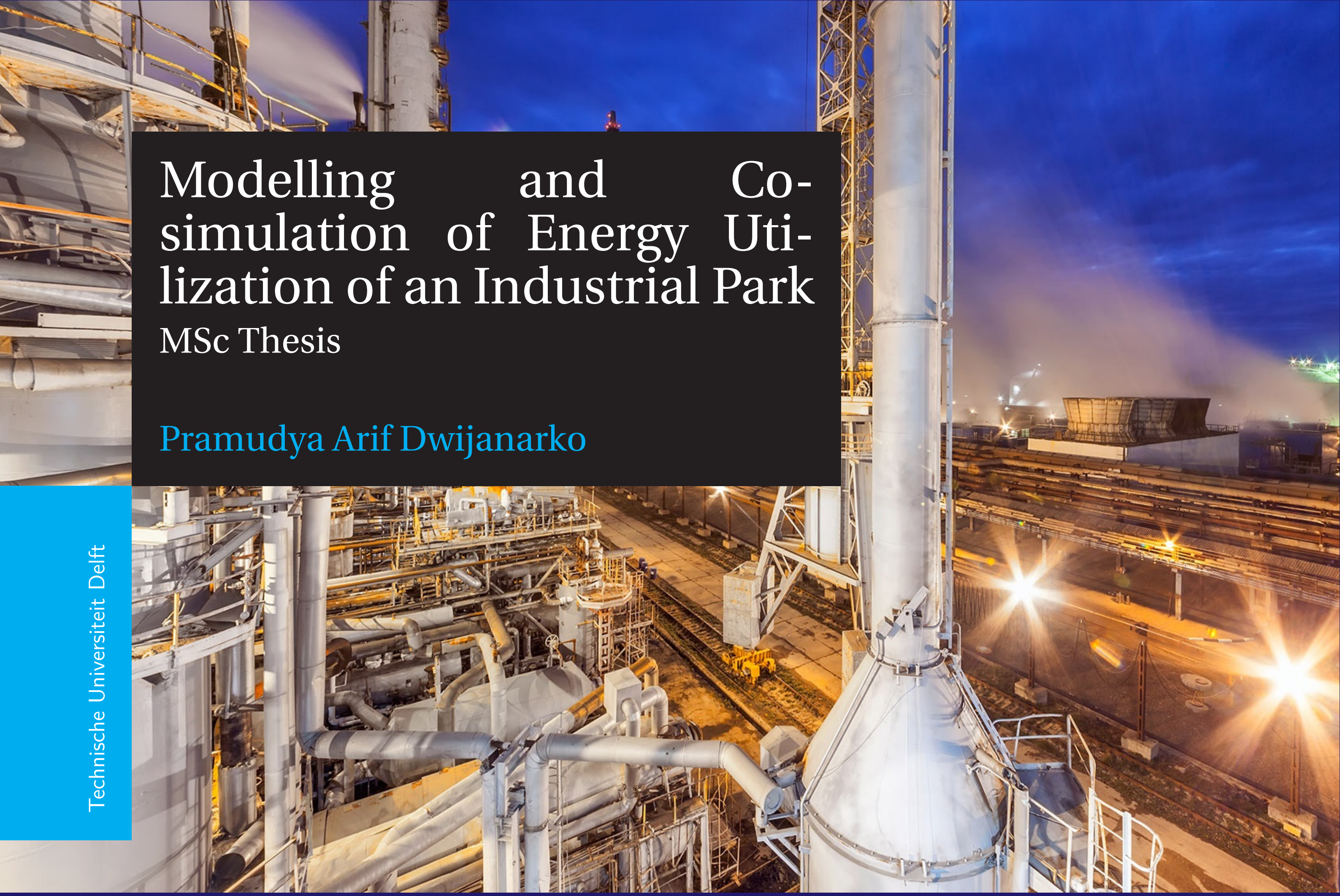

Modelling and Co-simulation of Energy Utilization of an Industrial Park

MSc Thesis

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Technische Universiteit Delft

Delft University of Technology

Challenge the future

Modelling and Co-simulation of Energy Utilization of an Industrial Park

MSc Thesis

by

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Abstract

The concept of microgrid has gained a significant interest of many scholars and engineers worldwide. Microgrid offers substantial benefit such as high reliability, adaptive to disturbance, improved load and generation control and extensive utilization of renewable energy sources (RES). However, the utilization of renewable energy resources leads to a problem due to its intermittency of the generated power. The conventional solution to measure the intermittency problem, such as network expansion and electrical energy storage, require huge cost and complicated planning. Therefore, the utilization of thermostatically controlled become a more viable solution.

Several forms of energies are involved in the industrial microgrid. The utilization of the various form of energies requires a platform that accommodates the co-simulation and data exchange of various models. The aim of this project is to observe the impact of a thermostatically controllable load to the energy saving and to offer a methodology that accommodates the co-simulation and data exchange of various components, such as microgrid network, boilers, and optimization algorithm.

Several steps are required in order to achieve the project's goal. Firstly, an extensive literature study is conducted to determine the characteristic of the network that has to be modelled. Optimal power flow is used as the optimization algorithm in order to achieve the optimum performance of the system.

The second step is performing a series of components modelling. The IEEE14 bus system is selected as a foundation of the network model. A separate boiler model is also developed since in the electrical domain, and it is modelled as a constant power load. A more detailed thermodynamic model is modeled for greater insights. Functional Mock-up Interface platform is used as a standard to accommodates the co-simulation between network model, boiler model, and optimization algorithm. The master code is developed to manage the simulation and data exchange of each component.

Finally, a simulation of a different seasonal cycle is implemented to observe the performance of the system. Winter and summer season is chosen as the case scenario due to its different profile on the wind turbines power.

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Introduction

Electricity has become one of the most fundamental human needs. People rely on electricity to run their lives. From the large-scale electricity network to a small gadget that people carry everywhere, it runs by using electricity. Therefore, a high level of power system stability and reliability is mandatory to be monitored and maintained in order to satisfy the global demand.

1.1. Background

The global demand for electricity has multiplied in the last decades. The total of global annual electricity generation increase about 2.8% in 2017[1]. Furthermore, the rapid penetration of renewable energy resources, namely wind power and solar, can be observed from the increasing portion of electricity generation. Compared to the previous decades, the operation of today power system becomes more challenging. It has to be reliable not only in technical terms, but also has to comply with the policy, economic, and social terms. The operational planning, load management, cost minimization already put a heavy burden on the old electricity grid. The presence of renewable energy sources also gives a significant impact on the power flow characteristic of the electricity grid. The intermittent characteristic of renewable energy sources resulting in a challenging behavior of dynamic power system.

In general, the growth of renewable energy resources (RES) shows a positive trend. Many countries, in order to comply with the Paris agreement, make a reasonable effort in creating a better environment to allow the growth of RES. China and India are currently leading the race in the development of renewable energy power plant which mainly consists of solar and wind. Other countries such as the US, Germany, and the Netherlands slowly follow with a positive trend. In 2016, RES significantly growth by almost as twice as the fossil fuel growth. Solar PV is accounted for the highest portion of growth and outperform other renewable resources with 46% followed by 33% from wind.

The characteristic of electricity generated by RES is unlike the conventional power system. They cannot be directly connected to the existing power grid due to different power flow characteristic. For example, PV technologies are based on power electronics. It does not have actual frequency value to support the actual frequency in the existing grid. Most of PV field is decentralized in a small-scale generation. Therefore, these systems are also termed as Distributed Generators (DG). Term DG is not only referred to PV generation but also other types of energy generation, such as wind, and Combined Heat and Power (CHP) system.

The future electricity networks have to contend the rapid and significant change of technology. The grid technologies have to maintain network stability and system security while maintaining the production cost as low as possible. The term Smart Grid is associated to the transformation of the conventional electricity grid which capable to integrate the actions of all users, producers, and customers, to deliver efficient, secure, and more economically feasible electricity. With the high penetration of RES and the introduction of the smart grid, a new concept of a microgrid is proposed. It employed several kinds of microgenerators such as PV, microturbine, CHP, and storage technologies and integrated together form a kW scale of power. It is also equipped with an intelligent control that allows interconnection with upstream grid or isolates the system in case of disturbance. Not only capable of complying with the technical problem, but the microgrid system also has to deliver the electricity at the minimum cost. Therefore, a suitable algorithm control is needed, not only to deliver a secure and stable power flow, while minimizing the production cost.

1.2. PROBLEM DEFINITION

The concept of microgrid has gained major interest of many scholars worldwide. Microgrids are composed of a distribution network that contained with distributed energy resources (DERs) and electrical loads which can be operated either in connected to the grid or stand-alone. Microgrids have several substantial benefits, such as high reliability, adaptive to disturbance, improved load and generation control and high utilization of renewable energy sources (RES). Therefore, microgrids have increased attention of the users[2].

Microgrid that is designed for the industrial area is termed as industrial microgrids (IMGs). It relies upon renewable energy sources, such as wind and PV to satisfy their energy demand. However, the renewable energy resources have a predominant problem of the intermittency of the generated power. PV fluctuates during the day-night period. During the day, PV generated an adequate amount of energy, while during the night when there is no presence of the sun, the energy generated by PV is zero. In addition, the annual seasonal cycle profoundly affects the energy produced by not only wind turbine but also PV power plant.

It is not enough to only rely on energy capacity to satisfy the energy demand. Therefore, ancillary services are needed in order to control the demand and supply to stay in balance through the time [3]. However, studies show that the larger the penetration of renewable energy, it will be followed by a considerable increase of ancillary services required [4]. For example, to achieve a target of renewable energy penetration to 33% in California, a four folds increase in energy reserve is required. An increase in load is also required to optimize energy utilization [5]. If a fossil-based generator supplies it, it abates the benefit of renewable energy as a carbon-less energy generator. Furthermore, it becomes less efficient and become more expensive.

Therefore, a demand-side optimization becomes a viable alternative in providing less-emission energy integration. These services include energy storage, thermostatically controlled load, electric vehicles, etc. Energy storage technology is crucial to tackle the fluctuation problem of energy production. When the energy produced is higher than the demand, the surplus energy is used to charge the battery. On the other hand, while the load requires more energy than the powerplant produced, the energy can be utilized from the energy storage. The energy storage systems also contribute to the efficiency of energy utilization.

However, electrical energy storage require high additional investment cost to match the difference between charge and discharge capacity of the storage. Additionally, the average time required to reach the Return of Investment of a large scale electrical energy storage may up to 15 years while the battery lifetime is only 15-20 years [6]. Therefore, utilizing the end-user flexibility is more viable compared to network reinforcements and additional electrical energy storage. These facts show the importance of thermostatically controlled loads as one of ancillary service. The concept of the multi-energy system also attracting since it enhances energy utilization efficiency. The presence multi energy system in an IMG will bring more challenge to the future power system since it has dynamic variable load and require more complex optimization algorithm[7].

Compared to residential microgrid, industrial microgrid has a more complex system. In a terms electricity consumption, a unit of industry consumes megawatt scale of electricity. Meanwhile, the daily average households electricity consumption is only around 4kWh-5kWh [8]. Furthermore, many electrical equipment such as, sensors, controllers and communication networks already exists in the industrial area. Therefore, it does not require dramatic hardware change and extra investments since most of the equipment is already there. Since the demand of a single unit household is relatively lower, to accommodate the improvement is much complicated and time-consuming in the residential area at the similar energy consumption level [8].

Most of energy consumption in industrial sector in the world is in form of electricity, around 500TWh in 2015. The electricity is mainly used for Machine drive purpose, around 90% of electricity demand and followed by small portion of facility lighting and other facility support. Meanwhile, the thermal energy consumption is accounted for around 45% of total energy consumption in industrial area. In Europe, 54% of electricity consumption is used for heating, and cooling purposes with more than half of it are used for space heating [9]. The thermal energy are mainly used in process heating and space heating. The portion corresponds to the sector of the industry. In example, 80% of thermal energy are used in process heating in Iron and Steel Industry, while in chemical industry, heating process only accounted for 40%. In machinery industry, space heating consumes 70% of thermal energy demand. However, for more than 50% of the thermal energy is produced by fossil-fueled boiler and mainly are powered by gas [8].

As stated above, an IMG consists of a complex system with various energy resources and characteristic. Optimization algorithm is needed to assure the balance between demand and energy generation. Different model from different platform will be involved in this project. Therefore, the challenge to simulate a multi-energy system will be a key contribution in this project.

1.3. RELATED WORK

This project will be mainly focused on developing the model of Industrial Park's energy utilization. The network model will be mainly based on the existing libraries inside the OpenModelica. Several studies had been conducted in order to observe the performance of thermostatic loads as load mitigation. The earliest research related to the promising utilization of thermostatic load can be found in [10]. It shows the performance of a thermostatics load when combined with a high-frequency signal, such as a wind turbine. The study shows that the thermostatically four hour time step controlled load can follow the one minute energy variation of wind turbine. [7] introduce the utilization of thermostatically controlled loads in the microgrids as the answer of energy fluctuation from PV. Both studies agree that by utilizing the thermostatic loads will significantly reduce the investment cost compared to another option, such as, increasing the electrical energy storage capacity.

Several studies had been conducted to determine the best method to generate an excellent optimization algorithm adapted to the optimization problem characteristics of different grid structure. Morais et. al.[11] adopted mixed integer linear programming (MILP) to generate optimal scheduling for the microgrid. They create a model of a microgrid consists of Solar PV, solar thermal, wind turbine, to satisfy the energy demand and utilization of fuel cell and battery as the energy storage. A control block acted as the primary control to determine the power flow. It measures and controls the power flow of the system. In addition, to maintain the power balance, the control center also has a task to achieve the goal, which is reducing the cost to its minimum. The modeling and simulation were done in CPLEX in GAMS platform. The simulation uses 2 scenarios to validate the result. The scenarios are based on energy consumption level, high consumption level energy scenario, and low energy consumption. In general, the formulated MILP problem is able to satisfy the objective function. The energy balance between demand and production is achieved at its lowest cost.

Wan et. al.[12], and Sortomme et. al.[13], applied optimal power flow algorithm to microgrids to achieve the minimum cost production neglecting the heat plant and energy exchange to the upstream network. Wan et. al.[12] adopted the event-triggered systems which sample the sensor in a sporadic approach. The system allows the communication for each sensor, which will deliver information to its neighbor if there are some unexpected measurement. This event will trigger the system to recalculate the Optimal Power Flow. Therefore, the event-triggering method is claimed to reduce the communication bandwidth effectively.

