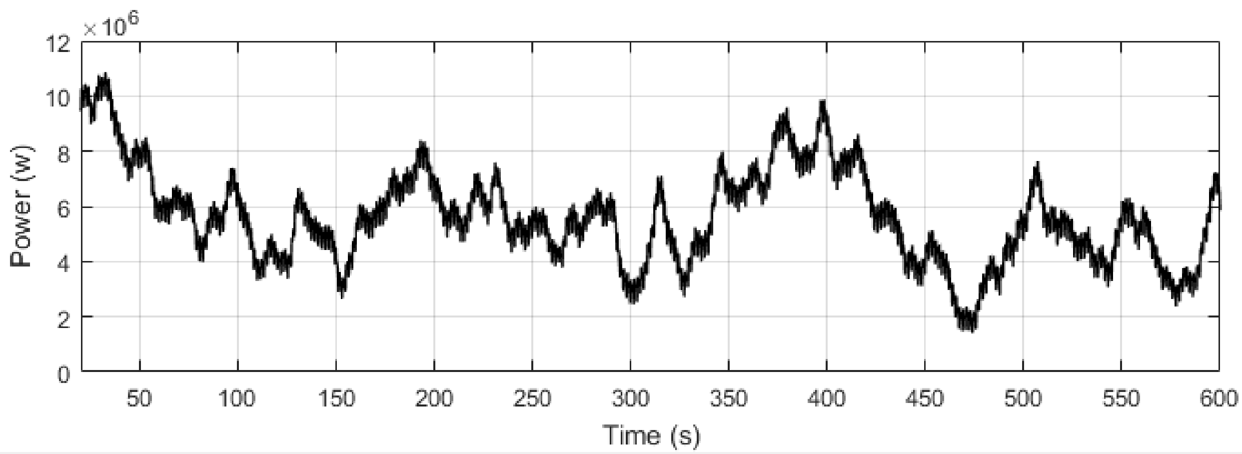

Figure 6.2 The measured power production from wind farm

The 3p oscillation component caused by wind shear and tower shadow effect is added to the wind speed model, and then, together sent to the wind turbine models. With the influence caused by the wind shear and tower shadow effect, the output of the wind turbines is shown as figure 6.2. It can be seen that the overall power production of wind turbines varies due to the variation of the wind speed. Besides fluctuation of the overall power production, the 3p oscillation component, which is caused by wind shear effect and tower shadow effect, also exists in the wind power production.

The fluctuation of the power production needs to be compensated by the dynamic control mentioned before. To prevent the influence from the 3p oscillation frequency, the 3p oscillation frequency should be eliminated before power compensation. This is achieved by measuring the output power of the wind turbines, and sending the signal to BP filter designed before. The 3p oscillation signal is picked out by the BP filter and sent into the rectifier that connected to PEM electrolyzer as active power reference. According to the law of conservation of energy, once the 3p fluctuation component is picked out, the remanding power is mitigated. A DC component is added to the 3p oscillation component picked out by the BP filter to shift the 3p oscillation component above zero. The 3p oscillation component picked out by the BP filter is shown in figure 6.3.

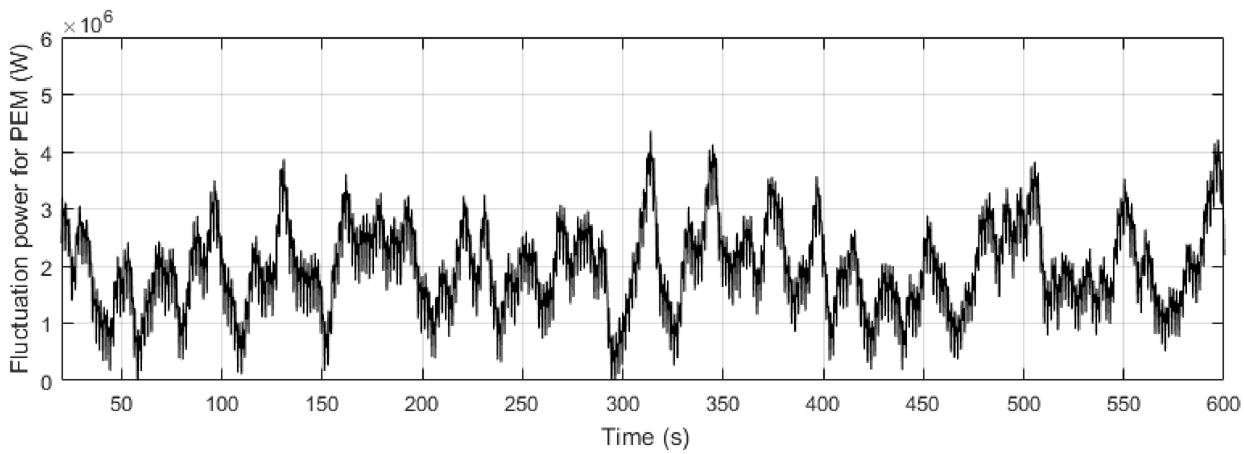

Figure 6.3 The fluctuation power picked out

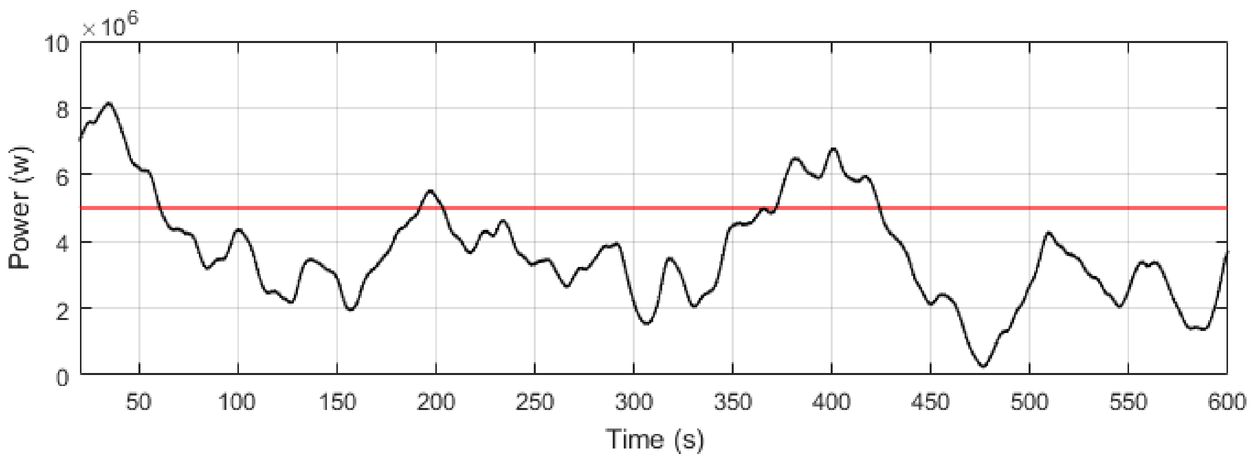

Figure 6.4 The power production after the fluctuation is consumed

The wind power production after the 3p oscillation mitigation process is shown in figure 6.4 by the black curve. It can be seen the power production is significantly smoothed after the 3p oscillation is consumed by the PEM electrolyzer. It also can be seen that the power production is still fluctuating because the variation of the wind speed. To compensate this fluctuation, the logic control which compares the power production with TSO order is built. The TSO order, which is 5 MW, is shown in figure 6.4 by red curve. It can be seen that the power production is sometimes greater than the TSO order and sometimes less than the TSO order.

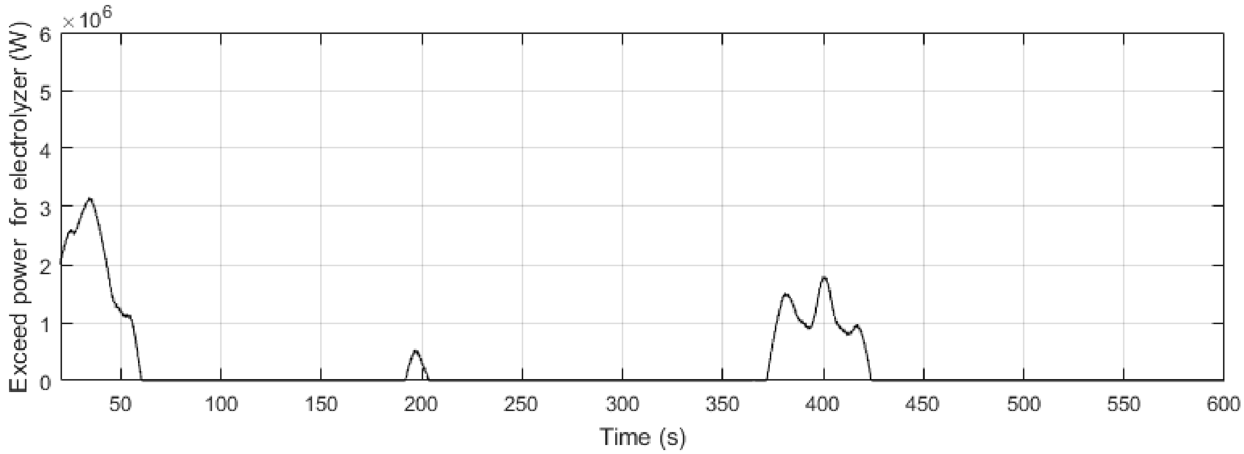

Figure 6.5 The exceed power for PEM electrolyzer to be consumed

The exceed power from the result of the comparison, which need to be consumed, is shown in figure 6.5. The exceed power only exist only when the power production is greater than the TSO order which is 5 MW. This part of power is consumed by the electrolyzer together with the 3p oscillation component and the DC component. The total power reference for the PEM electrolyzer should be the exceed power plus the 3p oscillation component plus a DC component, which is shown in figure 6.6 by black curve. To show the difference between the total power and pure fluctuation power, the pure fluctuation power is shown in figure 6.6 by red curve.

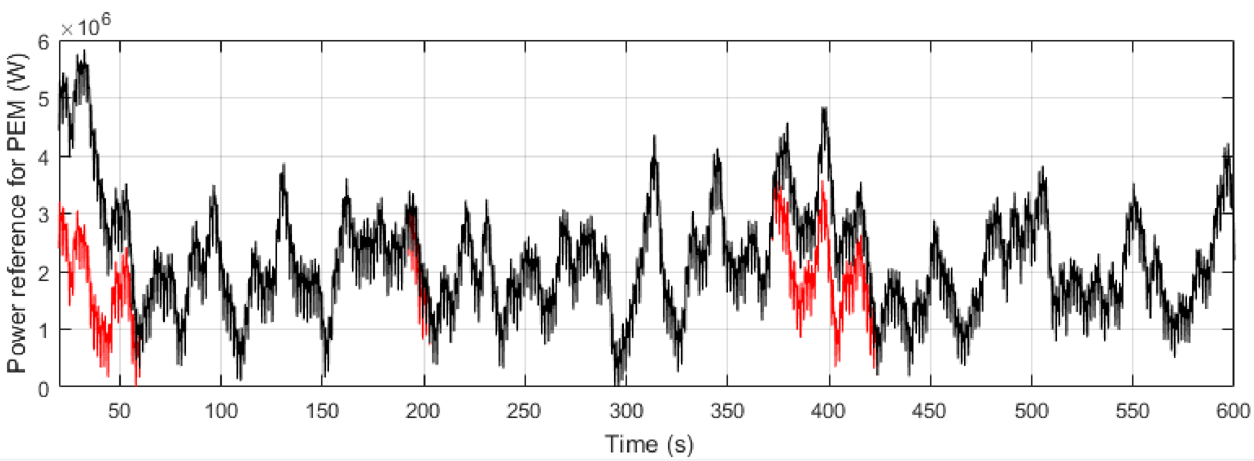

Figure 6.6 The total power for PEM electrolyzer to be consumed

The electrolyzer converts all the energy into hydrogen and oxygen for later use. The hydrogen production speed is shown in figure 6.7, the corresponding hydrogen output flow from negative pole is shown in figure 6.8. It should be point out that the hydrogen production speed is the chemistry production speed, while the hydrogen output flow is the hydrogen output speed from negative pole. The hydrogen output flow is calculated in chapter 4.1