There are several studies that are already conducted to observe different method of co-simulation platform in power system application. [14] investigate the integration Matlab/Simulink and NS-3 communication network simulator. The study used Matlab/Simulink to model a physical smart grid, while the NS-3 is used to model the communication network. An C++ based algorithm is developed to serve as the agent to manage the cross-platform data exchange. [15] introduce a platform called EPOCHS which integrates the powes system modelling tools and the communication network. EPOCHS utilizes three different simulation platform: PSLF, PSCAD/EMTDC, and NS-2. Each platform has different purposes. PSLF is used to model the power system and PSCAD/EMTDC is used for electromagnetic transient simulation. Meanwhile, NS-2 is used as the communication network simulator. NS-2 is the previous generation of NS-3 that are used in [14]. Both studies demonstrate the possibility to perform a co-simulation of physical microgrid modeling and communication network.

[16] introduce MESCOS, Multi-Energy Co-Simulator for City District Energy Systems, a simulation platform that accommodates a comprehensive analysis of a district level energy system. In a district level energy system, not only electrical but also thermal and gas supply system are involved. The simulation platform consists of three layers that represent the function of an actual energy system. The first layer is demand management system serves as a control layer that manage the operation of the system. The second layer is entity layer that contains sub-energy system system such as, building, CHP, boiler, ets. The third layer is the network layer that contains the interconnection of each components in entity layer.

[17] conduct a comprehensive study to compare several co-simulation platform in power system application. In general, they classify the co-simulation methodology in power system application into three main groups. The first methodology is time step sychronization. [14] and [15] utilize the time step synchronization method. In this methodology, all components such as the power flow optimization, microgrid model, etc run individually and independent to each other and at certain time step that are already determined, the software pause the simulation and start the data exchange. Therefore, a time delay is required during the data exchange period and it becomes the disadvantageous of this methodology.

The second methodology is event driven synchronization. [18] introduce a platfom named GECO. Firstly, they made a list of predetermined event that would occur during simulation and the simulation will rune according to that predetermined list of event. This methodology employ the benefit of event-based characteristic of microgrid components that run in the same time line.

The third methodology is master slave method where a software environment serve as the master that control others software environment as the slave. [19] introduce a platform named Functional Mock-up Interface that adopts the master-slave methodology. The master manage all the event that occur during the simulation and controls the data-exchange of all slaves.

1.4. OBJECTIVE AND RESEARCH QUESTION

The goal of this project is to design a model of an industrial microgrid that enhance the utilization of demand response framework in terms of thermal energy. This project is mainly focused on designing the industrial microgrid, and the boiler model as a representation of thermostatic loads. A co-simulation based approach will be taken to simulate the energy network with thermal and electrical components. Most of the components of the grid and boiler models will be used from existing libraries in the OpenModelica software. The optimization algorithm will be implemented in Python while the grid model will be developed in OpenModelica. Managing the interface and data exchange between Python and OpenModelica is also critical in this project.

The objectives of the project are listed below.

- Develop a simple model of an industrial microgrid that consist of various power generators such as wind turbine and a gas-powered generator.
- Develop a boiler model that represent the thermodynamic properties of an actual boiler.
- Develop a methodology that performs the co-simulation of the multi-energy system.
- Perform a simulation of different case scenario to observe the performance of the network.

With this project, we aim to answer the following two research questions.

- What methodology that can be used to simulate multiple components from different energy domains? Can the power flow models and continuous time models be effectively combined?
- What impact do seasonal variations in wind speed have on network? What are the impacts of boiler as a controllable loads?

1.5. Research Plan

Several tasks are required to answer the above formulated research questions. The first task that has to be done in this project is to develop a representative design of the microgrid. Our microgrid consists of a gas-powered plant, wind power plant, and a boiler. The models are mainly designed based on OpeniPSL library inside OpenModelica software. The optimization algorithm will be implemented on the python language.

The step-by-step method process is explained in detail.

1. Perform a literature study to determine the appropriate optimization method for industrial microgrids.
   - Identifying constraints specific to industrial usage
   - Defining suitable objective function for energy utilization.
2. Develop the model of the industrial microgrids in OpenModelica.
   - The microgrids model will consist of a renewable energy source such as wind turbines, electrical loads, and electric boilers.
3. Develop the boiler model
   - The boiler inside the network model is represented as an electric load. In the electrical domain, it is modelled as a constant power load. A more detailed thermodynamic model is modelled for greater insights.
4. Integrate the network model, boiler model, and optimization algorithm.
   - Co-simulation master is created to coordinate data exchange between thermodynamic boiler model, electrical model. and optimization process.
5. Analysis of the simulation result.
   - Two different case scenario is adopted to the system to validate the proposed co-simulation platform

1.6. Thesis Outline

This report will be divided into three main parts which are Literature Study, Modelling, and research Methodology and Simulation. Those three parts will be divided into six different chapters.

- **Chapter 2: Literature Study**

  Chapter 2 introduce the concept of microgrid and mentions the cost and benefit of it. Several types of microgrid will also be described with each own benefits. The concept of Multi-Energy Systems will also be briefly described.

- **Chapter 3: Modelling**

  This chapter describes the microgrid that is used in the model. The boiler model is also described here. Both models are modeled using OpenModelica while the optimization algorithm is built in python.

- **Chapter 4: Methodology**

  This chapter contains how to integrate the multi-energi domain system of the model. The Microgrid model is in the electrical domain while the boilers are in the thermodynamic domain. The interaction between optimization model and the microgrid model is also explained in this chapter.

- **Chapter 5: Simulation**

  Once the model is developed, a simulation of different case scenarios will be adopted in order to observe how the model react with different input.

- **Chapter 6: Conclusion**

  Lastly, a conclusion that is drawn from previous steps is explained in the last chapter.

2

LITERATURE STUDY

For the last half of the century, the electric industry faced challenging issues caused by the environmental, political, and economic situation. These problems made the electric industry to change and leave the status quo that already stabilized in decades. The fossil-based power plant is thinking hard to tackle the oil price issue. The fossil is utilized by the majority of electric power plant across the world. Moreover, the facility that was already aging cause an expensive unexpected problem. An old facility has many issues in handling efficiency and reliability resulting in higher profit losses. On the other hand, the electricity demand keeps increasing due to deeper penetration of electricity network in the rural area and industrial growth.

Facing those challenges, it pushes the electric industry to look beyond their current technology. Scholars proposed a smart and controllable grid termed as intelligent or smart grid as a solution. The difference between the smart grid and the conventional grid is the manner of the generation side towards demand variation. Instead of increasing the number of generators, smart grid uses a different approach to satisfy the energy demand, such as minimize energy losses, manage energy demand, and energy conservation. That is a radical change in the paradigm of energy production. However, the system transition will not be as smooth as a falling off a log. It cannot be done overnight. It needs years of process and involving every stakeholder [20].

This chapter presents the explanation of the concept of the microgrid. A literature study is conducted prior to start the project. The concept of microgrid will be introduced in Section 2.1. Section 2.2 will explain further about industrial microgrid in details and what is the difference between other types of a microgrid. A concept of Multi-Energy System is described in Section 2.3, and lastly in Section 2.4 describes the importance of boiler utilization in Industrial Microgrid.

2.1. INTRODUCTION TO MICROGRID

The concept of gradual system transition from the conventional grid to the smart grid requires a well-prepared strategy and implementation. An approach was proposed to start the transition with a niche strategy combining the nearby fundamental component of the electricity grid, power plants and loads. However, it does not guarantee that the generated power will be able to satisfy the local demand. Therefore, the energy shortage will be compensated by the upstream network. This system is considered as a small scale of an electricity grid. Therefore it is called microgrid. In general, a microgrid is a small scale of intelligent, smart grid equipped with similar capabilities, such as energy demand-side management, and smart control and monitoring of the systems.

There are various definitions of microgrids in many scholarly articles. Moreover, different communities also have a different definition of a microgrid. It caused by the different background of the communities involved in microgrid research. An environmental activist concerned that microgrid has to maximize the utilization of renewable energy. Meanwhile, for those who consider the energy certainty, demand access to the larger electricity network. However, there is a fundamental definition that can be identified: microgrid is an electricity network consists of energy production and demand that locally interconnected that can be operated connected to the upstream network or isolated in autonomous operation.

Therefore, there is three key requirement that a system can be considered as a microgrid[21].

1. Microgrid is a concept of integrating each aspect of the electricity network, such as the supply side, demand side, and energy storage in a small distribution network.
   - The concept of a microgrid is physically integrating all the generators supplying the local demand in a designated area. Therefore, an aggregator model such as virtual power plants, cannot be considered as a microgrid.
   - The requirement is locally integrated. The voltage level can be various. However, it mainly connected in LV scale since it is connected to the local load. An MV scale can be considered if only it is used as an interconnection purpose.
2. A microgrid has to be able to operate either under Grid-tied connection or isolated in islanded operation.
   - For most of the time, future microgrids will be in the majority performed while connected to the upstream network. Therefore it is considered as the normal operation. An islanded operation only occurred during an emergency situation. However, in case of a grid which is built on an isolated island, it also can be considered as a microgrid.
   - If a microgrid aimed to accomplish an everlasting independent operation, it has to be able to compensate all the energy demand equipped with a sufficient size of energy storage while all the generators have to meet the capacity ratings to supply the energy continuously. Alternatively, it may depend on the flexibility of the demand
3. A microgrid is featured with management and coordination of its assets in which become the main difference between the microgrid and the passive distribution network.
   - the most excellent benefit compared to the conventional generation network of a microgrid is the term “smart” in which is able to fully manage the conflict of interest between interested party and achieving the optimum benefits of the system. Therefore, the term microgrid and smart microgrid are interchangeable.
   - A microgrid operates way more than a just generator network. It is not only just a provide a service or manage the load or reduce the $CO2$ emission. A microgrid handle more complicated function not only in the technical aspect but also economic and environmental aspects.

2.1.1. ARCHITECTURE OF A MICROGRID

A microgrid system serves a various range of generation structures. It can either be centralized, distributed or combination of both. It also encourages users to have active participation in managing energy consumption and increase energy efficiency. A smart grid also has a self-healing mechanism, in which allow the smart grid to predict the imminent failure and take a measure by evading it or mitigate and isolate the problem. Furthermore, a microgrid also consider an economic aspect by utilizing an optimization method to achieve the minimum operation cost.

However, knowing the state of the art of current technology and compared to what is aimed in the future, there is one key issue that is needed to be addressed. That issue is the arising demand of intelligent energy management system that is flexible and can be scaled in various level. It is also required to have capabilities to accommodates not only the growth of the technical aspects, such as the power system, IT, and communication system but also the growth of the system itself. Moreover, since 90% of the grid failure, i.e., power outage, is happened because of the root problem from the distribution network, it will be a high challenge to implement a distribution level microgrid[21].

Today’s cost of the fossil fuels fluctuates rapidly. Meanwhile, the demand for electricity keeps increasing. However, the utility company is barely increasing their generation capacity. These facts result in fixating the development of energy conservation and modernizing the current grid technology that focused on demand-side management. Therefore, the next measure is modernizing the current grid structure and introduce robust control strategies over the grid network. There has to be able to achieve the grid development purpose: conserve the energy utilization and optimize the distributed generation. Therefore, not only the technical problems are resolved, but the minimum cost is also can be achieved.

Moreover, the determination to follow the Paris Agreement to reduce the carbon emission, cause the presence of Renewable energy resources is critical. Moreover, the swift technological evolution of distributed energy resources (DERs) interests the utility industries to adopt the system. Therefore, a microgrid can be defined as a group of DERs units supplying nearby loads that can be either operated independently or connected to the upstream network.

Figure 2.1 illustrates the basic topology of a microgrid. At least, a system can be called a Microgrid if it complies with three factors, the cogeneration power plant equipped with storage capabilities, a series of a load profile, and an intelligence system that monitor and control the system to assure the reliability and capability of the system. Due to its complexity and demand for high-level reliability, it is required that the control system has to able to manage the requirement within the network. The control system controls both the demand side and the generator side. Both are connected in two ways direction, allowing the control system to acquire the data and send the command to the essential components.

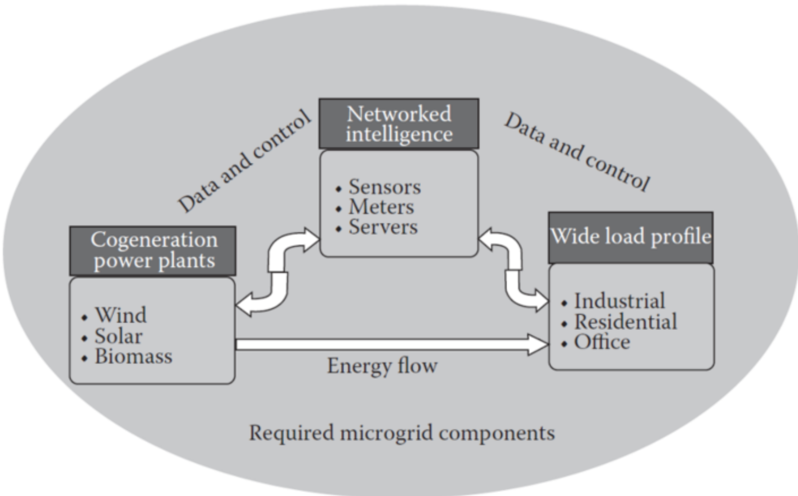

Figure 2.1: Basic Microgrid's building block [20]

However, the location of the control, either it is distributed or centralized, highly depends on the size of the microgrid itself. The constant output, data size, and bandwidth and frequency of data exchange determine the complexity of the system and the architecture of the system. Is it more efficient if it is configured as distributed control or does it perform better under centralized network.

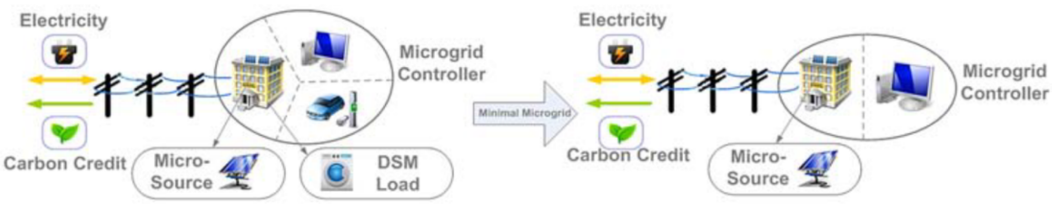

Figure 2.2: Microgrid in a scale of LV for building operation[21]

An example of microgrid can be seen in figure 2.2 depicts a microgrid in an LV scale supplying the energy demand of an. As can be seen in the picture, it utilizes PV to satisfy the energy demand of the building. It is also featured with the controller to process all the economics and technical problem. In addition, it is connected to the upstream network to allow energy exchange with the electricity network. However, the microgrid can be scaled up into several MW, depends on the demand connected to the grid.

2.1.2. TYPES OF MICROGRID

As stated previously, the structure of a microgrid is quite flexible depends on the size, the capacity, and even the geographical location. A microgrid can be categorized based on their characteristics and applications. 2.3 illustrates the architecture of the three different types of a microgrid. As can be seen in the picture, there are three types of microgrid namely, utility microgrid, commercial and industrial microgrid, and remote microgrid. Each grid has different architecture depends on the size and the purpose of the service [22].

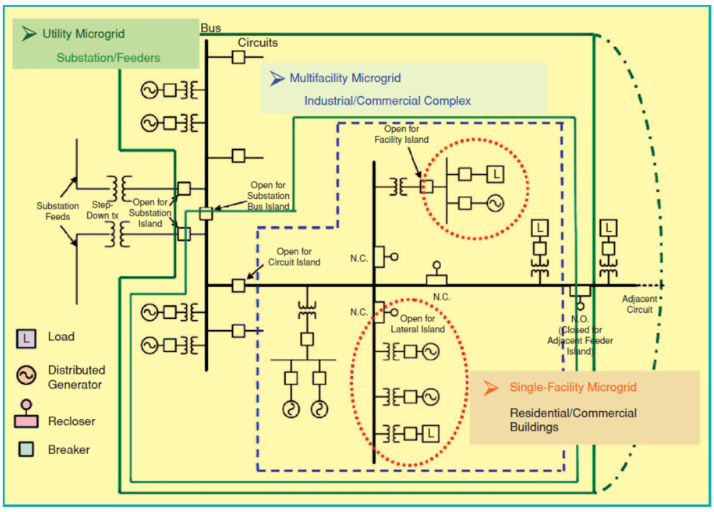

Figure 2.3: Topography of different types of microgrids[22]

1. Utility Microgrid

   A microgrid concept is capable of serving a large number of generation and load network, and it can be arranged as an element or a full feeder of a distribution system. Utility microgrid utilizes a large number of distributed energy resources (DERs). A utility microgrid is also capable of operating while connected to the upstream network or isolated during the maintenance period.

2. Comercial and Industrial Microgrid

   As implied by the name, Commercial and Industrial Microgrids are mainly adopted in the commercial and industrial sector. Their users demand a reliable and stable power and sensitives to any disturbance. Commercial and Industrial Microgrids are equipped with a high-level control system that monitors not only the local power flow but also the power exchange with the upstream network. If the power quality of the upstream network does not meet the high requirement, it can easily be disconnected and operated independently.

3. Remote microgrid

   A remote microgrid is not connected to any upstream network. It is exclusively off-grid and depends exclusively on its own resources. Therefore, reliable energy storage is critical in case of emergency to prevent any power outage. However, since there is no connection to the larger network, it does not require any special code or restriction, and thus, the controller is less complicated. The remote microgrid is suitable for remote area or an isolated island. However, unlike urban microgrid, the remote microgrid is barely growing in numbers due to lack of investments.

2.2. INDUSTRIAL MICROGRID

As stated previously, Industrial Microgrid is commonly named by Commercial and Industrial (CI) Microgrid, since it is mostly used in commercial and industrial application. Compared to residential microgrid, industrial microgrid has a more complex system. In a terms electricity consumption, a unit of industry consumes megawatt scale of electricity. Meanwhile, the daily average households electricity consumption is only around 4kWh-5kWh.

Industrial microgrids are usually incorporated with several DERs supplying the local load demand. Following the concept of multi-energy system, Industrial microgrid utilizes various types of energy. The electricity resources in industrial microgrids are typically used CHP, wind, and solar power plant. The CHP system is used to satisfy the heat demand, while the electricity demand is compensated by wind and solar power plant. An industrial microgrid requires a capability to work in isolated mode or connected to the upstream network. In islanding mode, the microgrid is isolated upstream network. The microgrid has to be able to satisfy its own electric loads through stable coordination of its DGs. Moreover, the presence of energy storage is required in order to tackle the intermittency problem.

While connected to the upstream network, the microgrid is permitted to perform an energy exchange with the upstream network. When it is required, the microgrid is allowed to purchase the electricity with agreed fees. Moreover, in the case of overproduction, the microgrid is also allowed to sell the energy excess to the upstream network. All of those operations required complex energy management and control. Thus, the presence of a reliable and robust optimization algorithm is required.

Industrial Microgrid (IMG) usually used in different cases, depends on the purpose of the grid. Some of the IMGs is used only in islanded mode since they are located in a remote area while the others are used in order to assure the electricity supply and prevent any shortage. However, the interest in IMGs keeps increasing. Currently, several firms are adopting a microgrid system in order to improve their economics.

For the latter case, the system is more complicated compared to the previous two. When used in the off-grid area, the microgrid does not have to follow the specific code from the above network. Isolated microgrid only focuses to supply its own demand. While in the second case, the system gets more complicated since it has to follow a particular requirement from the upstream network. However, for the last case, the system will be a lot more complicated. Not only it has to follow the requirement from the upstream network, but it also has to consider the economic aspect. When to utilize its own generator or when to sell and buy the electricity from the upstream network, without neglecting the technical and economic aspect. The microgrid requires a robust control system with a reliable optimization method. Therefore, developing an optimization algorithm that can handle both the technical and economic requirements of an industrial microgrid will be challenging.

Industrial microgrid adopts the multi-energy system concept that involves several energy resources to satisfy the local demand. They usually combine renewable energy resources, such as PV, wind turbine, and biomass, together with low carbon emission gas turbine. Not only electricity, but industrial microgrids also need a quite high number of thermal demand. An industrial area utilizes heat not only for office or district heating but also for industrial purposes, such as to accelerate a chemical reaction, or polymer production.

Industrial Microgrid is a complex system that the users require more reliable and stable power system compared to what found on most grids. Designing an industrial microgrid will be much challenging since it requires high-level power management strategies and supported by the reliable control system to prevent any disturbance. The energy exchange to the upstream network is also strictly monitored to limit the influence of the upstream network that may cause unstable frequency or unexpected voltage drop. It can be isolated from the upstream network if the power quality of the upstream network does not meet the microgrid requirement.

2.3. MULTI-ENERGY SYSTEMS

An industrial microgrid consist of various utilities. It can be in the form of PV, wind turbine, Combined Heat and Power (CHP) plant, Electric heat pump (EHP). The energy stakeholders emphasize cleaner and more efficient energy system to be adopted in any electricity grid, especially the microgrid. Therefore, a platform named multi-energy systems (MES) is introduced in order to give a better understanding in developing greener and cheaper energy system. It encourages an active interaction between all energy function like electricity, heat, and fuels. MES framework is excelling classic energy system in every aspect, not only in the technical aspect but also in economic and environmental aspect.

Compared to the classical energy system, MES has a significant advantage. It encourages the conservation of energy concept, thus lead to better energy efficiency. It also multiplies the energy flexibility since a form of energy does not depend only on one form of energy. For example, the utilization of CHP that allow the generation of heat from electricity. Moreover, through optimal market interaction, is capable of promoting the optimal arrangement of centralized and decentralized assets in a smaller level.

In general, all form of energies is “multi-energy” in physical terms. Departing from that idea, MES gives a broader perspective on the concept of multi-energy. A concept of MES involving every aspect in energy system from the generation side to the demand side where can be directly utilized by the users. Therefore, the concept of the microgrid can be expanded further, not only involving electricity, or other forms of energies, but also expanding the service and different aspects. An MES can be categorized into different platform, depends on the perspective as mentioned below,

1. Spatial Perspective

   A concept of MES can be identified by the scale of the system, from a single area, for instance, building, into a more extensive network, such as a city, or even a country. For example, in a building level, the electricity and natural gas are used to satisfy the demand for electricity and heat of the building. This building interacts with another building, which also utilizes local multi-energy system no matter what the form of the energy is. Several buildings interact as a scale of a district, and several districts interact in size of the region. To give a better understanding of the concept, Figure 2.4 illustrate the structure of MES in a spatial perspective.

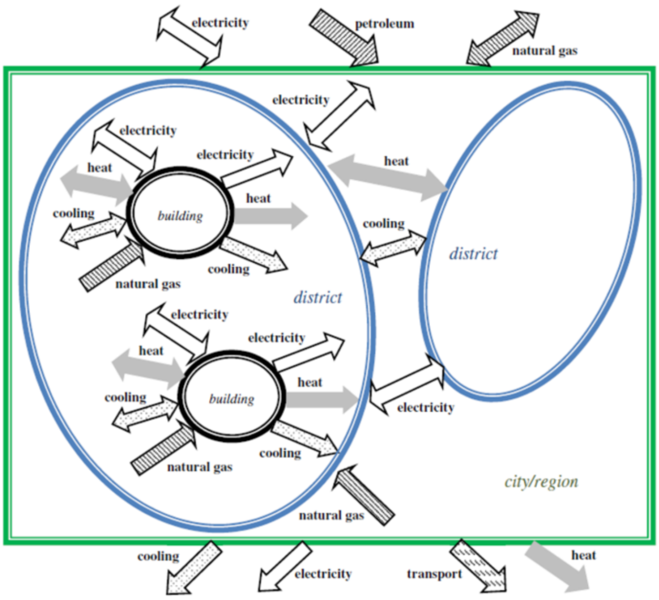

Figure 2.4: Multi-energy systems in spatial perspective [23]

2. Multi-service Perspective

   Figure 2.5 illustrates the multi-service perspective in the multi-energy system. As can be seen in the picture, this perspective is mainly focused on the service or the output of the system. A CHP plant is an excellent example of this perspective since it is produced heat and electricity. This system is claimed to have more efficiency compared to the single output system. In the case of CHP, instead of dumping the heat generated by the system, it can be used to supply the local heat demand.

3. Multi-fuel Perspective

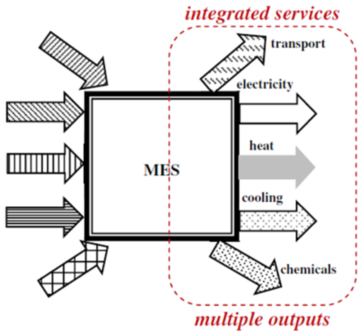

Figure 2.5: Multi-energy systems in multi-service perspective [24]

On the fuel perspective, utilizing several fuels to generate one or multiple forms of energy is already quite familiar. In this perspective gives the highlight of how various types of fuel from natural gas to renewable resources, are integrated together and used to supply the local demand.

4. Network Perspective

   Figure 2.6 shows the scheme of a multi-energy system from a network perspective. As can be seen in the picture, the network perspective integrates several MES in a single network. The interconnection of each system can be in various types of energy. This MES interconnection facilitates the optimal management of MES. Even though it is more complicated, it allows each MES or MES component to operate in more proper and efficient according to its purpose

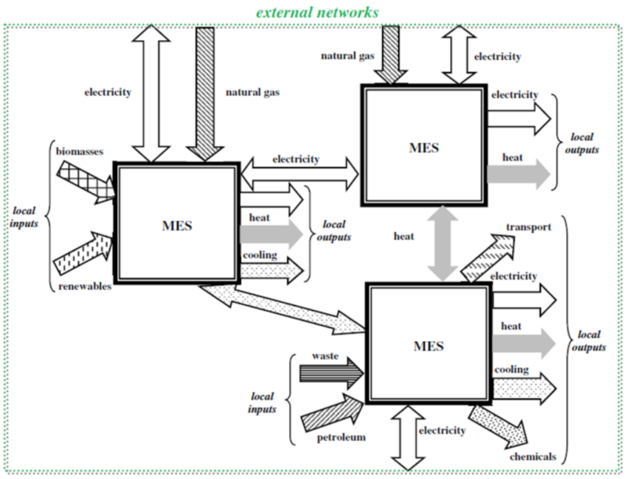

Figure 2.6: Multi-energy systems in multi-service perspective [24]

2.4. UTILIZING BOILER FLEXIBILITY AS A CONTROLLABLE LOAD

The main drawbacks of renewable energy sources are its intermittency. PV fluctuates during a day-night period. During the day, PV generated an adequate amount of energy. However, The electricity generated by PV during the night is almost zero since there is no sunlight to generate the photo-electric process. Furthermore, the wind is more fluctuated daily, depending on the gust and wind speed variation throughout the day. Additionally, the energy generation of wind and PV are also varied during a seasonal period.

Researches come with several solutions to answer the renewable energy fluctuation problem such as increase the power system capacity and energy storage utilization. However, a considerable amount of expense comes as a result of deeper renewable energy penetration. Electrical energy storage is less viable due to its high expense requirement. It also has a limitation to be used in a significant energy system. Moreover, it also a considerable expense is needed to increase the power system expansion. For example, a four-folds energy reserve is required in order to increase wind energy utilization by 33% in California [4]. Moreover, if the generator is powered by fossil fuel, it will neutralize the benefit of zero carbon emission of wind energy utilization.

Therefore, a demand-side optimization become a more attractive solution to greener energy optimization. Thermostatically controlled load, electric vehicles, and electrical energy storage are considered to be the most common solution to accommodate demand-side optimization. Several studies proved the viability of the solution. For example, Pacific Gas and Electric in United states introduce a program called SmartAC. SmartAC capable of accommodating the load shaving and management by reducing the Air Conditioner power in a residential area.

Thermal Load serves an essential role in the Industrial sector. More than 20% of electricity consumption in the US is in the form of thermostatic loads. The same goes in Europe. As can be seen in Figure 2.7 50% of electricity in Europe is used for heating, and cooling purposes with more than half of it are used for space heating [9]

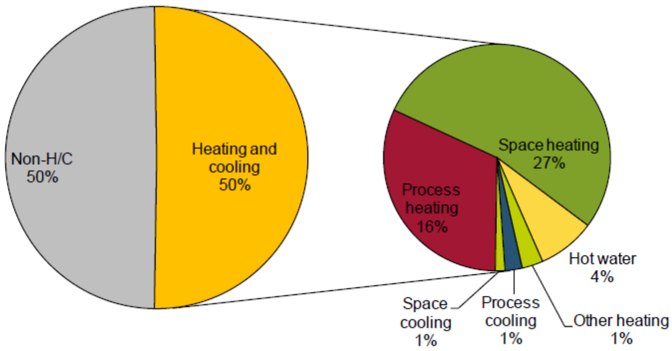

Figure 2.7: Heating and cooling demand of EU28 in 2015 [9]

Thermostatic Loads can be served in a different form. Space heating is the most common application, followed by Process heating. Additionally, the thermostatic load can also be used as a cooling process even though only share a small portion in Industrial application. Moreover, the thermostatic load is more manageable to be scaled up into larger capacity compared to electrical loads. Additionally, not only it is flexible, but also bring no negative impact to another equipment performance while operating together.