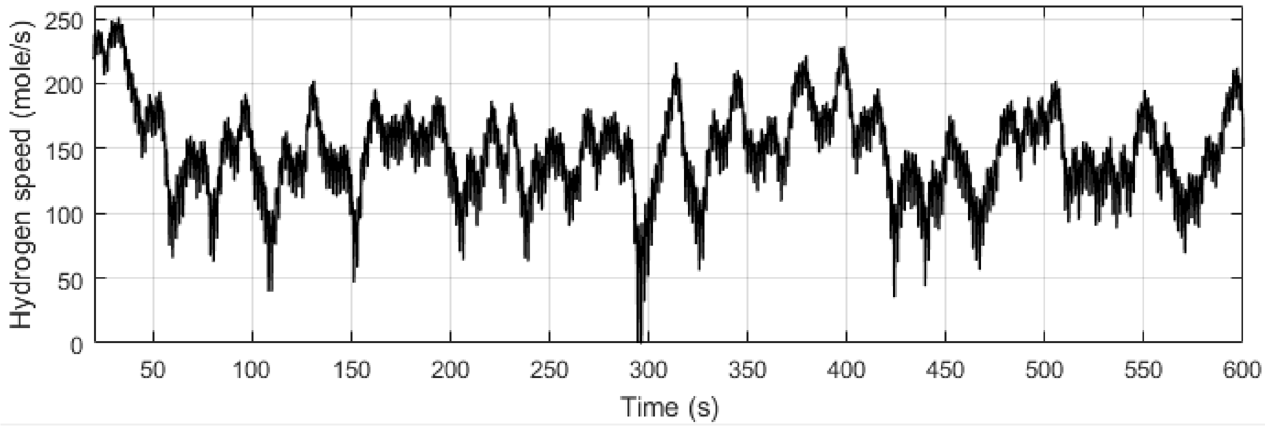

Figure 6.7 The hydrogen production speed

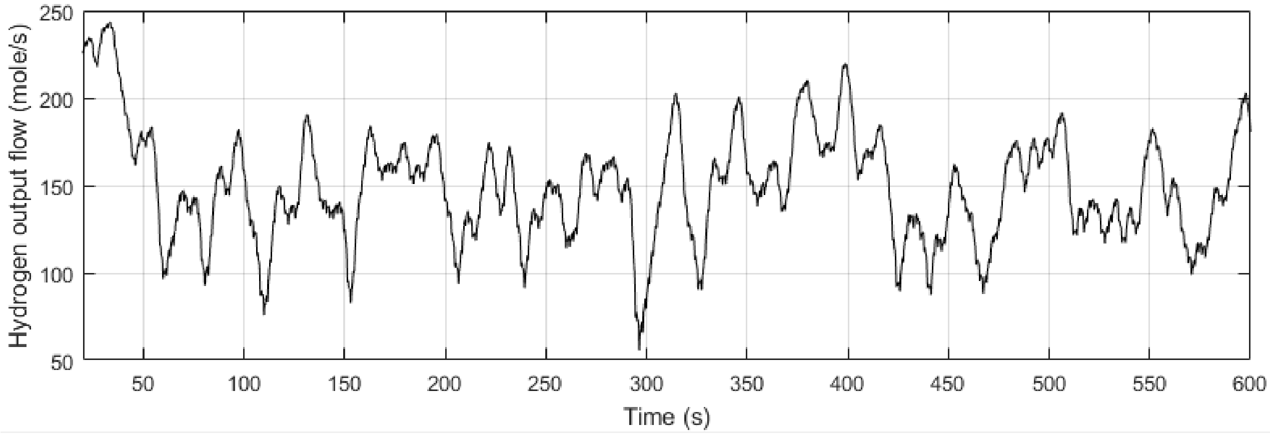

Figure 6.8 The hydrogen production output flow

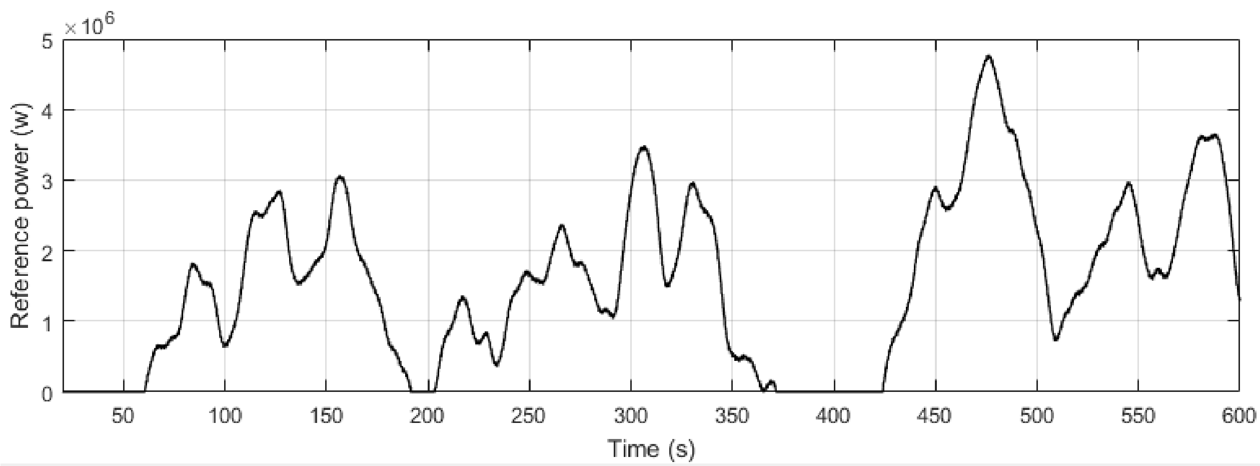

Figure 6.9 The insufficient reference power for combustion turbine

The insufficient power which is less than the TSO order is shown as figure 6.9. This insufficient power reference is from the comparison of result of the logic control. This insufficient power is designed to be compensated by the combustion turbine driven generator. The combustion turbine model, which is described in chapter 4.5, generates the power according to the given reference. The energy requirement is converted into hydrogen quantity requirement and sent into hydrogen combustion turbine to drive the generator. The energy losses through this energy transfer process are hypothesized to be 60% percent due to the low efficiency of the combustion turbine. The power generated by the generator is shown in figure 6.10. It can be seen that the generated power follows the power reference given by the logic control.

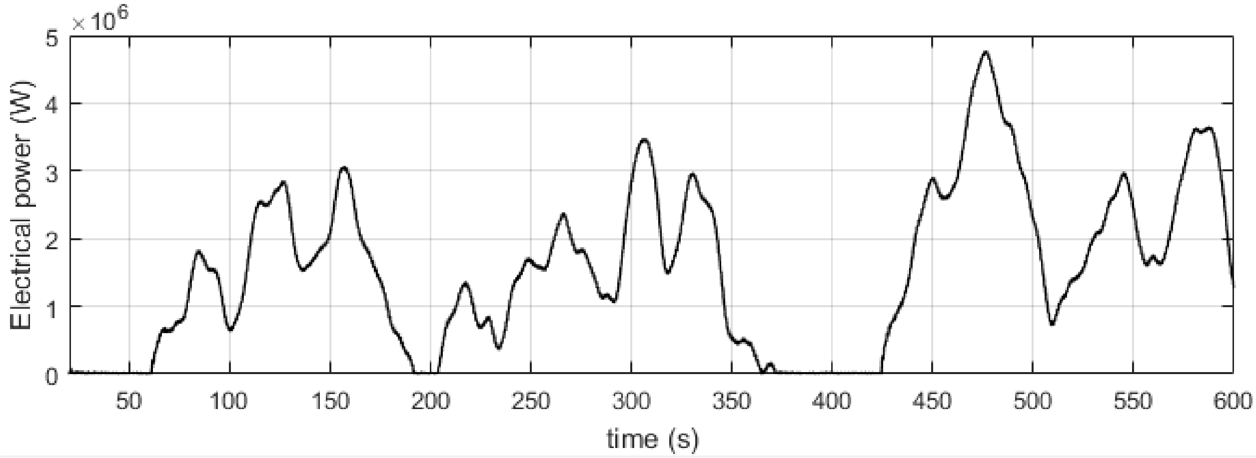

Figure 6.10 The power generated by combustion turbine driven generator

After all the power coordination, the final power output of the whole system is shown in figure 6.11. It can be seen that the final output power is a constant as 5 MW, which follows the TSO order. It can be seen that with the proposed control strategy, the whole system could work properly as the objective of this project. The power output characteristic is like a conventional power plant, which is constant and following the TSO order.

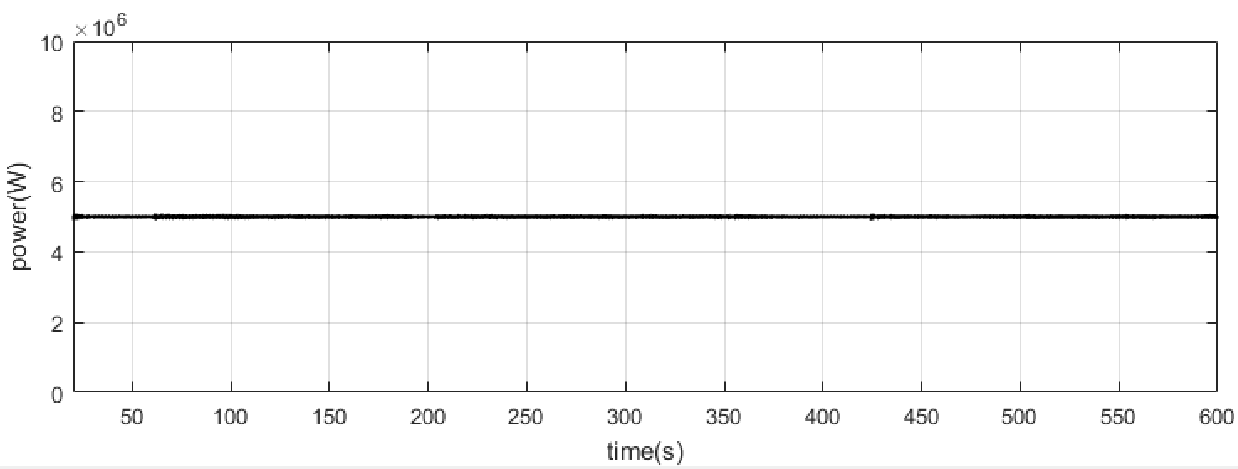

Figure 6.11 The final output power of the proposed system

6.2 Operation mode with changing energy requirement

This case study shows the responds of the system with changing TSO requirement. The requirement of TSO is shown in figure 6.12. The TSO order is 4 MW in the beginning, and then changes into 6 MW at the 150th second. Then this requirement changes into 5 MW at the 400th second. The system is designed to follow this requirement with the coordination strategy. The responds of the system is shown in figure 6.13. It can be seen that the responds of the system follows the TSO requirement.

It should be point out that combustion turbine is driven by the hydrogen as fuel. The variation of TSO order is sent into combustion turbine as a variation of hydrogen quantity. According to the ideal gas equation, the pressure of gas cannot be changed suddenly; this is because the pressure is a function of gas quantity when the volume is constant, and the gas quantity is an integration of gas flow. Therefore, the responds o gas supply to this TSO order has a function rate changing limitation.

The others equipment in the system have similar reaction, the operation principle is the same, thus, the detailed reaction of other equipment will not be presented here.

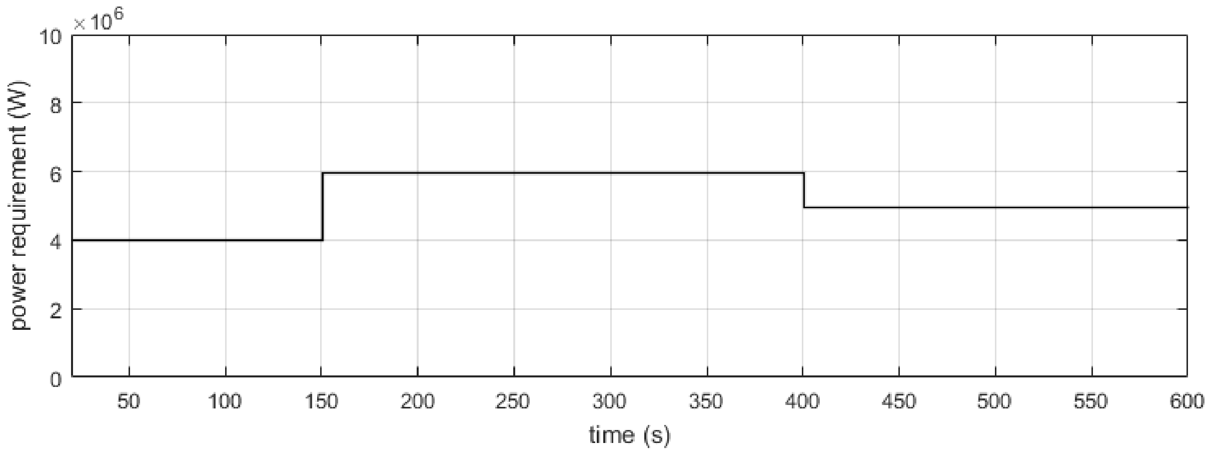

Figure 6.12 The TSO order

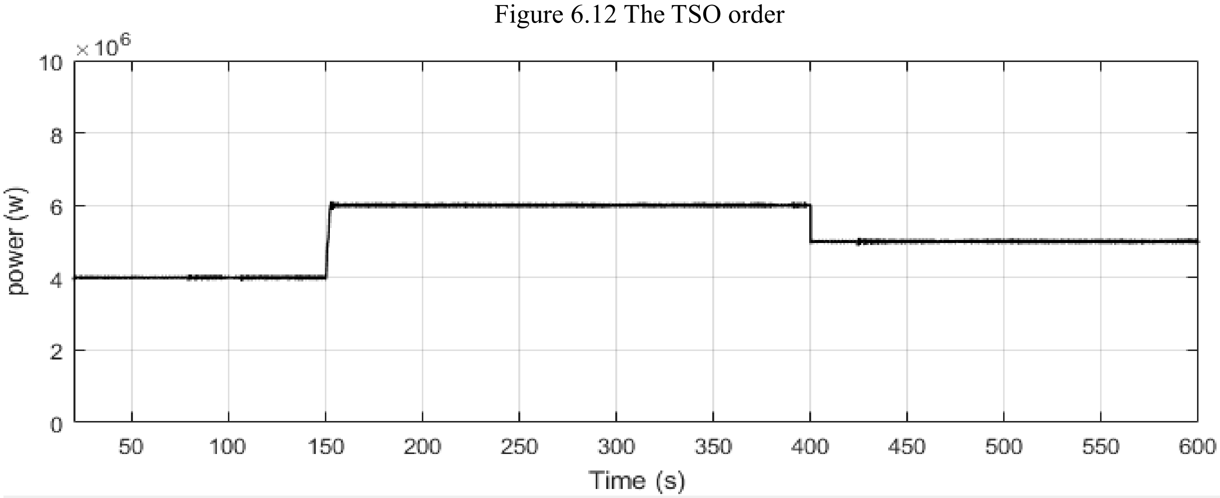

Figure 6.13 The final output power of the proposed system with changing TSO order