These facts show the importance of a thermostatically controlled load as one of ancillary service. Moreover, the concept of a multi-energy system drawing more attention to the scholars since it enhances energy utilization efficiency. The presence multi-energy system in an IMG will bring more challenge to the future power system since it has dynamic variable load and require more complex optimizing algorithm[7].

2.5. CONCLUSION

The utilization of renewable energy in a Microgrid is a must in order to produce less carbon emission. However, the conventional solution leads to a higher cost. Therefore, a demand response management is considered as one of the most viable solutions compared to network expansion and electrical energy storage technology. The thermal load has various advantages that are considered by many scholars suitable to the application of demand-side management to a microgrid.

3

MODELING

This chapter provides information about the network and model that are used in the project. The project involves various software environment and package. Section 3.1 explains the utilization of OpenModelica and python software to develop the system. The details of network and boiler modelling is explained in Section 3.2 and Section 3.3. Lastly, the utilization of Optimal Power Flow is described in Section 3.4.

3.1. SOFTWARE ENVIRONMENT

As stated in Chapter 1 this thesis will be involving work with grid modeling, developing optimization algorithm, and integration of multi-energy model. To carry this project, two software platforms are used to serve each purpose. OpenModelica will handle the network and boiler modeling, while the Optimization algorithm will be developed in python. The cross-platform simulation is also performed in python. The optimization is performed in python. Once, the objective function is obtained, the result will be dispatched to the corresponding model. FMPy module in python is used to build the master algorithm that manages the co-simulation and data exchange of network model, boiler model, and the optimization algorithm.

3.1.1. OPENMODELICA

OpenModelica is an open source programming software that is based on object-oriented programming. It was first introduced in 1997 and currently, hundreds of developers were actively involved in contributing and developing OpenModelica [25]. Openmedilca is a comprehensive programming language, which not only capable of modeling physical modeling, but also compile and simulate the model. The physical model can be built inside the OpenModelica Connection Editor. Figure 3.1 illustrates the OpenModelica Connection Editor in a graphical interface model.

OpenModelica supports a graphical interface and text mode programming. These features give flexibility to the user to develop the model. The graphical interface is more suitable to understand the building block of the model. The model that was built in the graphical interface is automatically translated to the corresponding programming text. The text mode allows the user to develop the model in more detail, such as providing extras mathematical equation to the model. Users can easily use these modes interchangeably. Given this flexibility, OpenModelica allow the user to build a robust model with great detail.

A standard library, named Modelica Standard Library, is a free library that already bundled inside OpenModelica software. The library equipped with various types of physical model that can be quickly built with drag and drop to the edit screen. The model also can be modified to develop a new model for further use.

Along with the Modelica Standard Library, Open-Instance Power System Library (OpenIPSL) is utilized in this thesis. OpenIPSL is currently developed by SMartTS Lab. OpenIPSL is originally a fork of iPSL library developed by the same research group. Figure 3.2 shows the component of OpenIPSL library. As can be seen in the picture, OpenIPSL consist of many packages of electrical and non-electrical parts.

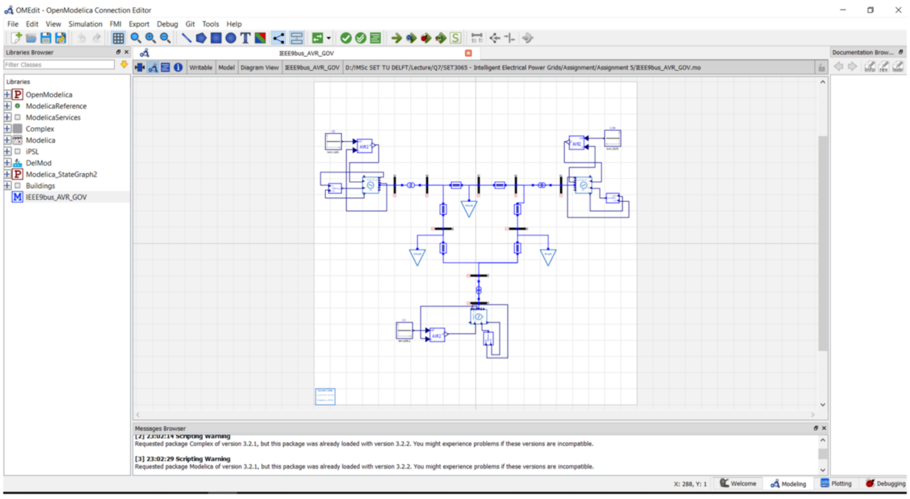

Figure 3.1: Graphical interface of OpenModelica Connection Editor

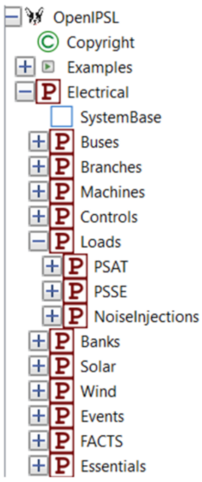

Figure 3.2: Open iPSL library of OpenModelica

3.1.2. PYTHON

Python is an interpreted programming language that can be used in the various range of application. Interpreted programming means that the users write the instruction of source code directly. Many libraries are also available which will ease the users to develop their program. Python is categorized as a general purpose language programming which means, it can be used for any kind of purposes.

3.2. NETWORK MODEL

As stated previously, the network will be integrating Industrial Microgrid and multi-energy system concept. The wind turbine will produce the energy and supply the demand. Gas powered turbine is prepared in order to supply additional electricity if the energy produced by wind cannot satisfy the energy demand. Besides the electricity, heat is a major demand in an Industrial Microgrid. Factories need not only for maintaining the room temperature of the office, but also for industrial purposes, such as for chemical reaction, or polymer production. Therefore, an electric boiler is used to convert the electricity into heat to supply the thermal load.

3.2.1. IEEE 14 BUS SYSTEM

Developing the grid will be another challenge in this thesis. The level of the details of the grid will determine the complexity of the system. The grid model will be built based on the standard IEEE 14 bus system. the reason to use IEEE 14 bnus system is that it is MV distribution level, and is commonly used to model industrial networks. Therefore, IEEE 14 bus system is considered to be an excellent representative to model an actual industrial park electricity network.

However, there are several modification implemented to the IEEE 14 bus system. Generator 1 is the main generator, while Generator 3 and Generator 6 act as a backup generator if there is not enough power generated from Generator 1. Generator 2 and 8 will be replaced with a wind turbine in order to comply with the renewable energy integration. Load 6, Load 9, Load 10, Load 11, Load 12, Load 13, and Load 14 will represent the electric loads. Load 2, Load 3, Load 4, and Load 5 represent heating loads represented as large boilers. Table 3.1 summarize the modification of the IEEE 14 bus system into the network and Figure 3.3 shows the network model in OpenModelica.

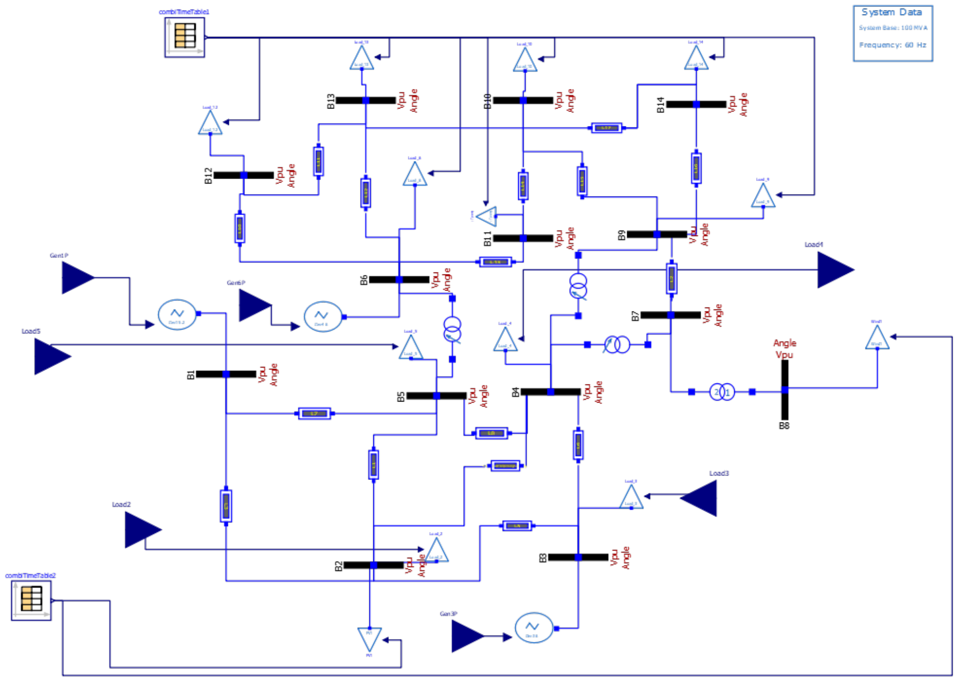

Figure 3.3: The Network model in OpenModelica

Table 3.1: List of Modification of IEEE 14 bus system.

Generator	Wind Turbine	Electric Load	Boiler
Generator 1 (Main)	Generator 2	Load 6	Load 2
Generator 3 (Backup)	Generator 8	Load 9	Load 3
Generator 6 (Backup)		Load 10	Load 4
		Load 11	Load 5
		Load 12	
		Load 13	
		Load 14	

3.2.2. GENERATOR MODEL

Synchronous machine generator from PSAT library will be used as a base model of the generator. The model is able to represent a real generator and show the dynamic of a generator such as frequency response and voltage response. Figure 3.4 shows the work flow diagram of the generator model. As can be seen in the figure, the model used several inputs as an initial condition such as frequency, active and reactive power, and mechanical properties. Once connected to the network, the model will respond and give output signal according to the network variable and environment.

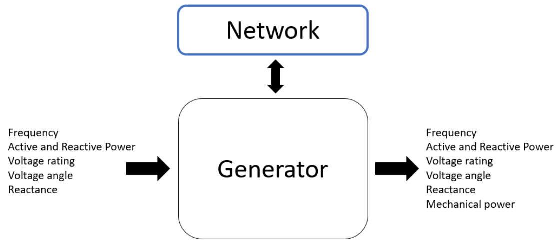

Figure 3.4: Work flow diagram of the Generator Model

Since the input of the generator variously changes, an Automatic Voltage Regulation (AVR) model is needed. The AVR is required in order to maintain the stability of the voltage. The high variation of voltage may damage the power system equipment [26]. Figure 3.5 illustrates the control loop diagram of the AVR model in OpenModelica. AVR works by sensing the difference between the measured voltage and the reference voltage which is known as an error voltage. The error voltage goes to the controller that amplifies the signal. The exciter block represents the excitation system that delivers the winding current in order to produce the desired voltage level. Moreover, to obtain a more accurate value, a feedback signal is added in order to compensate any error calculation.

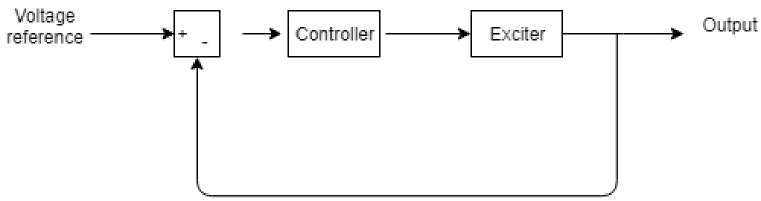

Figure 3.5: Control loop diagram of AVR model in OpenModelica

The stability of the system frequency determine the satisfactory level of a power system operation. The stability of frequency ensure the speed of the synchronous motors to remain constant. A noticeable drop in frequency may result a damage to the generator turbine. Therefore, a governor is needed as a frequency control to maintain the stability of the frequency. Governor is required to arrest the initial drop in frequency of a generator due to sudden changes in the electrical side of the generator [26]. Figure 3.6 illustrates the work flow diagram of the Governor model in OpenModelica. The governor measures the rotor speed of the generator. The difference will be stabilized by the controller. Moreover, an actuator is needed in order to compensate for the error and give a more accurate output of the required rotor speed.

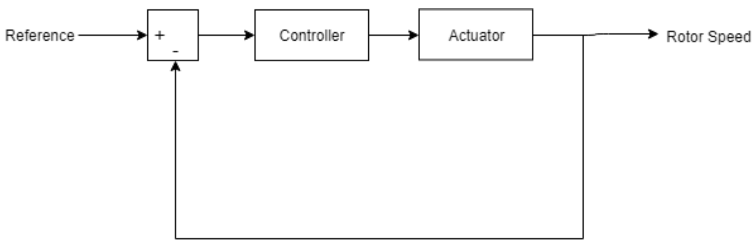

Figure 3.6: Control loop diagram of the governor model in OpenModelica

AVR and the governor serve as the controller for the generator. Figure 3.7 shows the entire component of the generator model. The voltage output of the generator is always monitored and controlled by the AVR. Meanwhile, the governor maintains the stability of the rotor speed of the generator.

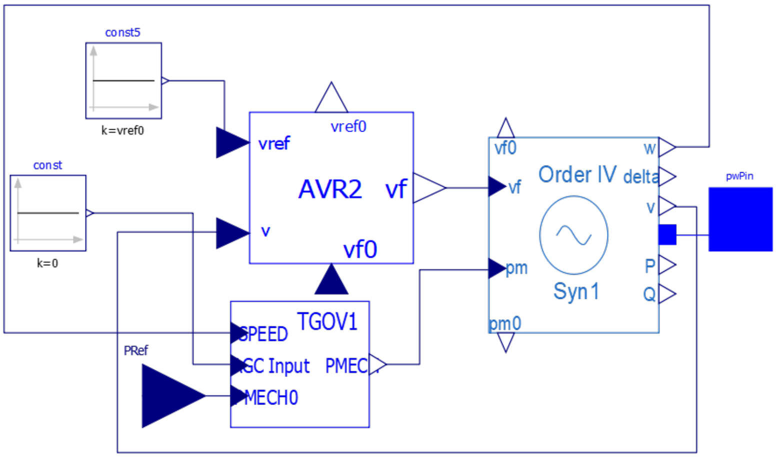

Figure 3.7: Complete generator model

3.2.3. WIND TURBINE MODEL

The wind turbine model is based on the variable load of Delmod library. In this model, the wind turbine is considered as a constant power source that only varies by the scaling factor input. There are several wind turbine model available in Open Modelica library, such as in iPSL and in buildings library. However, due to their incompatibility with the network system, utilizing wind model as a constant power source is more viable. Furthermore, constant power source also give less computational problem to the system.

The initial input of the model is the active and reactive power and wind speed as a variable input through the time. The model of a wind turbine is depicted in Figure 3.8. The combination of wind speed variable and the initial active power input gives an actual wind power at a certain time.

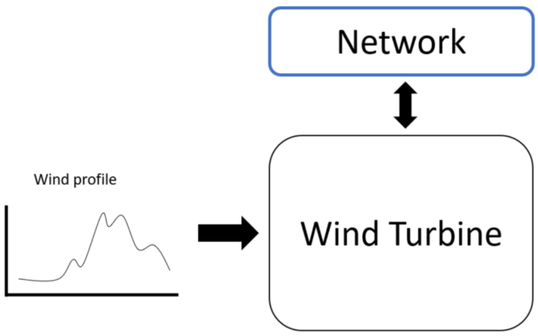

Figure 3.8: Work flow of Wind Turbine Model

The relation between wind ratio and wind power is shown by the equation below,

$$P_t = P_0 * r \tag{3.1}$$

where P_t is Wind power output at time t (MW), P_0 is the initial active power(MW) and r is the ratio.

The ratio is a scaling factor of the wind power. In the model, the wind power is initially at the maximum capacity. Therefore, a scaling factor that represent the wind speed is required in order to obtain the realistic wind power. The further explanation of wind turbine equation is described in Section 3.5.

3.3. BOILER MODEL

The boilers model inside the network is modeled as an electric load. Therefore, to give a further understanding of the thermodynamic response of an actual boiler another boiler model needs to be developed. The boiler model is developed based on AixLib library in OpenModelica[27]. By adopting the different model, the thermodynamic characteristic of an actual boiler such as temperature gradient, fluid flow rate, and tank pressure can be easily observed.

Figure 3.9 shows the workflow of the boiler model while figure 3.10 depicts the model of Boiler in OpenModelica. The Active power of the load act as an electric input of the boiler. This electric power than used to heat the heater inside the boiler to produce heat. The heater heats the fluid that flows from the source to the sink. The source and sink are used to avoid unnecessary complicated network. Basically, it can be replaced with more complicated heat network or any model required for more specific case study.

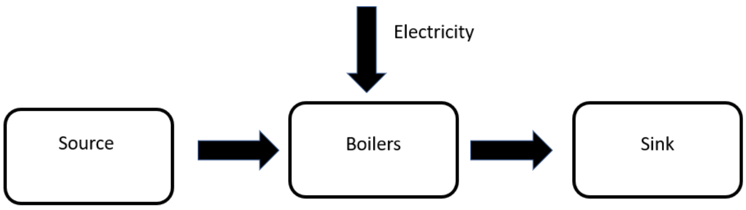

Figure 3.9: Work flow of the Boiler model

The input of the boiler is the electric power, while the output is fluid temperature. The relation between power, fluid temperature, and pressure drop are shown in the following equation,

$$\frac{\mathrm{dT}}{\mathrm{d}t} = \frac{P_t}{eff * \varphi_m * C_p} \tag{3.2}$$

$$dp = a * \varphi_V^2 + b * \varphi_V \tag{3.3}$$

$$\varphi_m = \rho * \varphi_V \tag{3.4}$$

where,
$\frac{\mathrm{dT}}{\mathrm{d}t}$: Temperature change through the time (K)
P_t: the active power of the boiler at time t (MW)
eff: the efficiency of the boiler
φ_m: mass flow rate of the liquid (kg/s)
C_p: the specific heat of the liquid (kJ/kgK)
dp: Pressure drop (Pa)
a: the quadratic coefficient $(Pa * s^2/m^6)$
b: linear coefficient $(Pa * s/m^6)$
φ_V: Volume flow rate (m^3/s)
ρ: Density of fluid (kg/m^3)

3.4. OPTIMAL POWER FLOW

Complex systems, such as power systems require constant optimization of their operation to be as economic as possible. There are many problems in power systems, and more generally, energy systems, that require application of optimization algorithms. Examples of such problems include parameter tuning, optimal PMU

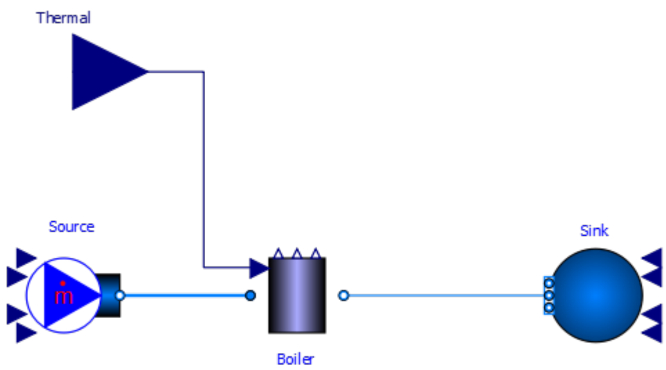

Figure 3.10: Boiler Model in OpenModelica

placement, optimal power flow for cost optimization, optimal capacitor banks placement for voltage control, etc. In this work, we are mainly interested with cost optimization and using boiler to mitigate effects of renewable energy sources. Hence, we make use of Optimal Power Flow.

Optimal Power Flow is one of the fundamental tool to obtain the feasible, economic, and secure power system operation. Optimal Power Flow contain mathematical equation that used to find the optimal solution of power system operation under the constraints and feasibility of the power system operation with the objective of cost minimization.

The input of the network and boiler model are generated as a result of optimal power flow. In this project, the OPF algorithm is built in python using the Pandapower module. Figure 3.11 shows the work flow diagram of the optimal power flow algorithm. The input of the algorithm is the load profile and the problem formulation of the Optimal Power Flow. The network model is translated into Pandapower network. Once the optimization result is obtained, the result is provided to the network and boiler model.

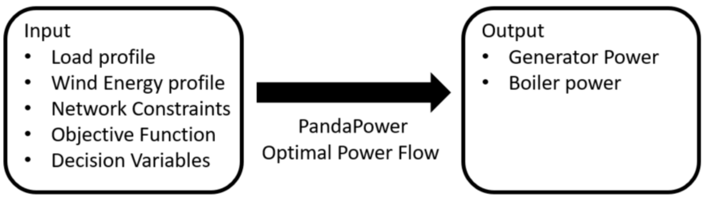

Figure 3.11: The work flow diagram of Optimal Power Flow Algorithm

3.4.1. PANDAPOWER NETWORK

Before performing an optimal power flow, a Pandapower network that represents the network model has to be built. Pandapower offer flexibilities to built the represented network. It can be either built manually in python language or imported from other files extension such as Matpower, json, excel, etc. Manually built network in python code offer faster simulation since it is already inside the software environment compared to importing the network from other file sources. However, it will become more complicated as the network getting larger.

In this project, the Pandapower network was built in combination between excel file and modification in python code. A base network that contain the parameter with initial condition is built in an excel file. Since the import process only occurs in initial condition, the difference in time required for simulation is not that much and it is easier to refine the components value inside the excel file. Meanwhile, the network components, such as, loads, generators, lines, bus and their parameters and constraints are written in separate sheet.

Once the base network is built in excel, the python code has to be built. The function of the python code is to perform the Optimal Power Flow. The python code also contains the cost function and time-dependant variables such as hourly load profile and wind turbine scaling factor. The interaction between the base network and the time-dependant variabled are managed by the python code. Combining the base network, cost function, and the time-dependant variables an optimal power flow algorithm can be performed with a comprehensive Pandapower network. Figure 3.12 shows the comprehensive structure of the Pandapower network.

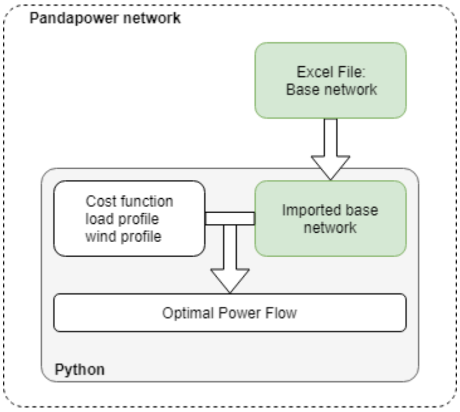

Figure 3.12: Diagram of a comprehensive Pandapower network

3.4.2. PROBLEM FORMULATION

- Objective Function

  The objective function of the simulation is to achieve the minimum generator production. By minimizing the generator production, the minimum cost production can be obtained. Moreover, low energy production by the gas-fueled generator lead to lower carbon emission. The objective function is shown as follows,

$$\underset{P}{\text{minimize}} \quad \sum f_i\,(P_i) \tag{3.5}$$

- Decision Variables

  The decision variables represent the parameters that can be controlled in order to achieve the objective function, such as:

  - The amount if power consumed by boilers ($P^b_{j,h}$)
  - The amount of electricity generated by generators ($P^G_{i,h}$)

- Constraints

  - Power Flow Equation

$$V_{i,h}\sum_{j=1}^{N} V_{j,h}(G_{ij}cos\theta_{ij,h} + B_{ij}sin\theta_{ij,h}) - P^G_{i,h} + P^D_{i,h} = 0 \tag{3.6}$$

$$V_{i,h}\sum_{j=1}^{N} V_{j,h}(G_{ij}sin\theta_{ij,h} - B_{ij}cos\theta_{ij,h}) - Q^G_{i,h} + Q^D_{i,h} = 0 \tag{3.7}$$

- Power Balance
  The total power generated by the generator has to be equal with the total demand electricity at each hour.
  $$\sum P^{G}_{i,h} = \sum P^{D}_{h} \tag{3.8}$$

- Heat demand Balance
  The total energy consumed by the boiler has to be equal with the thermal demand at each hour.
  $$\sum P^{b}_{j,h} = D^{th}_{h} \tag{3.9}$$

- Generator's Active Power Capacity
  The power generated by the generator has to be within the lower and upper bound limit.
  $$P^{G,min}_{i,h} \leq P^{G}_{i,h} \leq P^{G,max}_{i,h} \tag{3.10}$$

- Generator's Reactive Power Capacity.
  $$Q^{g,min}_{i,h} \leq Q^{G}_{i,h} \leq Q^{g,max}_{i,h} \tag{3.11}$$

- Boiler capacity
  The capacity of each boiler has to be between 80%-100% of the maximum capacity.
  $$0.8 * P^{b,max}_{j,h} \leq P^{b}_{j,h} \leq P^{b,max}_{j,h} \tag{3.12}$$

- Bus Voltage Rating
  The voltage of each bus has to be within the lower and upper bound limit.
  $$V^{min}_{j,h} \leq V_{j,h} \leq V^{max}_{j,h} \tag{3.13}$$

where,
G_{ij}, B_{ij} = Real and imaginary elements in the ith row and jth column of node admittance matrix
$P^{G}_{i,h}$ = Active power of generator i at time h (kW)
P^{D}_{h} = Active power demand at time h (kW)
$P^{b}_{j,h}$ = Active power of the boiler j at time h (kW)
D^{th}_{h} = Total thermal energy demand at time h (kW)
$Q^{G}_{i,h}$ = Reactive power of generator i at time h (kVAR)
$V_{j,h}$ = Voltage at bus k at time h

- Cost Function

  A cost function is required in order to determine the amount of electricity produced by the generator and wind turbine. The cost function that is used in this project is shown in Equation 3.14. Moreover, it can be used to determine the order of the priority of the components. As can be seen in Table3.2, each components has different cost function parameters. Negative sign indicate the function to minimize the generation while the number shows the priority order of generation. High negative number indicates the less in priority of the generator. Wind turbines has the highest priority since it does not require the fuel cost as a variable. Generator 1, as the main generator is assumed as CHP which has more economical and environmental benefit compared to the conventional gas-fueled generator[28]. Generator 3 and Generator 6 is assumed as gas-fueled generator which serve as the back up generator. Since the boilers are operated by electricity which in this case are in combination between renewable energy, CHP, and small portion of gas-fueled generator, the cost functionis between CHP and gas-fueled generator.

$$f_{pol}(p) = c_n * p^n + ... + c_1 * p + c_0 \tag{3.14}$$

Table 3.2: Cost Function of each components in Pandapower network

Components	c_1	c_0
Wind Turbine 1	-0.1	0
Wind Turbine 2	-0.1	0
Generator 1	-0.2	0
Generator 3	-0.4	0
Generator 5	-0.4	0
Boiler 2	-0.3	0
Boiler 3	-0.3	0
Boiler 4	-0.3	0
Boiler 5	-0.3	0

3.5. DATA SOURCE AND KEY ASSUMPTIONS

- **Network Parameters**

  Since the network model is built based on IEEE 14 bus system, the network parameters from the original IEEE 14 bus system is still used, such as the cable impedance, transformer parameters, and the mechanical properties of the generator. The network parameters will be described in detail in Appendix A.

- **Electric Load**

  The load that is used in the model is modeled as a constant power load. The initial value of IEEE 14 bus system in OpeniPSL library is used. Table 3.3 shows the value of each electrical load in the model.

Table 3.3: The Active and Reactive Power Demand of the Load in the Network

Load Number	Active Power (MW)	Reactive Power (MVAr)
Load 2	39.06	22.86
Load 3	169.56	34.2
Load 4	86.04	-7.02
Load 5	13.68	2.88
Load 6	20.16	13.5
Load 9	53.1	29.88
Load 10	16.2	10.44
Load 11	6.3	3.24
Load 12	10.98	2.88
Load 13	24.3	10.44
Load 14	26.82	9
Total	**466.2**	**132.3**

- **Load Profile**

  The load profile that is used in the network is based on average electricity demand on Industrial Area in Western Interconnection, USA[29]. Three different load profile that three different industry sector are used. Since the data is in the form of a graph, several additional steps are needed in order to obtain a precise value. To obtain the accurate value, the graph needs to be quantified. A software tool named GetData Graph Digitizer is used to quantify the value of each point from the graph. Figure 3.13 shows an illustration of Load profile graph being digitized in Graph Digitizer window.