6.3 Island operation mode

The case study of the island operation mode is conducted under the island operation strategy. The system is assumed to be disconnected from the grid at the 350th second. The system is operated with normal operation strategy for the first 350 seconds, then, since the 350th second, the system is operated under island operation mode with corresponding strategy. The system is tested under this scenario, the signal coordination and respond of the system is presented below.

Figure 6.14 shows the power reference for the combustion turbine. For the first 350 seconds, the system is operated with normal coordination strategy. The TSO order is 5 MW, the wind conditions and other simulation strategies are the same as case study 6.1. At the 350th second, the system is disconnected from grid, the system is switched into island operation strategy, and the reference power for combustion turbine is set into zero as shown in figure 6.14. The responds of the combustion turbine driven generator is the same as case study 6.1 for the first 350 seconds. When the system is switched into island operation mode, the combustion turbine driven generator is disconnected from the PCC due to the protection operate, thus, output power from the combustion turbine driven generator is zero.

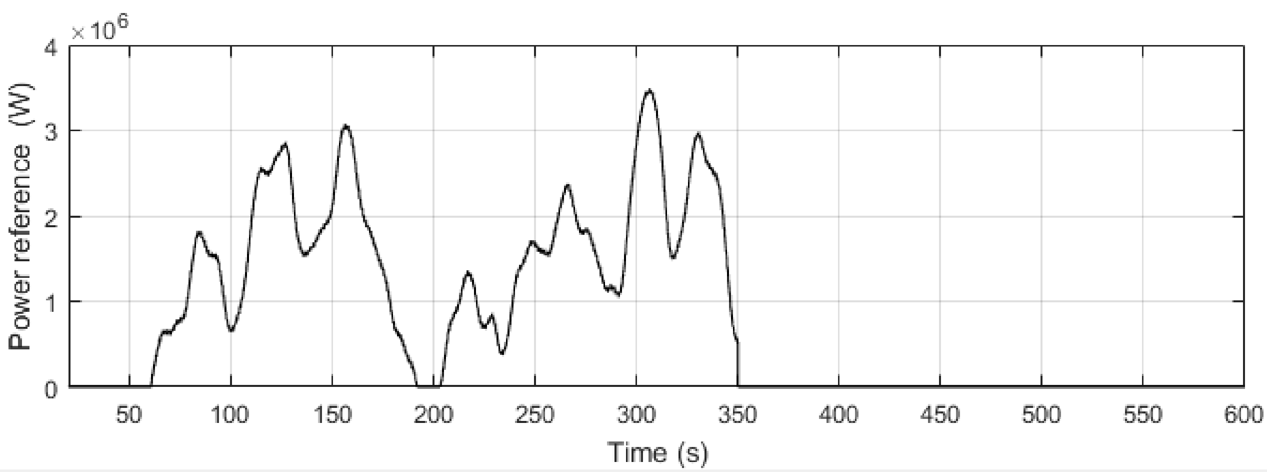

Figure 6.14 The power generation reference for combustion turbine under island control strategy

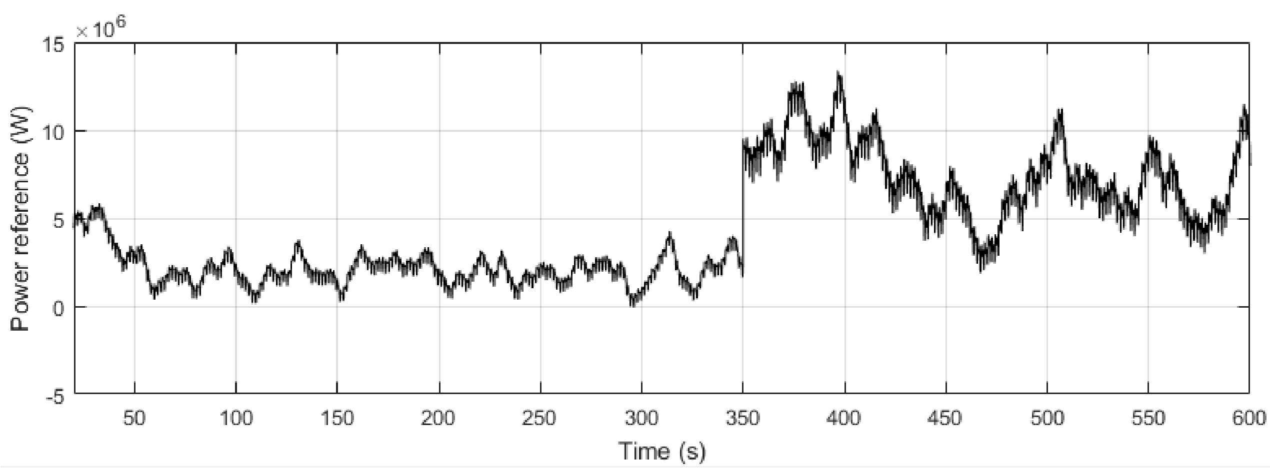

Figure 6.15 The power consumption reference for PEM electrolyzer under island control strategy

Figure 6.15 shows the power reference for the PEM electrolyzer. Before the 350th second, the system is operated under normal operation mode. The reference power shown in figure 6.15 in the first 350 seconds is the total power reference, which is fluctuation power reference that in figure 6.3 plus the exceed power reference that in figure 6.5. After the 350th second, the system is coordinated under island operation strategy, all the power production from the wind farm is sent into PEM electrolyzer to be consumed. The reference power shown in figure 6.15 after the 350th second is the total power production from the wind farm.

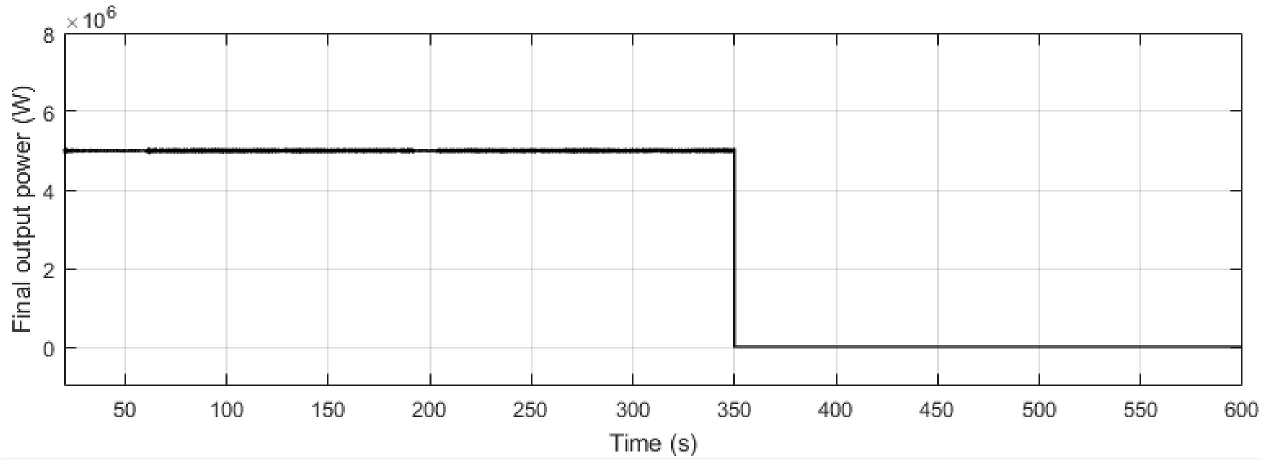

Figure 6.16 The final output power of the system under island control strategy

The final power output of the system is shown in figure 6.16. It can be seen that the power output of the system follows the TSO order as 5 MW for the first 350 seconds. At the 350th second, the system is disconnected from the grid, thus, the output power from the system is zero.

6.4 Voltage mitigation

The voltage flicker caused by the 3p oscillation component in the power production is shown in figure 6.17. After the voltage mitigation process, which is achieved by consuming the 3p oscillation component using PEM elctrolyzer, the voltage is shown as figure 6.18.

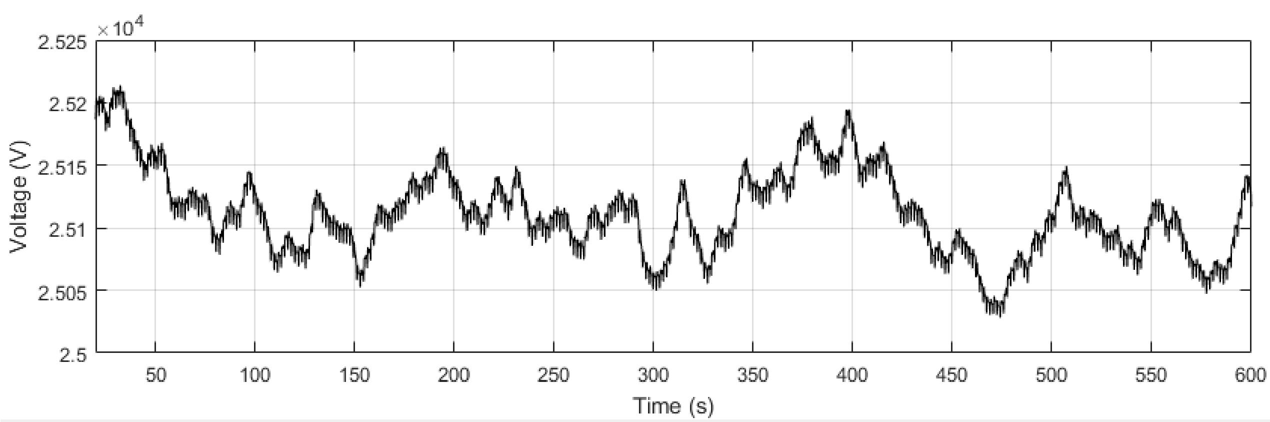

Figure 6.17 The initial voltage at PCC

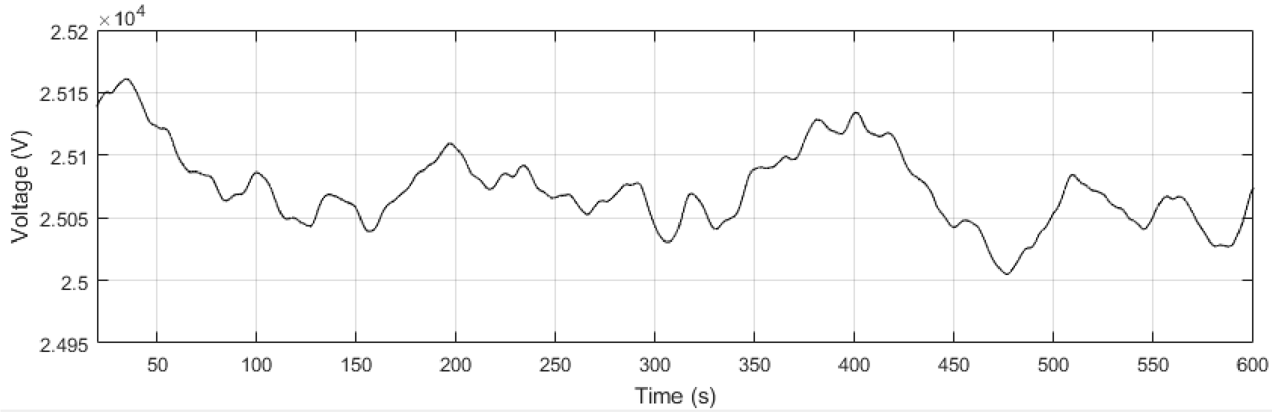

Figure 6.18 The voltage at PCC after 3p oscillation mitigation

It can be seen that the voltage after mitigation is significantly smoothed. It should be point out that the voltage mitigation process is achieved by active power mitigation as described in chapter 4.4. The 3p oscillation component contained in the active power is consumed by the PEM electrolyzer. A DC component in the active power is also consumed together with the 3p oscillation component, which causes a voltage drop to the whole voltage curve.