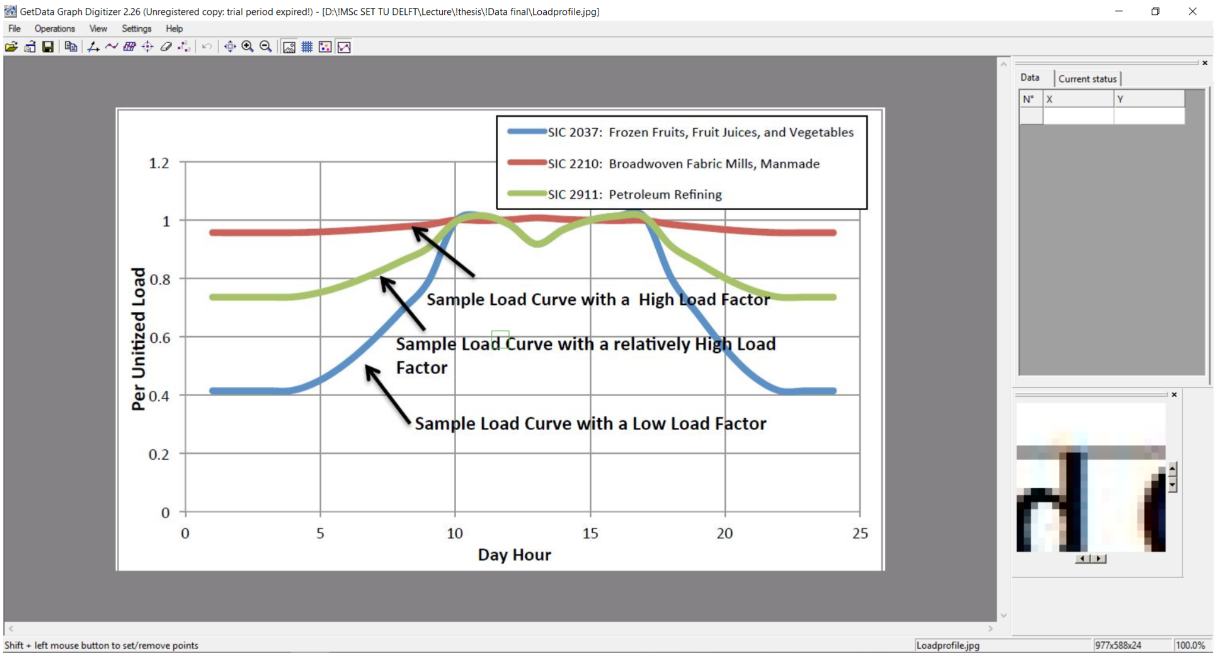

Figure 3.13: The value of the graph is quantified in Graph Digitizer window[29]

Since the initial value of the electricity load is already determined, the input of the load profile to the components is in term of the scaling factor. Figure 3.14 shows the scaling factor of the daily load profile in one hour time step.

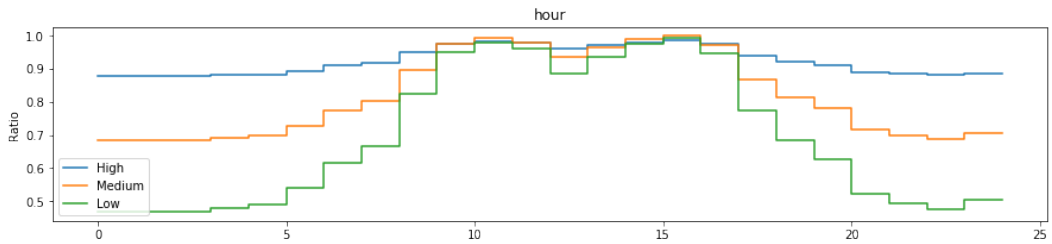

Figure 3.14: The electric load profile of the network

- **Wind Power**

  The wind speed is based Netherlands wind speed data that was obtained from the website of energyplus [30]. This website provides detail weather data from several countries and cities. Figure 3.15 illustrate the wind speed in the summer and winter period. As can be seen in the picture, the wind speed is slightly different for both season, especially in the afternoon.

  However, the wind component in the network model only requires the scaling factor since the capacity is already determined. The value of the capacity of each wind turbine can be seen in Table 3.4. According to equation 3.1 the scaling factor of wind power is required in order to obtain the actual hourly Wind Turbine Power

  The wind power can be obtained using the following formulas,

$$P = \frac{1}{2} * \rho * C_p * A * U^3 \tag{3.15}$$

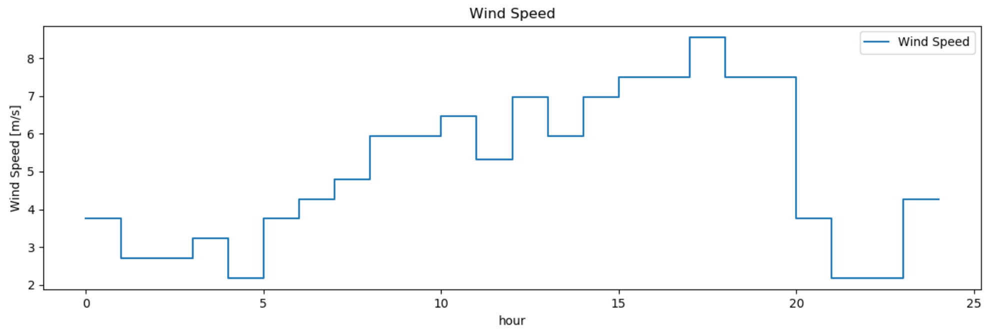

Figure 3.15: The daily wind speed in Netherlands

Table 3.4: Wind Turbine Capacity

Wind Turbine	Capacity (MW)
Wind Turbine 2	120
Wind Turbine 8	180

where P are the Wind power output, ρ is the air density, C_P is Power coefficient of the turbine, U is the wind speed (m/s), and A is the area of the wind turbine blade.

Therefore, in order to obtain the most relevant value, the parameter is taken from the real wind turbine, Vestas V-90 [31]. Table 3.5 shows the detail parameters of the wind turbine.

Table 3.5: Wind turbine parameter [31]

Parameter	Value
Wind Turbine Model	Vestas V-90 3MW
Capacity	3 MW
Air Density	1.225 $\frac{kg}{m^3}$
Rotor Diameter	90 m
C_P	0.502

Combining the Equation 3.1, Equation 3.15, and data from Table 3.5, The scaling factor required as an input for the wind turbine component in the network model can be obtained as shown in Figure 4.5

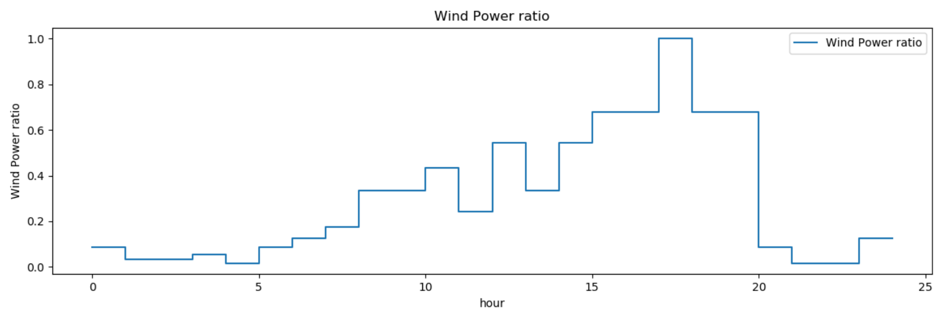

Figure 3.16: The wind power scaling factor that was used in the system

- **Boiler**

  The boiler model is modeled as an electric load inside the network model. However, to observe an actual thermodynamic characteristic of the model, the boiler used the parameter of the a gas-powered boiler from an industrial park. Table 3.6 shows the capacity of each boiler model. As can be seen in the table, each boiler has different capacity. The capacity of the boiler corresponds to the active power of the loads. The fluid temperature in industrial park has to be maintained around 80°C to 100°C[9].

Table 3.6: Boiler parameter

Boiler number	Capacity (kg/s)
Boiler 2	125
Boiler 3	550
Boiler 4	280
Boiler 5	45
Total	1000

Specialized water is used as the fluid medium of the boiler model where several parameters such as, heat capacity (C_p), density (ρ), viscosity (ν), and thermal conductivity (λ) change corresponds to the fluid temperature. Figure 3.17 shows the relation of heat capacity and the fluid temperature and Table 3.7 shows the physical characteristic of the fluid at 20°C.

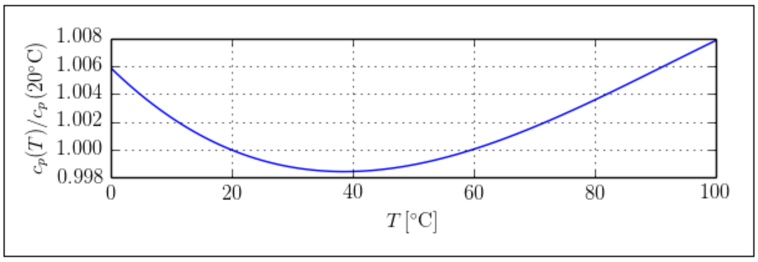

Figure 3.17: Heat Capacity profile of the boiler fluid

Table 3.7: Boiler fluid characteristic

Fluid type	Specialized Water
Heat Capacity	4184 $J/(kgK)$
Density	997 $kg/m3$
Gas Constant	8.31446 J/KgK
Molar Mass	0.018153 kg/mol
a	$1 \cdot 10^{10}$ $Pa * s^2/m^6$
b	0 $Pa * s^2/m^6$

3.6. CONCLUSION

To conclude, the network model is developed based on IEEE 14 bus system. The parameters are based on an actual industrial area with several adjustments in order to not overburden the network. A boiler model is used in order to understand the thermodynamic response of the boiler. An optimal Power Flow algorithm is built in python using Pandapower package. A base network contained initial condition of the component's parameters is built in excel and combined with time-dependant component to perform an Optimal Power Flow.

4

METHODOLOGY

This chapter will explain how the research is conducted. As stated in Chapter 3 the project involves a different software platforms. Therefore a correct method is required in order to attain a credible solution. Section 4.1 will describe how to conduct the research step by step. Section 3.5 explains how the input data is collected and assumptions that were made. A brief explanation of the implementation of a different case scenario will be explained in Section 4.2.

4.1. METHODOLOGY

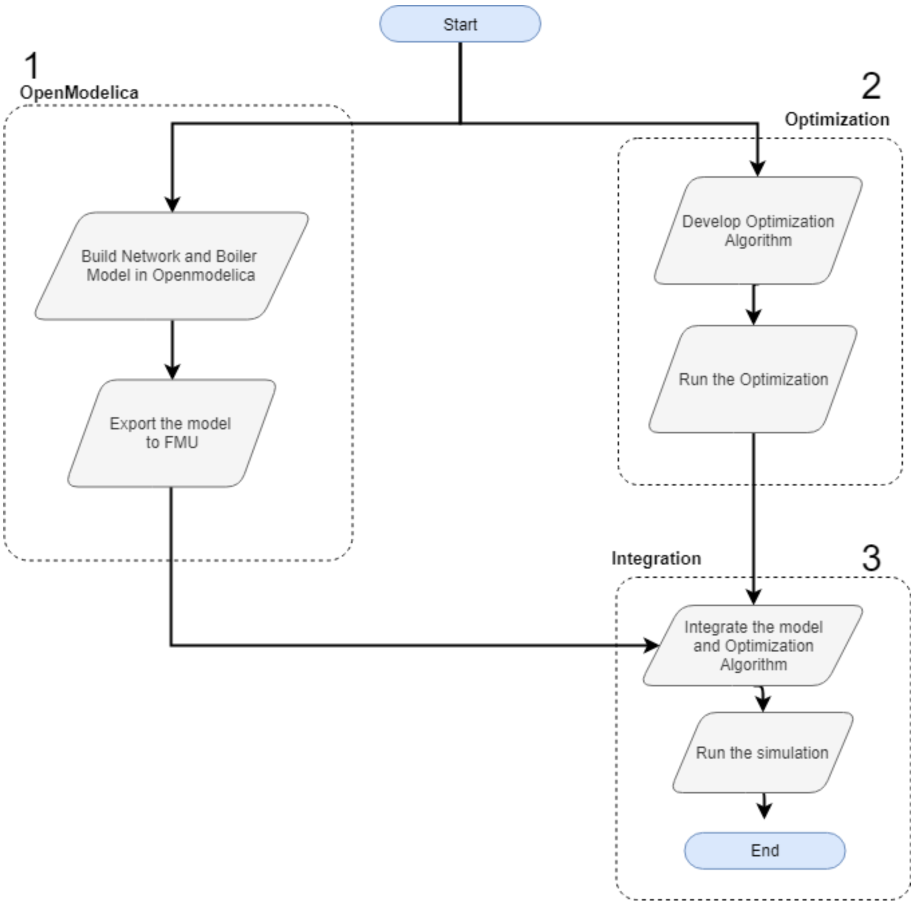

Figure 4.1: Flowchart of the project

In general, this project can be separated into three main steps. Figure 4.1 shows the complete workflow of the project. The classification of each step corresponds to the software environment and the function of each component. The three main steps are:

1. Building the network and boiler model in OpenModelica
2. Creating the Optimal Power Flow algorithm
3. Integrating the network model, boiler model, and the Optimal Power Flow Algorithm

As stated previously, this project involves models with different environment. An integration platform is required in order to manage the interconnection of network model, boiler model, and the optimization algorithm. The network, boiler model, and Optimal Power Flow algorithm are described in Chapter 3. This project utilizes the flexibility of Functional Mock up Interface as the standard to develop the interconnection platform of the models.

4.1.1. FMI FOR CO-SIMULATION PLATFORM

Previously, there is no platform that accommodates the model exchange between different simulation software. This condition creates a complicated process especially in manufacturing industries which involves various software platform to develop different equipment. Therefore, many research institutes led by Daimler initiate to create a platform that supports model exchange and co-simulation between different software simulation. The components that are implemented the interface is termed as Functional Mock-up Units (FMU) [19].

In general, there are two main application of FMI platform.

- FMI for Co-simulation
- FMI for Model Exchange

The differences between the two applications are mainly determined by the capability of the tools that are used as the master. Figure 4.2 shows the diagram of FMI for co-simulation and model exchange. As a co-simulation platform, the master only serves as the data center of the co-simulation environment. The simulation is performed individually in each subsystem by their solver. The master algorithm manage the synchronization and the data exchange of each models. Meanwhile, as a model exchange standard, the master algorithm has bigger role. In this application the models only contain a simpler algebraic equation while the solver is inside the master algorithm[32].

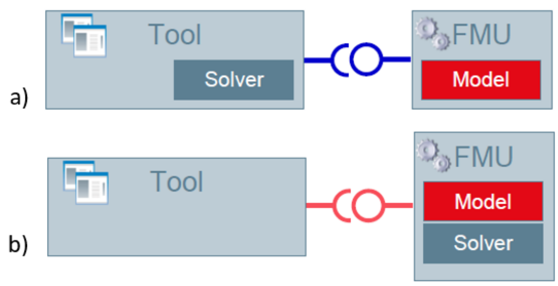

Figure 4.2: Illustration of the difference between FMI for model exchange (a) and co-simulation (b)[32]

In this project, FMI is used for co-simulation application. The network and boiler model is exported from OpenModelica to FMU file extension. Meanwhile, the master code is used to manage the data exchange and time coordination between the boiler, network model and the result of the Optimal Power Flow from pandapower case. The master code is built utilizing FMPy module in python to interact with FMUs.

Another viable option to manage the data simulation of OpenModelica and python is using OMPython module. However this methodology is more complicated since it has to define all the modul and libraries that are included in OpenModelica models. If the simulation require much libraries, it becomes more complicated and increase the computational problem of the simulation.

4.1.2. DATA FLOW STRUCTURE

Figure 4.3 illustrates the data flow from the master code to the network and boiler model. Firstly the Optimal Power Flow is performed and the hourly active power of each generator and boiler is obtained. The result of Optimal Power Flow then transferred by the master algorithm to the respective components in each model that already exported into FMU file. The FMUs simulate the continuous simulation and the result of FMU simulation are gathered by the data collector in master code. Each step is performed continously and managed by the master algorithm. The data transfer to and from FMU, data processing, and simulation command are all handled by the master code.

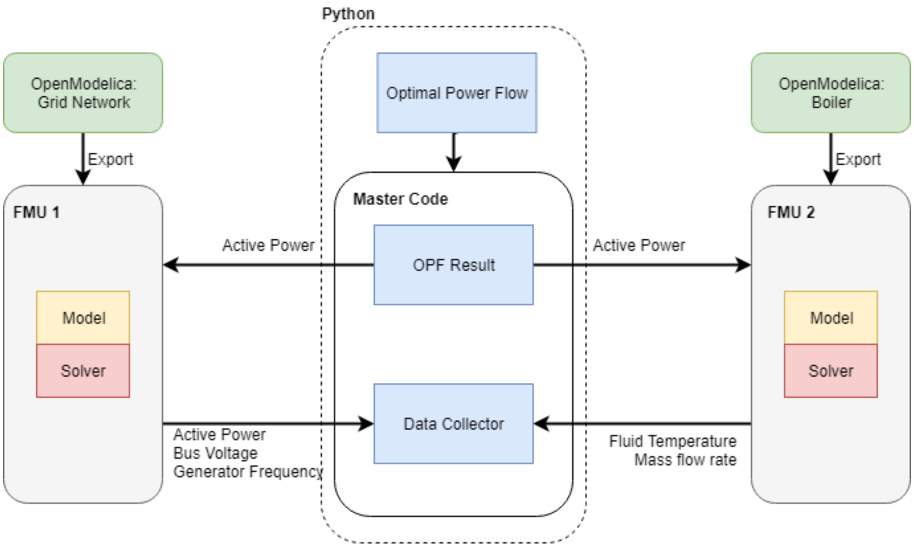

Figure 4.3: Data flow of from master code to the network and boiler model

4.1.3. SIMULATION TIME LINE

Figure 4.4 shows the time line of the simulation. Since, Optimal Power Flow is a time-discrete simulation, A 24 x 7 matrix of generator and boiler that active power are obtained. 24 x 7 matrix represent the hourly electricity generation by three generators and four boilers energy consumption for 24 hours. These result are dispatched to the corresponding components of the FMUs. Then, the master algorithm start to perform the continuous simulation of the FMUs. The time step for continuous simulation is 0.2s. For each time step, the result of the simulation are gathered by the master algorithm as shown in Figure 4.3. Once the time step of continuous simulation reach 1 hour, the new variable of generator and boiler active power are transferred by the master algorithm to the FMUs. The simulation is performed continuously until 24 hours.

4.2. CASE SCENARIO

To obtain a good detail of the performance of the system, four different case scenarios is implemented according to the seasonal and the load controllability,

1. Fixed Thermal Load (Default case)

   The first scenario is considered as a base case scenario. The four thermal loads are fixed at the capacity and cannot be controlled. However, the input of wind power corresponds to the seasonal period. Since renewable energy is affected by the seasonal cycle, two contrast seasonal cycle, winter and summer are used as the case scenario. As can be seen in Figure 4.5 the wind power ratio during winter and summer are not similar. Therefore, the effect of different wind power profile will give a deeper understanding of the characteristic of the model.

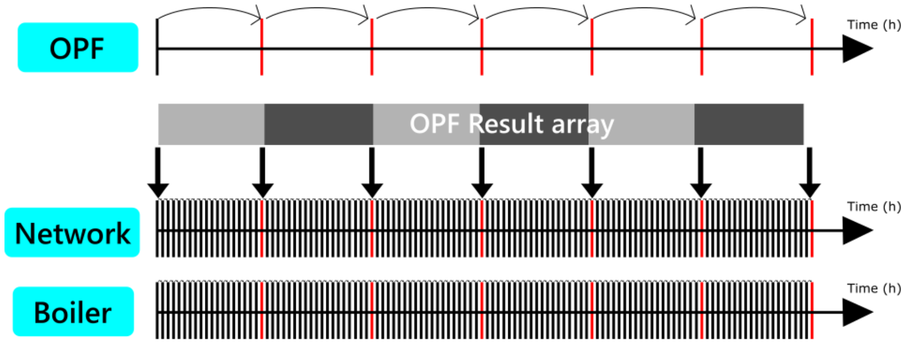

Figure 4.4: The time frame simulation of the Network, boiler model and the Optimal Power Flow

- Winter season
- Summer season

2. Controllable Thermal Load

   In this scenario, the effect of the controllable loads will be observed. Therefore, the thermal load can be controlled to 80%-100% to its capacity according to the power generated by the generator and wind power output[8]. Seasonal wind speed profile is also implemented in order to obtain further information.

   - Winter season
   - Summer season

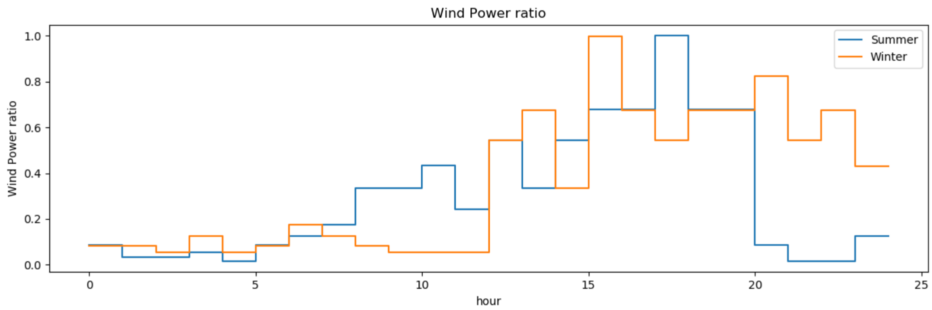

Figure 4.5: The wind power ratio for summer and winter

4.3. CONCLUSION

To conclude, there are three main steps in conducting this project. The first step is to build the network and boiler model in OpenModelica and export the model to FMU files. An Optimal Power Flow Optimization is performed to obtain the optimum solution for each model. Finally, a master code is developed to manage the co-simulation of the models.

5

SIMULATION

The simulation is performed in 24 hours. However, due to the computational performance limitation of the computer, 1 hour is given as a time step of the simulation. Therefore, there will be 24 of data input. This chapter describes the result of the simulation. As mentioned in Chapter 4, four different case scenario is implemented in order to get a more in-depth observation of the performance of the system.

5.1. TOOLS SPECIFICATION

Table 5.1 shows the specification of tools that are used to perform the simulation. As can be seen in the table, HP Omen with intel i-7 processor is used as the PC to perform the simulation. Meanwhile, the software are updated to the latest version to assure the software compatibility to perform the simulation.

Table 5.1: The specification of tolls used to perform the simulation

PC type	OMEN by HP Laptop 15-ce0xx
Operating System	Windows 10 Home 64-bit
Processor	Intel(R) Core(TM) i7-7700HQ CPU @2.8GHz
Memory	8192MB
Python Version	Python 3.7.2
OpenModelica Version	1.12.0 (64-bit)
FMPy version	0.2.5

5.2. RESULT AND DISCUSSION

SYSTEM STABILITY

To understand how the system work, a base case scenario is implemented in the system. The system will utilize the winter wind ratio profile, and the thermal load is fixed during the simulation. The fixed thermal loads also means that it does not contribute to grid energy efficiency. Figure 5.1 shows the frequency of the generator and the bus voltage. As can be seen in the figure, the generator frequency remains almost constant. High-frequency peak happened only at the first initialization due to the initialization process. As stated previously in Chapter 4, the value of loads, boiler, and the wind turbine is initially at the optimum capacity before the optimization. This values mismatch may cause a small oscillation. The maximum frequency reaches 60.33Hz, around 0,55% larger than the initial frequency. Meanwhile, the frequency nadir or the smallest frequency is 59.80Hz, around 0.34% smaller than initial frequency. Moreover, there are several oscillation occurred after around 15.00. This oscillation is occurred since the generator produce electricity much less than the generator capacity. However, the frequency is still within the range of permissible value with margin of 0.5%. The stability of the generator frequency indicates that the governor perform well in maintaining the generator frequency.

Similarly, the bus voltage also remains constant at the initially defined value, 1.06 p.u. The stability of the voltage suggests that the AVR perform well in maintaining the stability of the generator voltage.

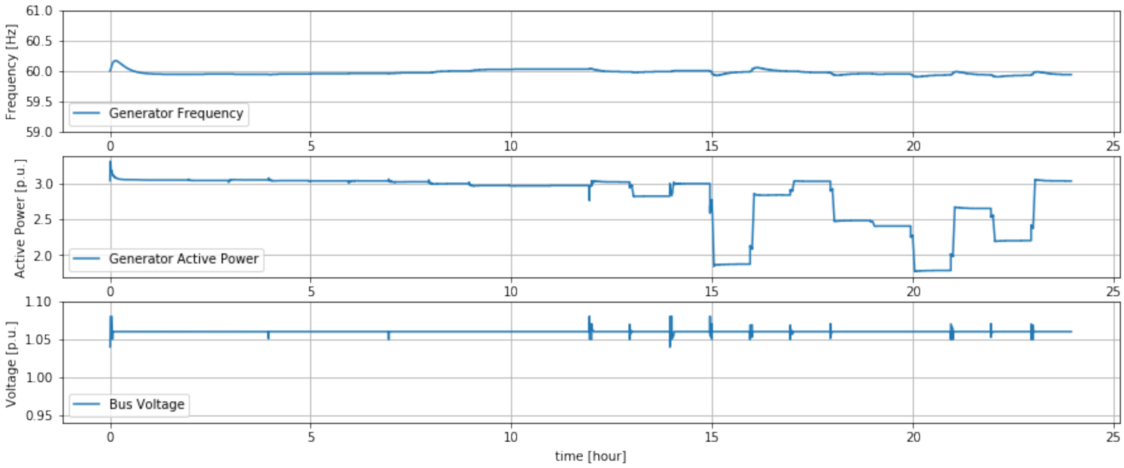

Figure 5.1: Frequency and active power of Generator 1 and the Voltage of Bus 1 in fixed load scenario during Winter season

GENERATOR PERFORMANCE

Figure 5.2 shows the priority order of the generator. The wind turbine generates electricity in response to the presence of wind. If the power generated from wind turbine less than the required power demand, Generator 1 act as the main generator to supply the electricity demand. However, if the demand required more electricity, Generator 3 and Generator 6 start to generate electricity as the backup generator.

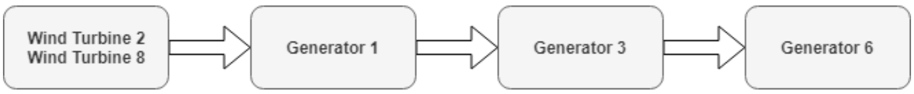

Figure 5.2: The priority order of Generator in fixed load scenario during Winter season

Figure 5.3 shows the active power curve of the generator, wind turbine, load, and the boiler. As can be seen in the picture, all electric loads adopt similar load profile while the thermal load remains constant. Generator 1 serve as the main generator to supply the electricity and support the wind energy production. However, if the wind turbine is able to satisfy the the energy demand, generator 1 start to reduce the electricity generation to the required electricity demand. Generator 3 and Generator 6 act as a backup generator to supply the remaining electricity demand during low wind energy production.

From 00.00 to 12.00 the wind production is low. Therefore, generator 1 act as the main generator to supply the electricity demand. However, even at its maximum power of 300MW, the demand requires more electrical power. The total amount of electricity demand varies from 335.4MW to 437.5MW. Therefore, Generator 3 and generator 6 serve as back up generator to supply the remaining electricity demand. In the afternoon, the wind turbine starts to generate electricity. When the electricity demand can be satisfied, the generator starts to generate lower electricity and follow the priority order as shown in Figure 5.2. At 15.00 the electricity generated by the wind turbine already satisfied the electricity demand. Therefore, no electricity produced by the back up generator at this time.

BOILER PERFORMANCE

Figure 5.4 shows the active power of the boiler and the fluid temperature of the boiler. As can be seen in the figure, the fluid temperature of the boiler corresponds to the active power of the boiler and follow Equation 3.2. Since the power of the boiler is constant, the fluid temperature also remains constant at around 369K or 96°C.