The voltage after the whole power coordination process is shown in figure 6.19. It can be seen that when the power output of the whole system is mitigated by the proposed coordination strategy, the voltage at PCC is constant. This means when the active power is coordinated to be constant by proper coordination strategy, the voltage at the PCC is constant.

It should by noticed here that, the voltage mitigation only takes active power into consideration, the voltage fluctuation caused by reactive power is not a concern of this project.

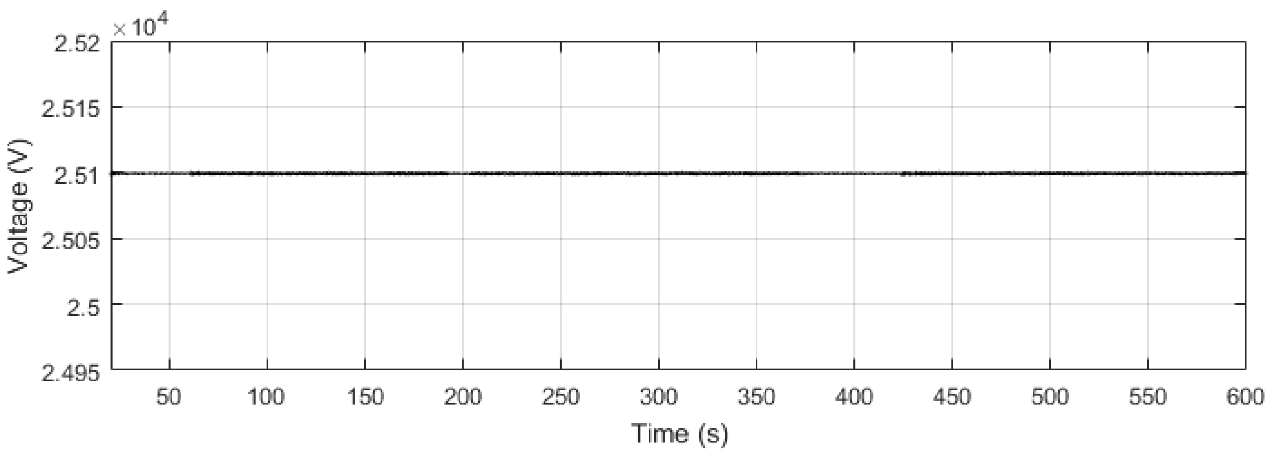

Figure 6.19 The voltage at PCC after all mitigation process

It can be seen that with the proposed method, the voltage can be mitigated by consuming the 3p oscillating component in active power.

6.5 Maximum profit operation mode

The price of electricity varies from day to day according to the TSO condition. The generation unite in the system usually makes the profit by selling the electricity to TSO. Thus, the variation of electricity price influences the profit of generation unit in the system.

The system designed in this project has two ways to make profit: by selling electricity and by selling the gas to gas network.

The gas network is usually used for methane transmission. The hydrogen production of the system could be used to produce methane and sell it to gas network. The transfer from the hydrogen to methane is described in chapter 4.8. The methane production is sent into gas network to make profit. Following assumption has been made to implement the simulation. It should be point out that how much profit a generation unite in the system makes depends on how much electricity it generated.

1. The price of methane is 0.643 DKK/m^3 for the first scenario
2. The price of methane varies for the second scenario (figure 6.21)
3. The efficient of Sabatier reaction is 100%
4. The initial energy/hear to start the Sabatier reaction is neglected
5. The average electricity consumption to produce hydrogen is 5 KWh/ m^3
6. The electricity data varies every hour during one day.
7. The electricity price data is from Energinet.dk (Danish TSO), the data is the electricity price of west Denmark in January of 2015.

For the first scenario, the price of methane is constant. To compare the profit made from electricity and the profit made from methane, the equation (49) in chapter 4.7 is applied, the result of the calculation is 0.03215 DKK/KWh. The price data of electricity is from energinet.dk, which is the TSO of Denmark. The electricity price varies every hour during January in 2015. The price variation of electricity is shown in figure 6.20 by black curve. The price of methane is shown in figure 6.20 by red curve. It can be seen that the price of electricity fluctuates every hour. When the electricity price per KWh is higher than the profit made by converting this 1 KWh electricity to methane and selling it, the system sells the electricity in the first priority. Otherwise, the electricity will be converted into methane and sold to gas network to make profit. The profit made by selling electricity and the profit made by selling the methane that converted from electricity is summed together to get the total profit.

The profit made by only selling the electricity is calculated and compared with the profit made under the coordination strategy mentioned above. The simulation result shows, for every KW output power, compared with only selling electricity 2.1 DKK more profit could be made with the proposed strategy per month.

For the second scenario, the price of methane varies around the average price of 0.03215

DKK/KWh. The variation of this price is shown in figure 6.21 by red curve. The variation is a random data generated by Excel. The strategy is still the same as the strategy proposed in scenario 2. The simulation result shows, for every KW output power, compared with only selling electricity, 10.1 DKK more profit could be made with the proposed strategy.

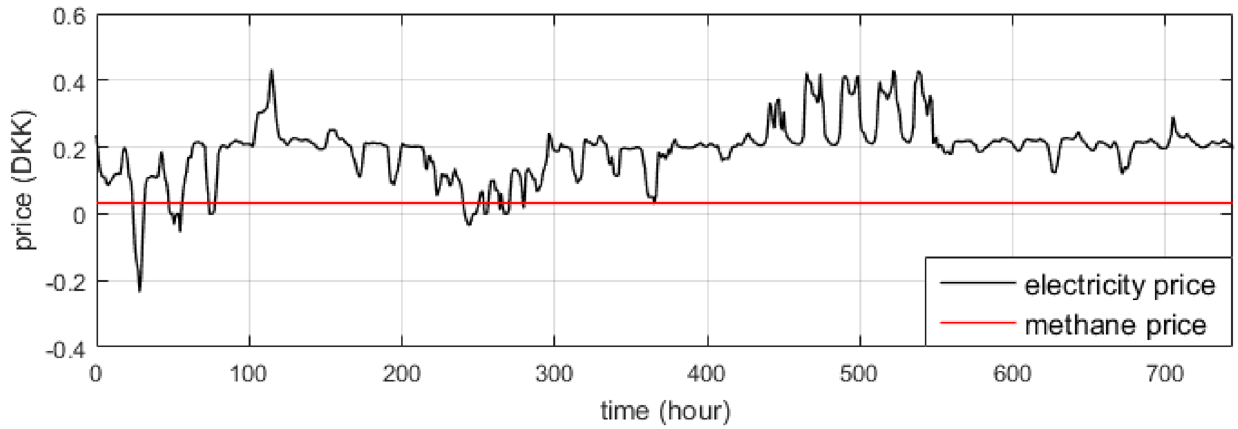

Figure 6.20 The price of electricity vs constant methane price

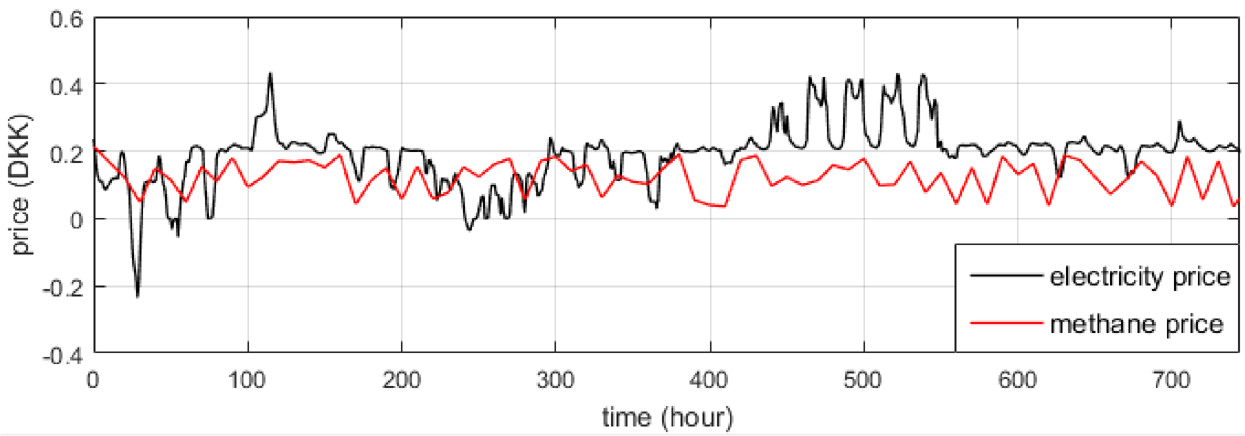

Figure 6.21 The price of electricity vs changing methane price

The wind power generation is not stable due to the fluctuation of the wind speed. The calculation for both scenarios above about profit is based on per KWh. The wind power generation is not stable due to the fluctuation of the wind speed. The profit made by a wind farm is highly depending on the electricity generated by it. To illustrate the total profit that could be made, the wind power generation data is applied. The wind power generation data is from the TSO in Denmark. The data applied in this project is the wind power generation in west of Denmark in January 2015, which is shown in figure 6.22. The profit could be made by selling the wind power generation without the strategy can be calculated as generation times the corresponding price, which is shown in figure 6.23 and figure 6.24 by black curve. For the first scenario with constant methane price, the profit can be made with the proposed strategy is shown in figure 6.23 by red curve. For the second scenario with changing methane price, the profit can be made with the proposed strategy is shown in figure 6.24 by red curve.

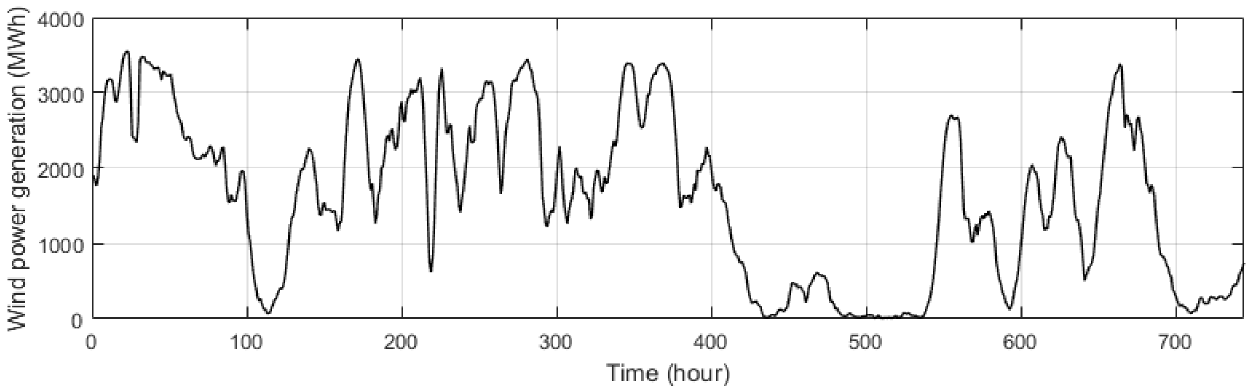

Figure 6.22 The wind power production in Denmark west in January 2015

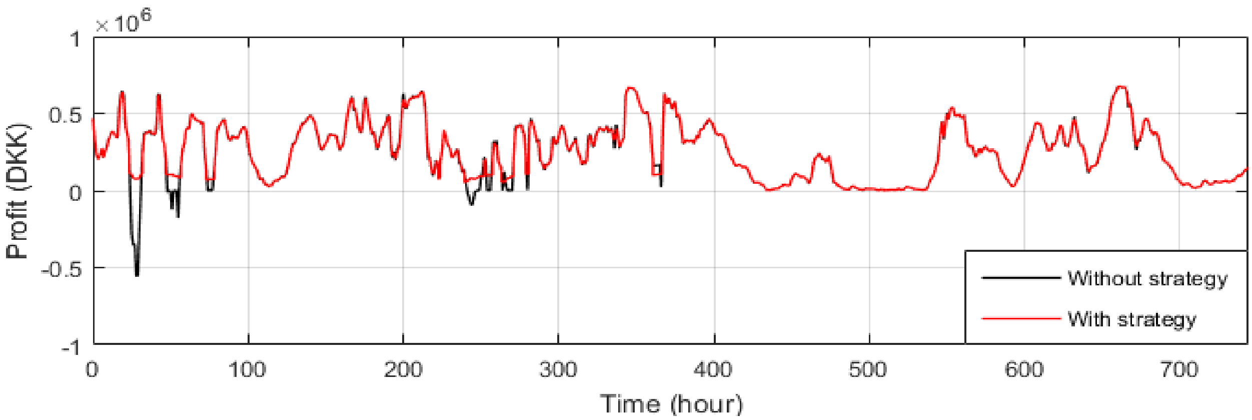

Figure 6.23 The profit could be made in first scenario

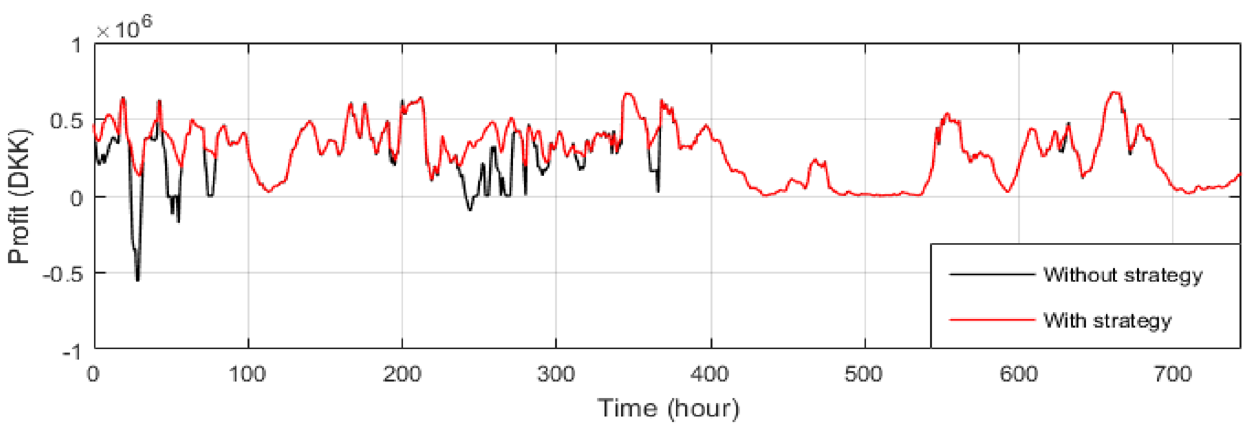

Figure 6.24 The profit could be made in second scenario

It can be seen from figure 6.23 and figure 6.24 that, more profits can be made with the proposed strategy during some period in January. These period that can make more profit corresponds to the period that methane price is higher than electricity price in figure 6.20 and figure 6.21. The simulation result of profit calculation is shown in table 5.

Table 5 Profit calculation result

Terms	scenario 1		scenario 2	
	Without strategy	With strategy	Without strategy	With strategy
Profit per KW output power	142.5 DKK	144.6 DKK	142.5 DKK	152.6 DKK
Total profit	187.1 million DKK	192.4 million DKK	187.1 DKK	213.1 DKK

7 Conclusion future works

This chapter presents the conclusion and future works of this project.

7.1 Conclusion

This project proposes a new topology and its corresponding control strategy. The proposed topology combines wind turbines, a PEM electrolyzer, a combustion turbine and its corresponding generator together. The active power coordination is the main concern of the project. The objective of this project is to make the wind farm works like conventional power plant from the grid perspective. The proposed topology and system is modeled as described in chapter 4. The control strategy for the proposed system is shown in chapter 5. The proposed system is simulated with the proposed control strategy under different case, which is presented in chapter 6.

The main purpose of the system is to coordinate the active power production. The power production from the wind turbines is measured, and then a BP filter is designed to pick out the 3p oscillation signal from the power measurement. The 3p oscillation signal picked out by the BP filter is then fed into the rectifier as active power reference. According to the law of the law of conservation of energy, once the 3p oscillation component is picked out, the reminding power which sent into the grid is smoothed. After smoothed, the fluctuation component in active power, which caused by the wind speed variation is compared with transmission system operator (TSO). The exceed power signal is sent into PEM electrolyzer to be consumed, the insufficient power signal is then sent into combustion turbine to be compensated. Thus, the final output power should be a constant.

From the case studies and analysis, it can be concluded:

- The proposed system works properly with the proposed control strategy to give constant power output.
- The proposed system responds properly to the TSO order with the proposed control strategy.
- From the grid perspective, the active power output characters are like conventional power plant, which is constant and could follow the order from TSO.
- The fluctuation components in wind farm power production could be mitigated with the proposed topology and control strategy.
- The proposed topology responds properly to extreme case of island operation mode with the proposed control strategy.
- The PEM electrolyzer could be used to achieve active power mitigation and voltage mitigation for wind farms.
- Voltage mitigation can be achieved by active power mitigation.

7.2 Future works

The future work of this project are:

- The project is simulated with some assumptions, the future work should verify the assumptions.
- The sizes of the wind farm, the PEM electrolyzer and combustion turbine should be optimized.
- More detailed models could be built to verify the result of this project.
- Control strategy for other extreme case could be developed.
- Fault respond of the system could be studied.
- The integration of the heat pump to connect the system to hear network should be developed.
- The experiment should be conducted to verify the performance of the proposed system and the control strategy.
- Simulation of connecting the proposed system to the gas network should be conducted.
- The combustion turbine driven generator has the ability to supply reactive power. Study and simulation about reactive power coordination of the proposed system should be conducted.

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Appendix

Appendix 1 Implementation of the simulation

The implementation of the simulation of this project is shown in this part of Appendix. The implementation of detailed equation is not presented due to the concern of report economy.

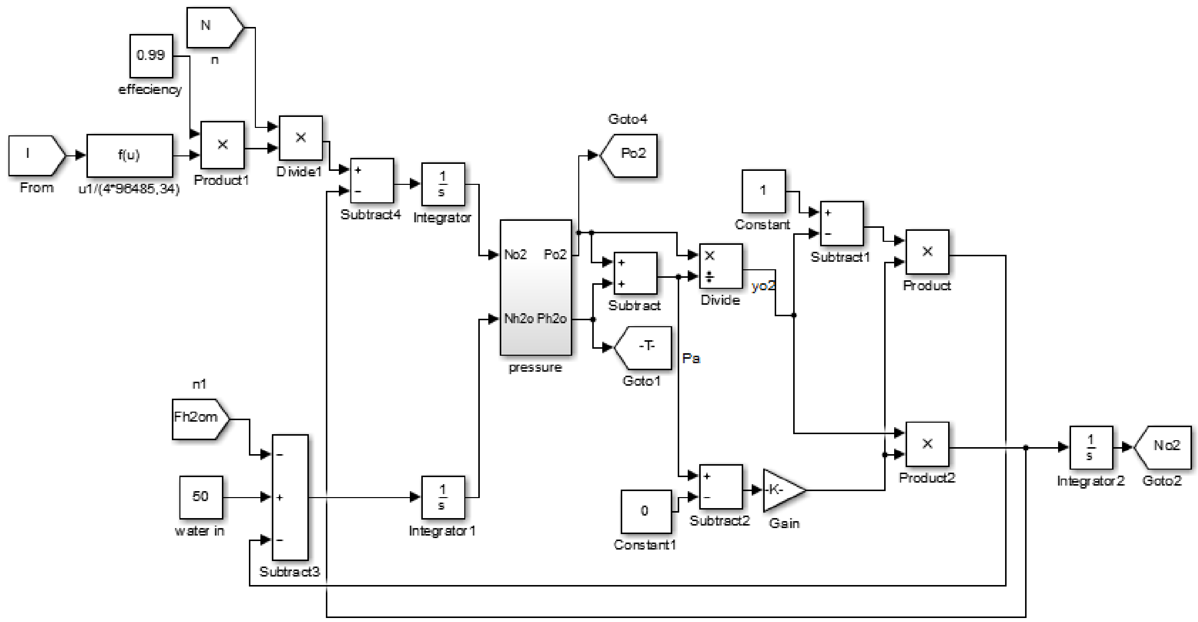

Figure A1. The simulation implementation of positive pole

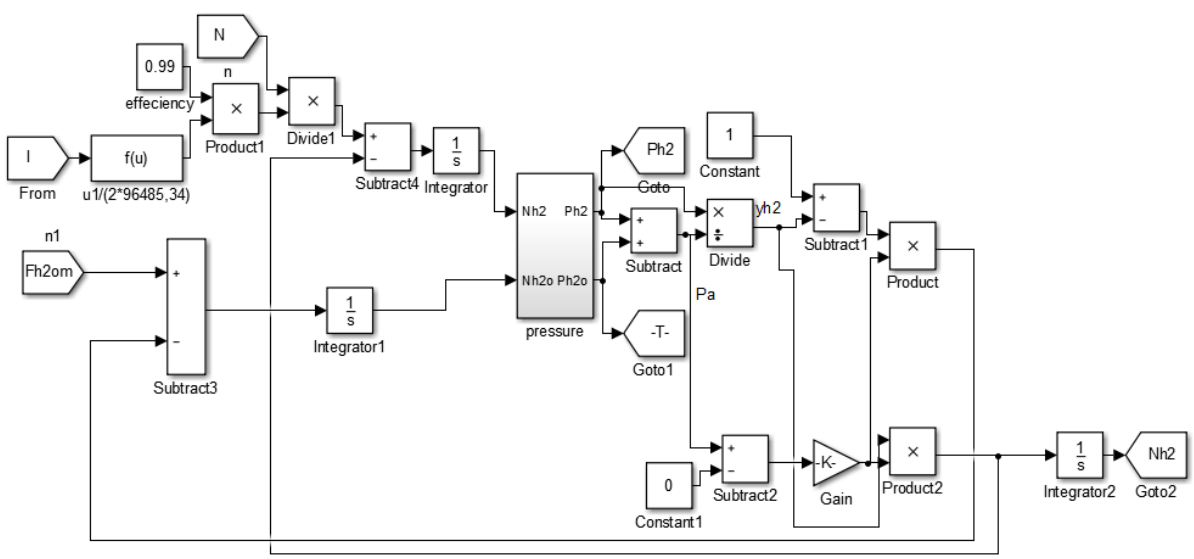

Figure A2. The simulation implementation of negative pole

The model of the possitive pole of the PEM electrolyzer is shown in figure A1. The model is built according to equation (10) to equation (18). The production of oxygen is calculated by this part of model. This model also calculates the necessary signal for other models. It should be mentioned that the integrators are given a very small initial values to prevent errors.

The output of the positive pole is assumed to be connected to a pump to take out the oxygen production, thus, the P_{ao} in equation (16) is assumed to be 0.

The model of the negative pole of the PEM electrolyzer is shown in figure A2. The model is built according to equation (19) to equation (27). This part of model calculates the production of hydrogen according to the applied current and other conditions. Some of the necessary parameters for other models are also calculated by this model.

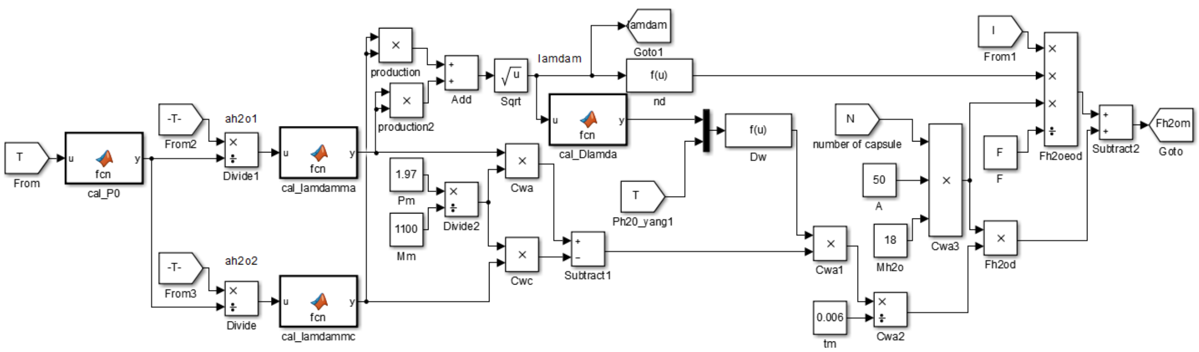

Figure A3. The simulation implementation of proton exchange membrane

The model of proton exchange membrane is shown in figure A3. This model is built according to equations (28) to (33). This model is to simulate the proton exchange membrane which is the model described in chapter 4.1. The calculations of equations (32) and (33) are programed in the "fcn" block. Necessary parameters for the calculations are sent into the block. The necessary parameters are calculated for further using, which is described in the chapter 4.1.

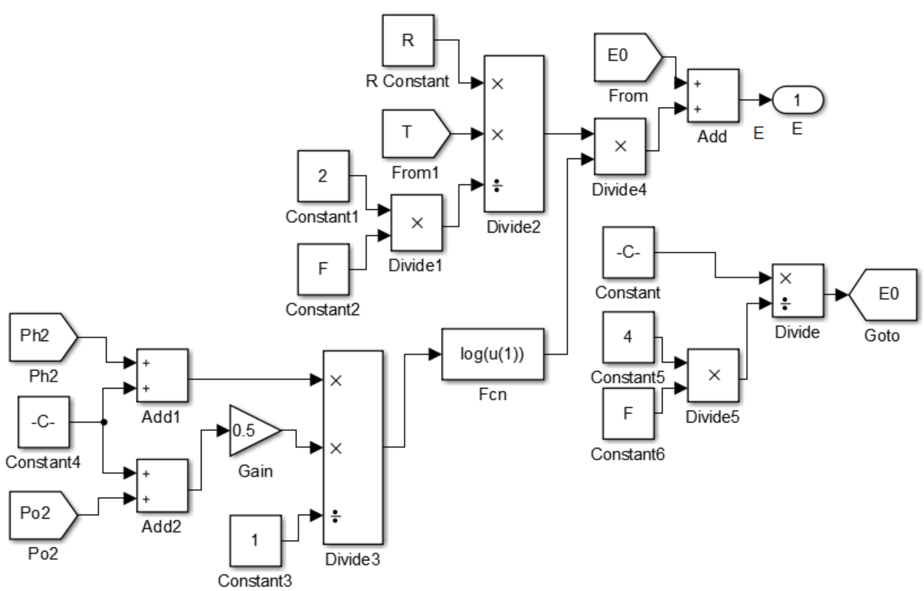

Figure A4. The simulation implementation of open circuit voltage

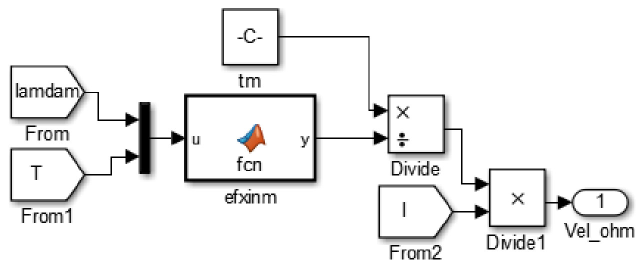

Figure A5. The simulation implementation of ohm polarization voltage

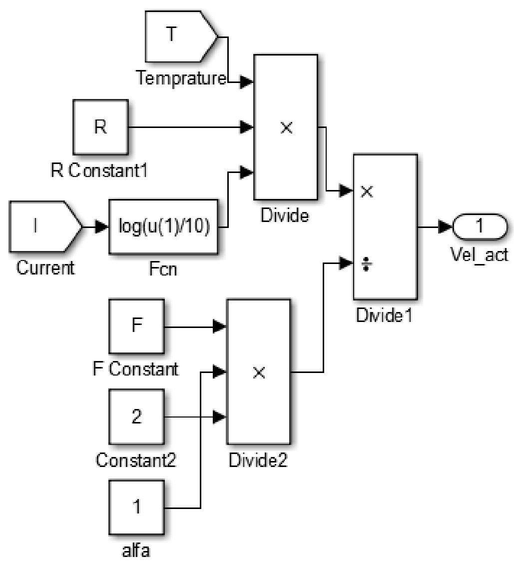

Figure A6. The simulation implementation of activation polarization

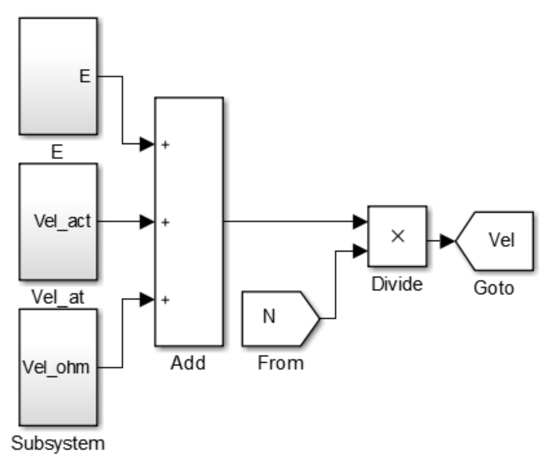

Figure A7. The simulation implementation of whole voltage model

The model of open circuit voltage calculation is shown in figure A4. This model is built according to chapter 4.1.5. This model calculates the open circuit voltage for the PEM electrolyzer. The model of the ohm polarization voltage, which is built according to description in chapter 4.1.5, is shown in figure A5. The model of activation polarization voltage is shown in figure A6. This model calculates the activation polarization voltage of the PEM electrolyzer according the equations that are presented in chapter 4.1.5. All the three voltage is summed together to get the total voltage for each capsule. It should be mentioned here that the total voltage of each capsule should be times the number of the capsule to get the final voltage, which is also shown in figure A7.

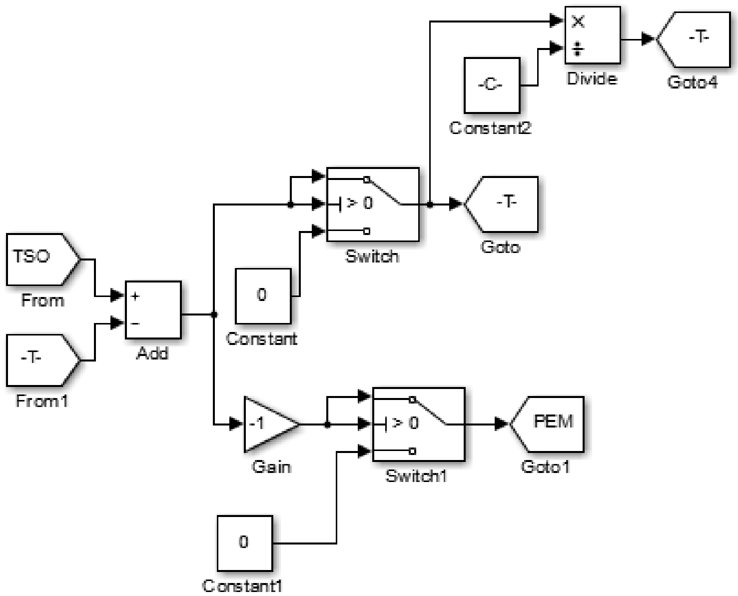

Figure A8. The simulation implementation of logic control

The logic control simulation is shown in figure A8. The measured power production is compared with TSO order. The result of the comparison is sent into logic signal control block. The function of the switch block is: pass signal 1 when signal two satisfies the selected criterion, otherwise pass signal three. The block passes the signal with logic judge. With the connection shown in figure A8, the block passes the power reference for combustion turbine or PEM electrolyzer when the reference power is greater than zero, otherwise, the reference power is set to zero.

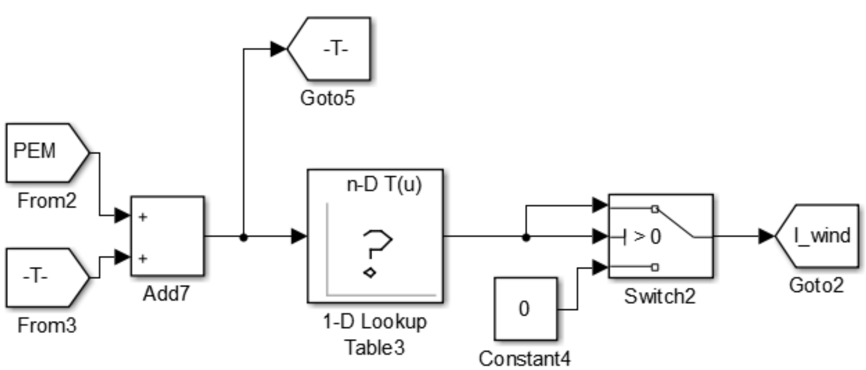

Figure A9. The simulation implementation of PEM current model

The current for PEM electrolyzer is decided by the corresponding power need to be consumed. The current block is shown in figure A9. The total power for PEM electrolyzer, which is the exceed power plus the fluctuation power, is sent into a look-up table. The look-up table gives the corresponding current according to the power value. The PEM electrolyzer could only consume current, thus, the current signal for PEM electrolyzer must be greater than zero. A logic block is applied to only pass the current signal greater than zero. When the current signal is smaller than zero, a zero is passed instead of current signal.

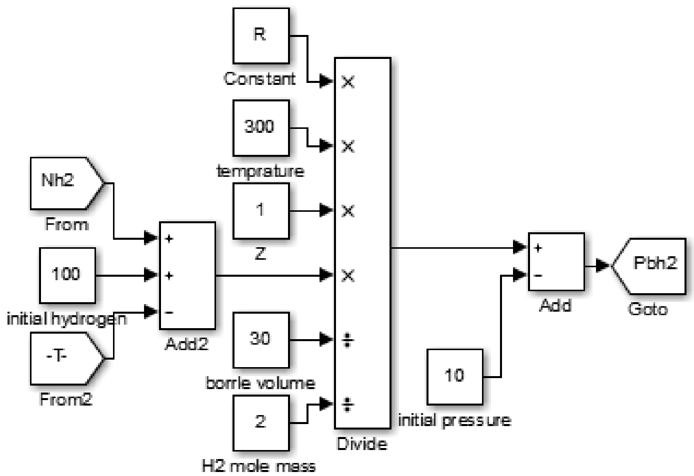

Figure A10. The simulation implementation of hydrogen tank

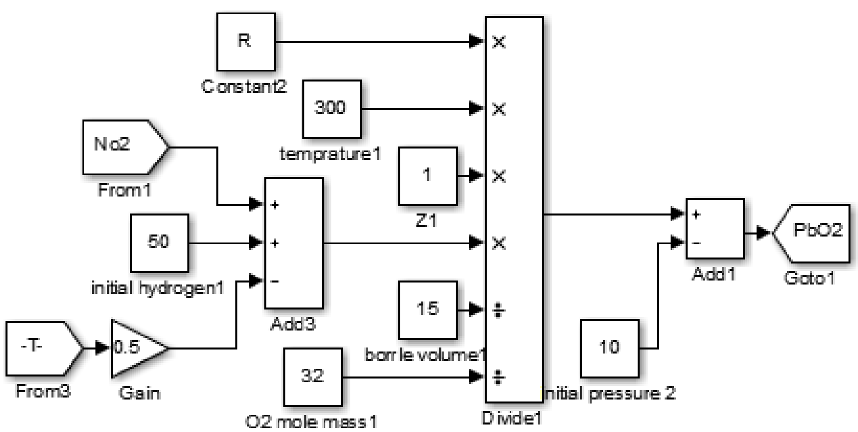

Figure A11. The simulation implementation of oxygen tank

The storage model is shown in figure A10 and A11, the model is to calculate the pressure in each tank. The model is built according to the equation (28) in chapter 4.1.6. The output flow for combustion turbine is subtracted from the input flow. The volume of different tanks is different. The volume of hydrogen tank is two times bigger than oxygen tank.

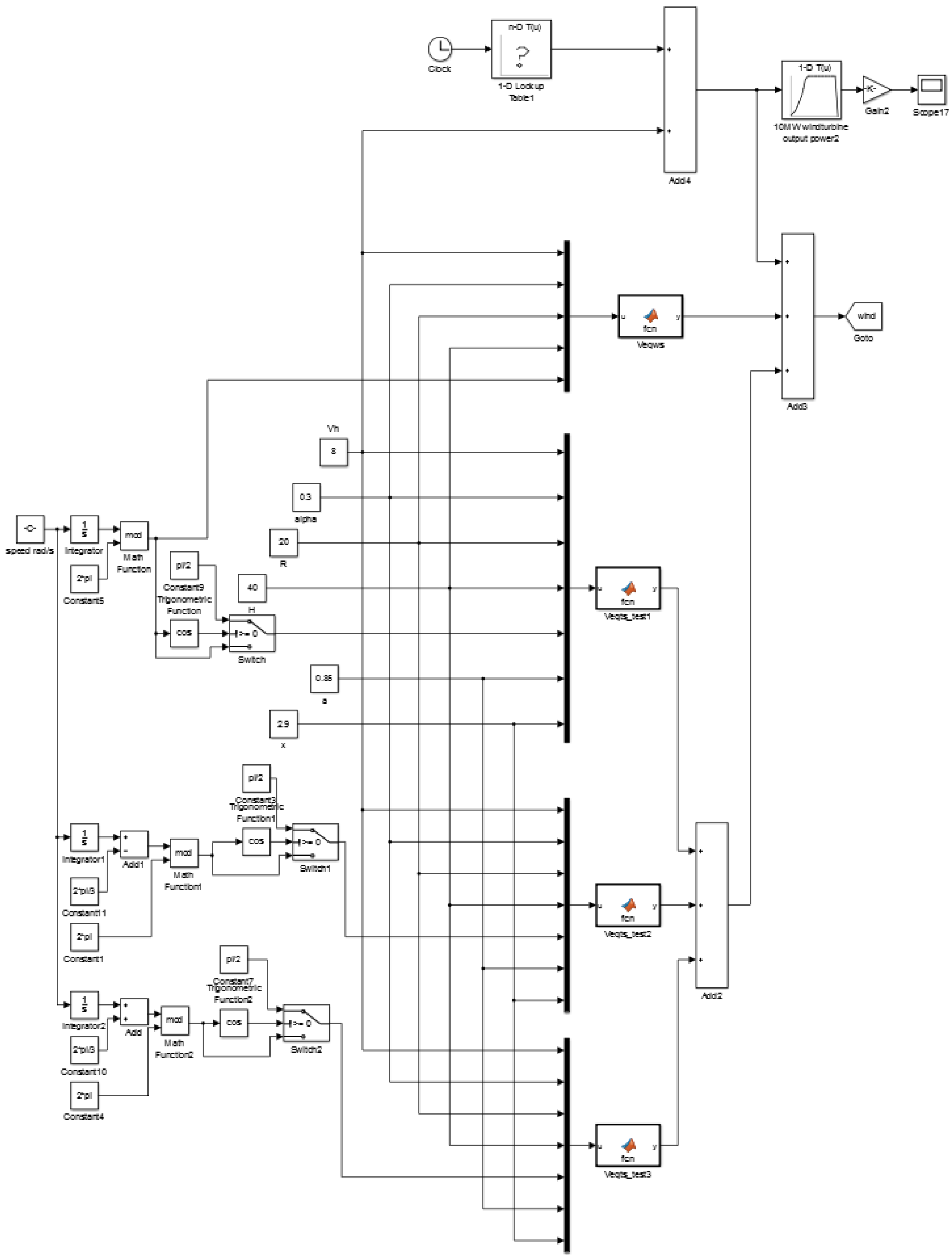

Figure A12. The simulation implementation of hydrogen tank

The wind speed model is shown in figure A12. The equivalent wind speed caused by tower shadow effect for each blade is calculated separately and then summed together. The fluctuation of wind speed at hub height is implemented in a look-up table. The fluctuation is the variation of wind speed at corresponding time. The fluctuation is added to the average wind speed to formulate the fluctuating wind speed at hub height. The equivalent wind speed caused by wind shear effect is calculated with necessary parameters. The final wind speed is a sum of equivalent wind speed that caused by tower shadow effect, equivalent wind speed that caused by tower shadow effect, and the fluctuating wind speed at hub height.

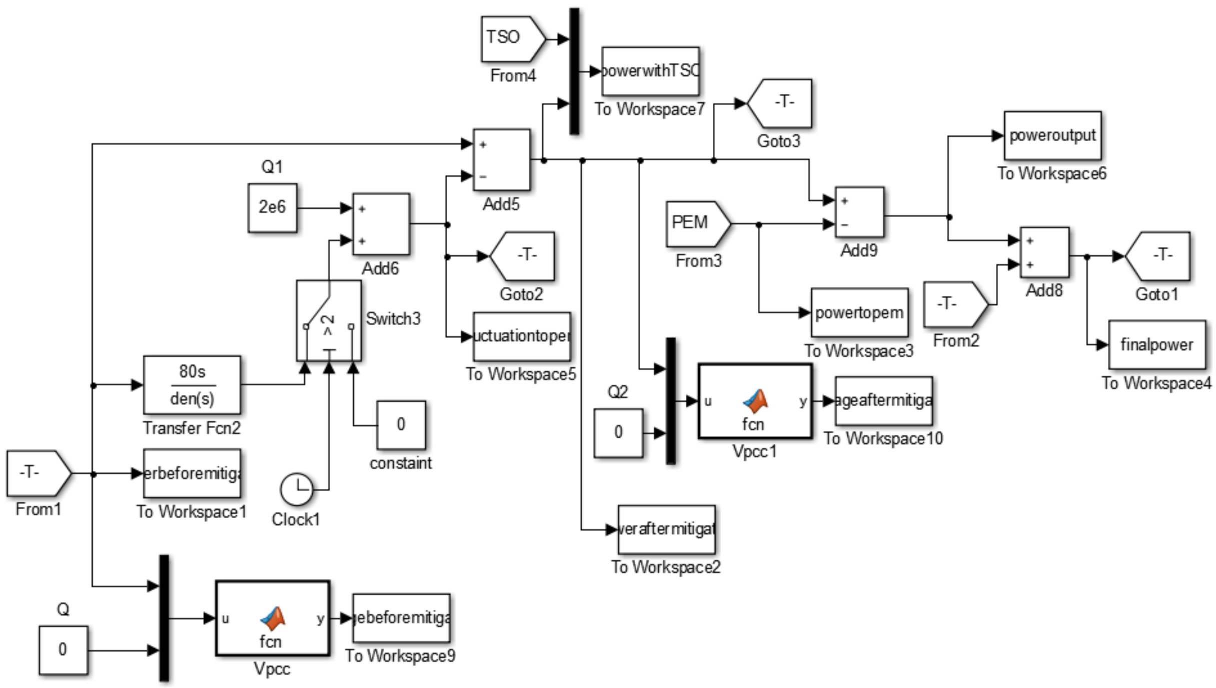

Figure A13. The simulation implementation of hydrogen tank

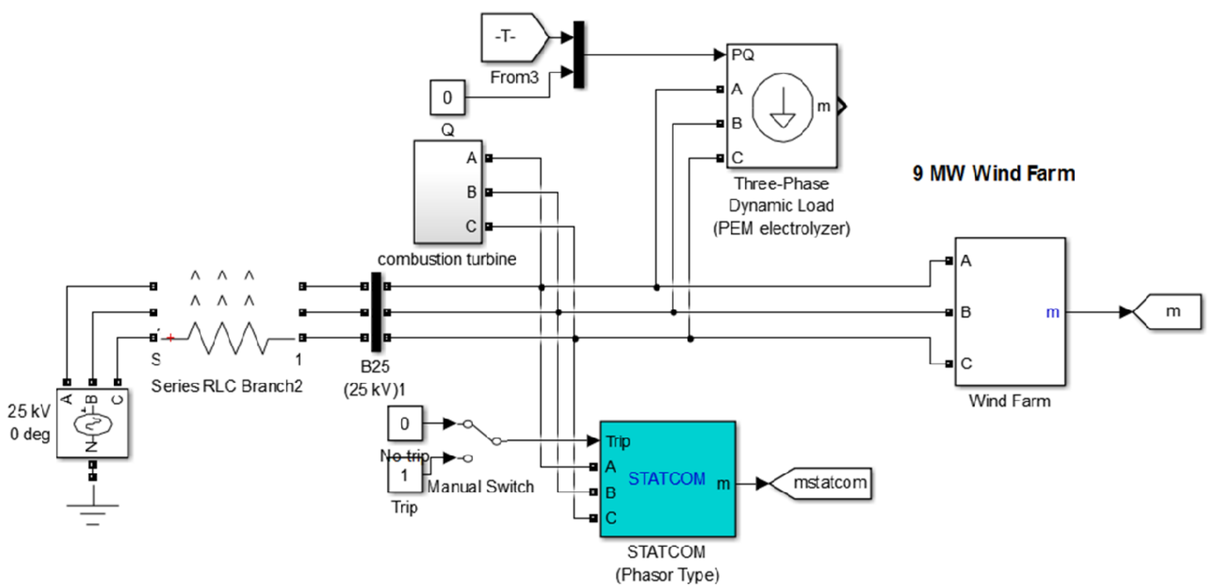

Figure A14. The simulation implementation of the electrical model of the system

The power coordination is shown in figure A13. The power production from wind farm is measured and sent into power coordination. The 3p oscillation component is extracted by BP filter and sent into PEM electrolyzer as power reference. The rest power is sent into logic control with TSO order. The power consumed by PEM electrolyzer is subtracted from the power production, and then the insufficient power compensated by the combustion turbine is added to the power production. The voltage calculation uses the power signal here. The implementation of voltage calculation is by using "fcn" in Simulink.

The simulation of power system is shown in figure A14. The wind farm model, PEM electrolyzer model, the combustion turbine model and the STATCOM model are connected to 25 KV bus. The bus is connected to 25 KV infinite grid through a small resistor. The existence of the small resistor is to prevent simulation error.

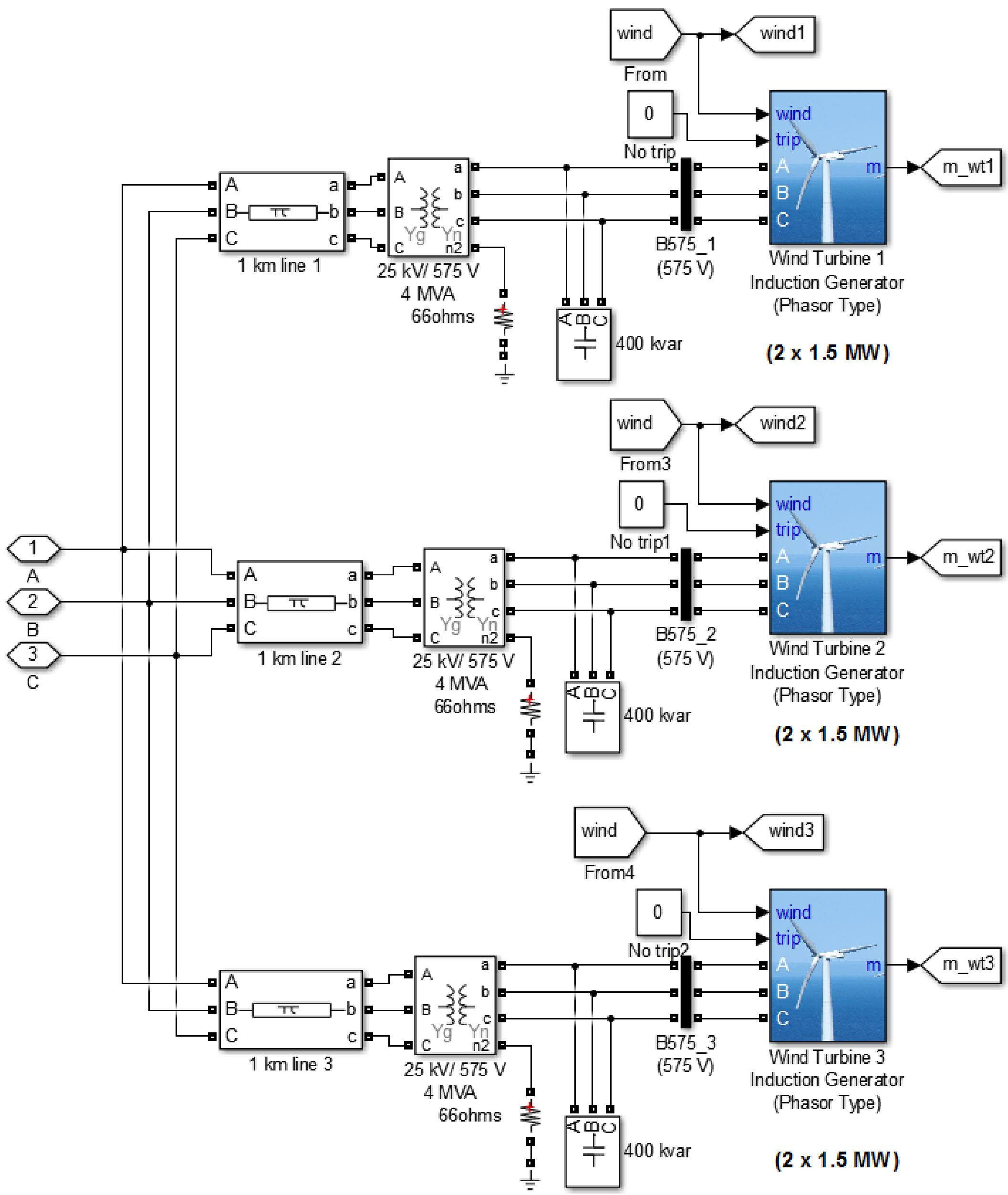

Figure A15. The simulation implementation of the wind farm

Figure 15 shows the model of the wind farm. The wind farm model is made up three branches. Each branch is made up by one wind turbine block, a 575 V bus, a shunt capacitor, a transformer, and a cable. These three branches are connected to 25 KV bus. The wind speed signal is sent into wind turbine block, the responds of the wind turbine models are measured.

Appendix 2 Power-current relation of PEM electrolyzer

The data below is the look-up table which decides the current for PEM electrolyzer corresponding to the power that needs to be consumed. The look-up table applied in the simulation has 2690 points to smooth the curve, while the data that is presented here is only 336 points due to the limitation of the length of the report. The figure of power-current curve is shown as figure A16. The figure A16 is plotted with 2690 points.

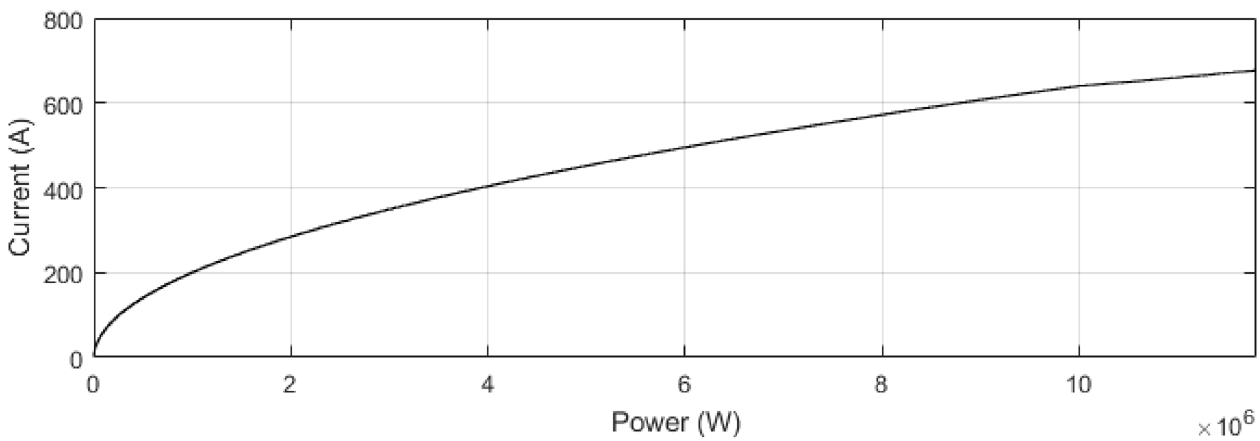

Figure A16 The power-current curve of PEM electrolyzer

The voltage of the PEM electrolyzer is decided by lot of factors, which is shown in chapter 4.1. The instantaneous power of PEM electrolyzer is a product of the current and voltage. The purpose of the PEM electrolyzer is to consume the exact power as required, thus, the current for PEM electrolyzer must be decided in a way that the product of the current and corresponding voltage is exactly the power that need to be consumed. To simplify the simulation, the current of for the PEM electrolyzer is decided by a look-up table. The table gives the current value according to the power value. To get the look-up table, the PEM electrolyzer is operated under different current, and the corresponding power is calculated and recorded. The look-up table is formed by using the data recorded as described above. Once a power value is given, the corresponding current is given so that the product of the current, under which current, the production of the current and the voltage is exactly the power that needs to be consumed.

Power (W)	Current(A)	Power (W)	Current(A)	Power (W)	Current(A)	Power (W)	Current(A)
181.63817	1	239774.17	96.25	815098.123	180.25	1731497.8	264.25
1305.9633	4.75	249508.26	98.25	832953.553	182.25	1757473.7	266.25
3260.6854	8.75	259435.73	100.25	851002.334	184.25	1783643	268.25
5991.9373	12.75	269556.59	102.25	869244.466	186.25	1810005.6	270.25
9498.6472	16.75	279870.83	104.25	887679.949	188.25	1836561.5	272.25
13780.278	20.75	290378.45	106.25	906308.783	190.25	1863310.7	274.25
18162.123	24.25	301079.45	108.25	925130.967	192.25	1890253.3	276.25
20932.242	26.25	311973.82	110.25	944146.5	194.25	1917389.3	278.25
23895.939	28.25	323061.58	112.25	963355.383	196.25	1944718.5	280.25
27053.194	30.25	334342.71	114.25	982757.614	198.25	1972241.2	282.25
30403.992	32.25	345817.21	116.25	1002353.19	200.25	1999957.1	284.25
33948.318	34.25	357485.09	118.25	1022142.12	202.25	2027866.4	286.25
37686.161	36.25	369346.34	120.25	1042124.4	204.25	2055969	288.25
41617.508	38.25	381400.96	122.25	1062300.02	206.25	2084265	290.25
45742.35	40.25	393648.95	124.25	1082668.99	208.25	2112754.3	292.25
50060.678	42.25	406090.31	126.25	1103231.31	210.25	2141436.9	294.25
54572.484	44.25	418725.04	128.25	1123986.97	212.25	2170312.9	296.25
59277.76	46.25	431553.14	130.25	1144935.98	214.25	2199382.2	298.25
64176.5	48.25	444574.61	132.25	1166078.33	216.25	2228644.8	300.25
69268.697	50.25	457789.44	134.25	1187414.04	218.25	2258100.8	302.25
74554.346	52.25	471197.64	136.25	1208943.08	220.25	2287750.1	304.25
80033.441	54.25	484799.2	138.25	1230665.47	222.25	2317592.7	306.25
85705.978	56.25	498594.13	140.25	1252581.21	224.25	2347628.7	308.25
91571.953	58.25	512582.42	142.25	1274690.28	226.25	2377858	310.25
97631.36	60.25	526764.07	144.25	1296992.71	228.25	2408280.7	312.25
103884.2	62.25	541139.09	146.25	1319488.47	230.25	2438896.7	314.25
110330.46	64.25	555707.46	148.25	1342177.58	232.25	2469706	316.25
116970.14	66.25	570469.2	150.25	1365060.04	234.25	2500708.6	318.25
123803.24	68.25	585424.3	152.25	1388135.83	236.25	2531904.6	320.25
130829.76	70.25	600572.75	154.25	1411404.97	238.25	2563294	322.25
138049.69	72.25	615914.57	156.25	1434867.45	240.25	2594876.6	324.25
145463.03	74.25	631449.74	158.25	1458523.27	242.25	2626652.6	326.25
153069.78	76.25	647178.27	160.25	1482372.44	244.25	2658621.9	328.25
160869.93	78.25	663100.16	162.25	1506414.94	246.25	2690784.6	330.25
168863.48	80.25	679215.4	164.25	1530650.79	248.25	2723140.6	332.25
177050.44	82.25	695524	166.25	1555079.98	250.25	2755689.9	334.25
185430.79	84.25	712025.96	168.25	1579702.51	252.25	2788432.5	336.25
194004.54	86.25	728721.27	170.25	1604518.37	254.25	2821368.5	338.25
202771.68	88.25	745609.93	172.25	1629527.58	256.25	2854497.8	340.25
211732.22	90.25	762691.95	174.25	1654730.13	258.25	2887820.5	342.25
220886.15	92.25	779967.32	176.25	1680126.02	260.25	2921336.5	344.25
230233.46	94.25	797436.05	178.25	1705715.25	262.25	2955045.8	346.25

Power (W)	Current(A)	Power (W)	Current(A)	Power (W)	Current(A)	Power (W)	Current(A)
2988948.4	348.25	4587436.3	432.25	6526951.9	516.25	8807487	600.25
3023044.4	350.25	4629652.1	434.25	6577287.3	518.25	8865942	602.25
3057333.7	352.25	4672061.2	436.25	6627816	520.25	8924590	604.25
3091816.3	354.25	4714663.6	438.25	6678538	522.25	8983432	606.25
3126492.3	356.25	4757459.4	440.25	6729453.4	524.25	9042466	608.25
3161361.6	358.25	4800448.5	442.25	6780562	526.25	9101695	610.25
3196424.3	360.25	4843630.9	444.25	6831864	528.25	9161116	612.25
3231680.2	362.25	4887006.6	446.25	6883359.4	530.25	9220731	614.25
3267129.5	364.25	4930575.7	448.25	6935048	532.25	9280539	616.25
3302772.1	366.25	4974338.1	450.25	6986930	534.25	9340540	618.25
3338608.1	368.25	5018293.8	452.25	7039005.2	536.25	9400735	620.25
3374637.4	370.25	5062442.9	454.25	7091273.9	538.25	9461123	622.25
3410860	372.25	5106785.2	456.25	7143735.8	540.25	9521704	624.25
3447275.9	374.25	5151320.9	458.25	7196391	542.25	9582479	626.25
3483885.2	376.25	5196049.9	460.25	7249239.6	544.25	9643447	628.25
3520687.8	378.25	5240972.3	462.25	7302281.5	546.25	9704608	630.25
3557683.8	380.25	5286087.9	464.25	7355516.7	548.25	9765962	632.25
3594873	382.25	5331396.9	466.25	7408945.2	550.25	9827510	634.25
3632255.6	384.25	5376899.3	468.25	7462567.1	552.25	9889252	636.25
3669831.5	386.25	5422594.9	470.25	7516382.2	554.25	9951186	638.25
3707600.8	388.25	5468483.9	472.25	7570390.7	556.25	10013314	640.25
3745563.4	390.25	5514566.1	474.25	7624592.5	558.25	10122503	642.25
3783719.3	392.25	5560841.8	476.25	7678987.7	560.25	10216565	644.25
3822068.5	394.25	5607310.7	478.25	7733576.1	562.25	10326853	646.25
3860611.1	396.25	5653972.9	480.25	7788357.9	564.25	10437733	648.25
3899347	398.25	5700828.5	482.25	7843333	566.25	10565179	650.25
3938276.2	400.25	5747877.4	484.25	7898501.4	568.25	10661270	652.25
3977398.7	402.25	5795119.7	486.25	7953863.1	570.25	10773927	654.75
4016714.6	404.25	5842555.2	488.25	8009418.1	572.25	10887175	657.25
4056223.8	406.25	5890184.1	490.25	8065166.5	574.25	11001016	659.25
4095926.4	408.25	5938006.3	492.25	8121108.2	576.25	11099065	662.25
4135822.2	410.25	5986021.8	494.25	8177243.2	578.25	11230473	664.25
4175911.4	412.25	6034230.7	496.25	8233571.5	580.25	11329537	666.25
4216193.9	414.25	6082632.8	498.25	8290093.1	582.25	11462298	669.75
4256669.8	416.25	6131228.3	500.25	8346808.1	584.25	11579099	672.25
4297339	418.25	6180017.1	502.25	8403716.4	586.25	11713310	674.25
4338201.5	420.25	6228999.3	504.25	8460818	588.25	11831381	677.25
4379257.3	422.25	6278174.7	506.25	8518112.9	590.25	11950041	680.25
4420506.4	424.25	6327543.5	508.25	8575601.1	592.25	11958490	682.75
4461948.9	426.25	6377105.6	510.25	8633282.7	594.25	11958536	686.25
4503584.7	428.25	6426861	512.25	8691157.5	596.25	11958544	690.25
4545413.8	430.25	6476809.8	514.25	8749225.7	598.25	11958614	694.25

Appendix 3 Power-current relation of PEM electrolyzer

The figure A16 shows the pure fluctuation of the wind speed at hub height. The fluctuation is added to average wind speed to get a fluctuating wind speed around the average speed. The detailed fluctuation data will not be presented in concern of the report economy.

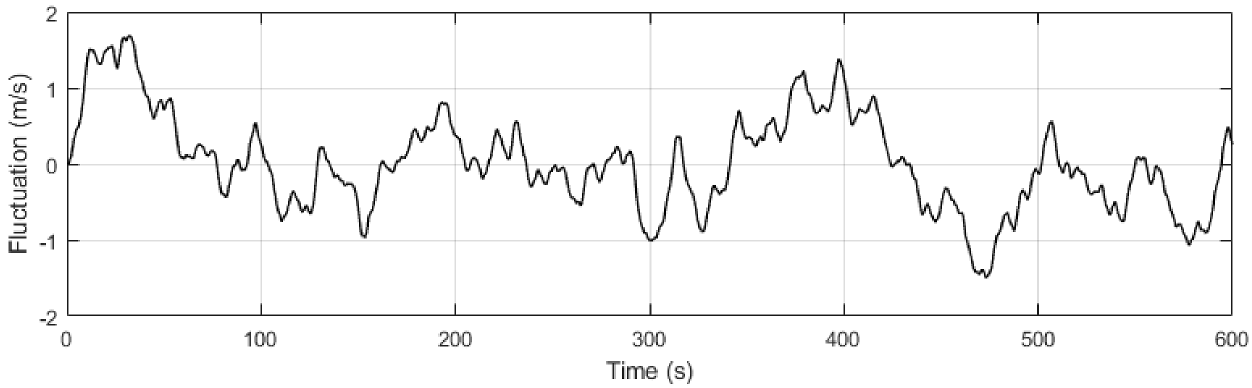

Figure A16 The power-current curve of PEM electrolyzer