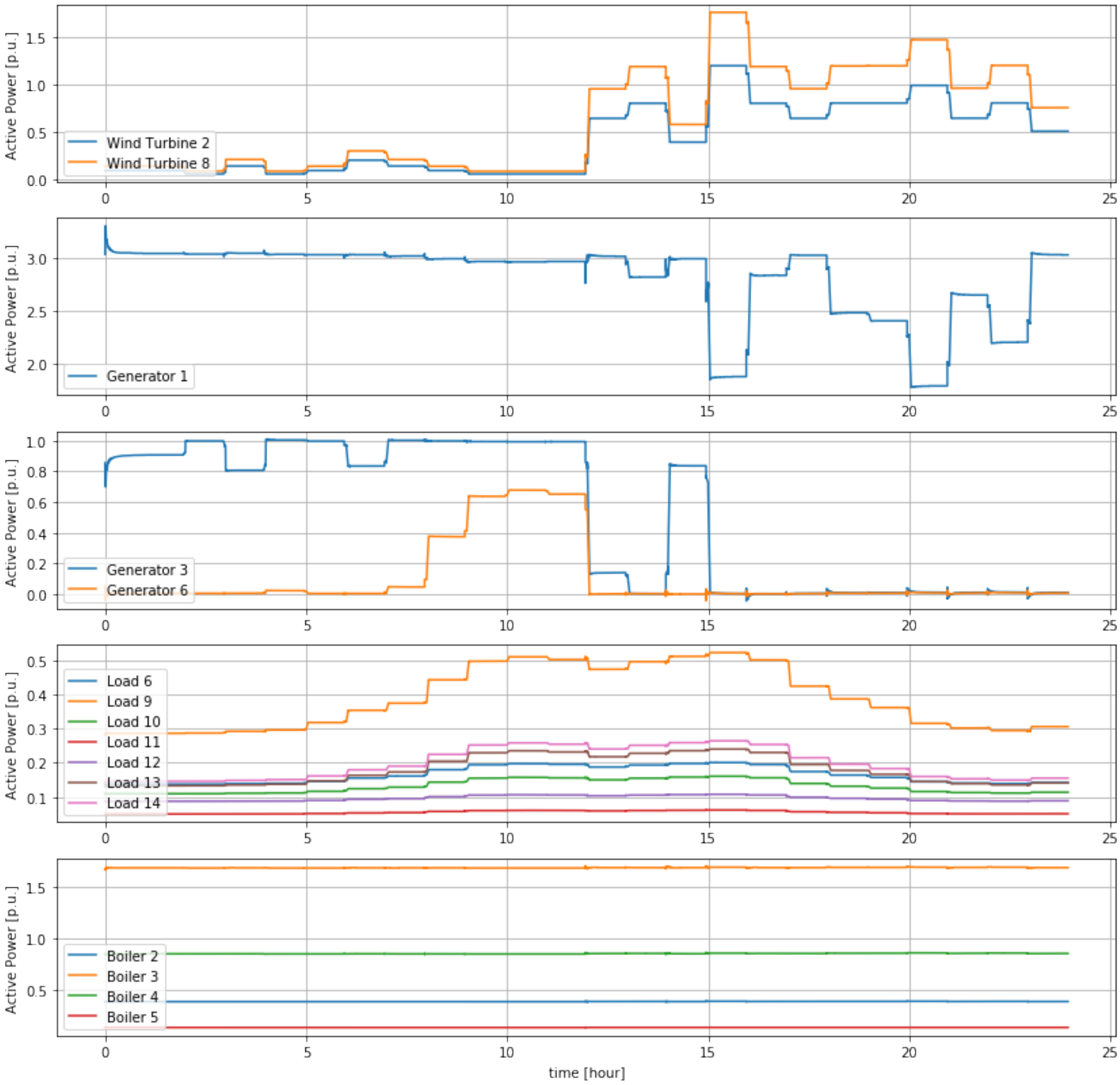

Figure 5.3: The active power of all Generators, Wind turbines, loads and the boilers in fixed load scenario during Winter season

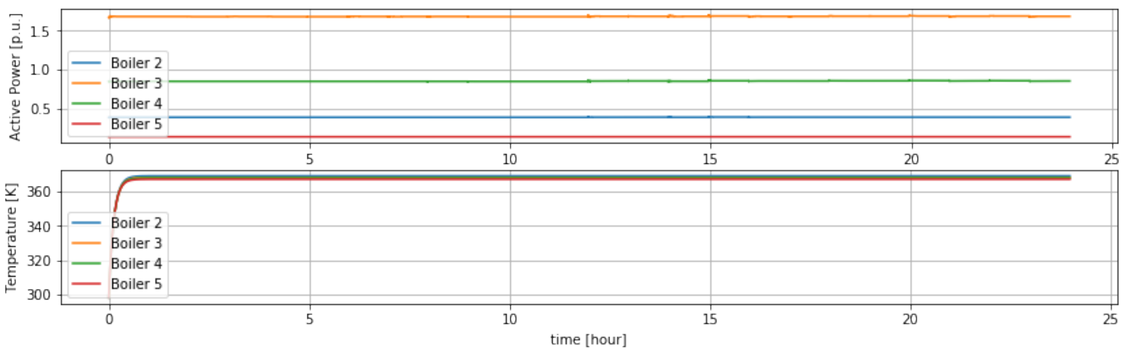

Figure 5.4: The active power and fluid temperature of the boiler in fixed load scenario during Winter season

5.3. CONTROLLABLE LOAD SCENARIO

On the controllable load scenario, the boiler serves as a controllable load. Figure 5.5 illustrate the priority order of the boiler and Generator. When the wind produces low energy, the boiler reduces the active power demand. However, if the loads require more energy, the Generator start to supply the electricity demand as their priority from Generator 1 as the main generator, and Generator 3 and Generator 6 respectively.

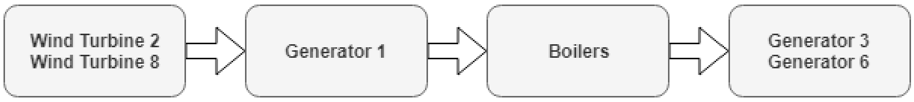

Figure 5.5: The priority order of Generator in controllable load case scenario in Winter season

GENERATOR FREQUENCY AND BUS VOLTAGE

Figure 5.6 shows the frequency of the generator and the bus voltage in the controllable load scenario. As can be seen in the figure, the generator frequency remains almost constant. The shape of the curve is almost similar to the fixed load scenario. High-frequency peak happened only at the first initiation. The maximum frequency reaches 60.38Hz, around 0.57% larger than the initial frequency while the frequency nadir or the smallest frequency is 59.86Hz. Meanwhile, the bus voltage remain stable at 1.06 p.u.

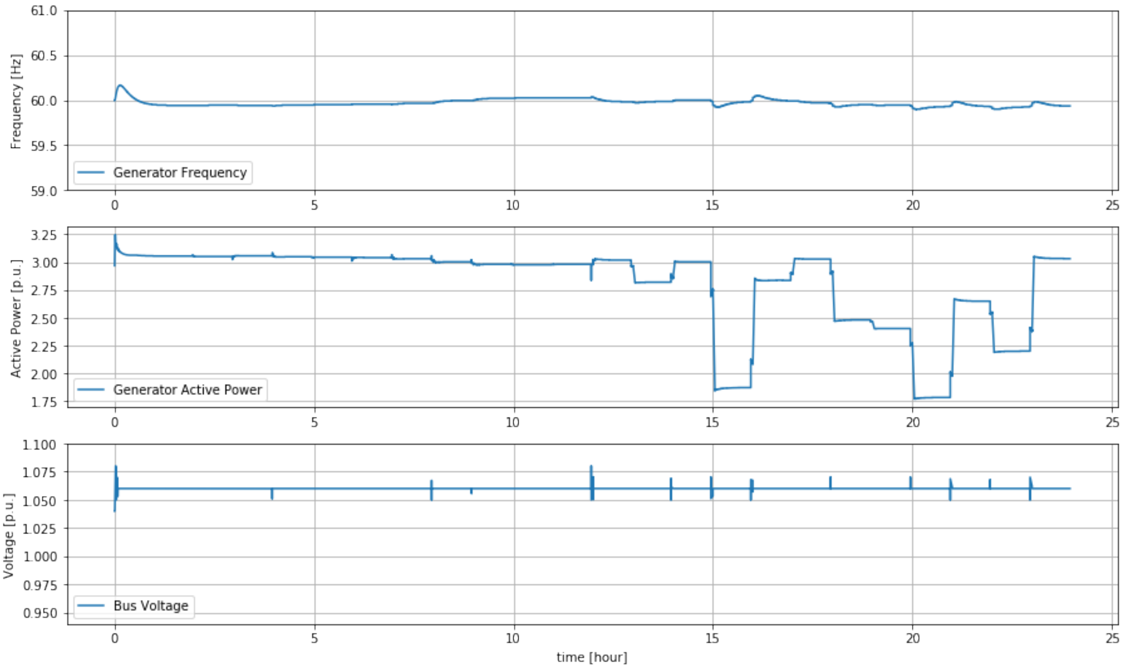

Figure 5.6: Generator Frequency and bus Voltage in Controllable Load Scenario during Winter season

ACTIVE POWER CURVES

Figure 5.7 illustrates the active power curves of all generators, wind turbine, loads and boilers. From 00.00 to 12.00 wind production is low. Therefore, the boilers reduce their demands and only require up to 80% of their capacity. The total electricity demand decreases around 8.65%. In the afternoon, when wind turbines start to generate electricity more than the electricity demand, the excess power is dispatched to the boiler. However, still, if the wind energy production is lower than the electricity demand, the boiler decrease their energy demand. As can be seen in the figure, the active power of the boilers are different. This difference in value corresponds to the maximum capacity of the boiler. The priority start from the boiler with low capacity to the boiler with larger capacity.

BOILER PERFORMANCE

Figure 5.8 shows the active power of the boiler and the fluid temperature of the boiler. As can be seen in the figure, the fluid temperature of the boiler corresponds to the active power of the boiler and follow Equation

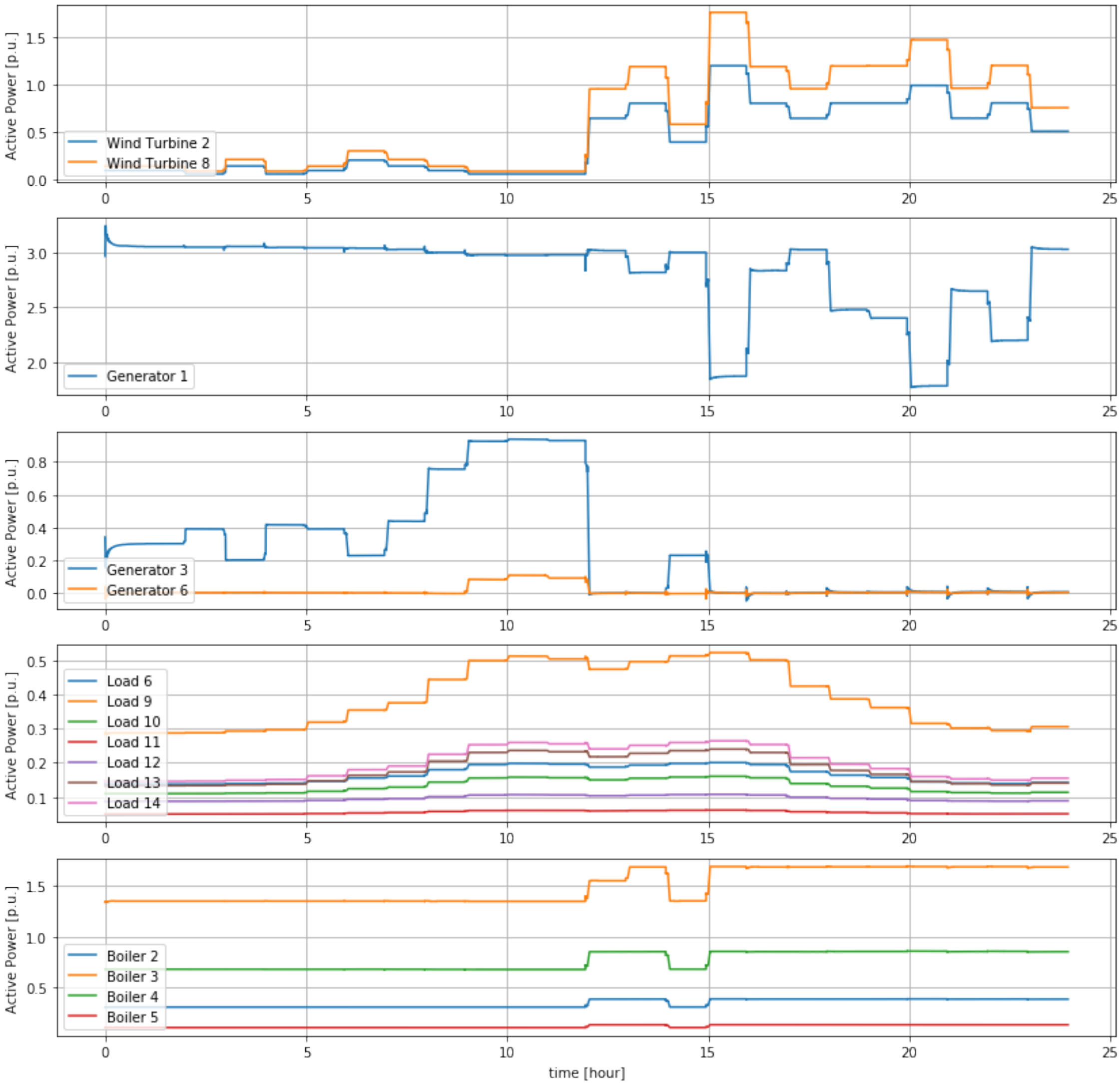

Figure 5.7: The active power of all Generators, Wind turbines, loads and the boilers in controllable load scenario during Winter season

3.2. When the boiler power decrease, the fluid temperature is also reduced. On the other hand, when the boiler power is increased, the energy also increases and corresponds to their active power. The lowest boiler temperature is 353.36K while the maximum temperature is 369K. The value is within range of permissible space heating boiler, around 80°C to 100°C[8].

5.3.1. FIXED AND CONTROLLABLE LOAD COMPARISON ANALYSIS

Since the algorithm of the controllable and fixed load is different, the result is also different, especially in the boilers. Figure 5.9 shows the active power curves. Since scenario adopts similar wind profile in winter, the electricity produced by the wind turbine for both scenarios is also similar. However, the active power curves of the generator are different.

In the fixed load scenario, the active power of the boiler remains constant while in controllable load scenario the active power of boiler varies from 80% to 100% of its capacity. In total, the controllable scenario saves 12.38% of electricity consumption during low energy production.

The output power of Generator 1 is similar for both scenarios. There are only small different output power of generator 1. However, significant differences can be spotted in the Generator 3 and Generator 6. Since both

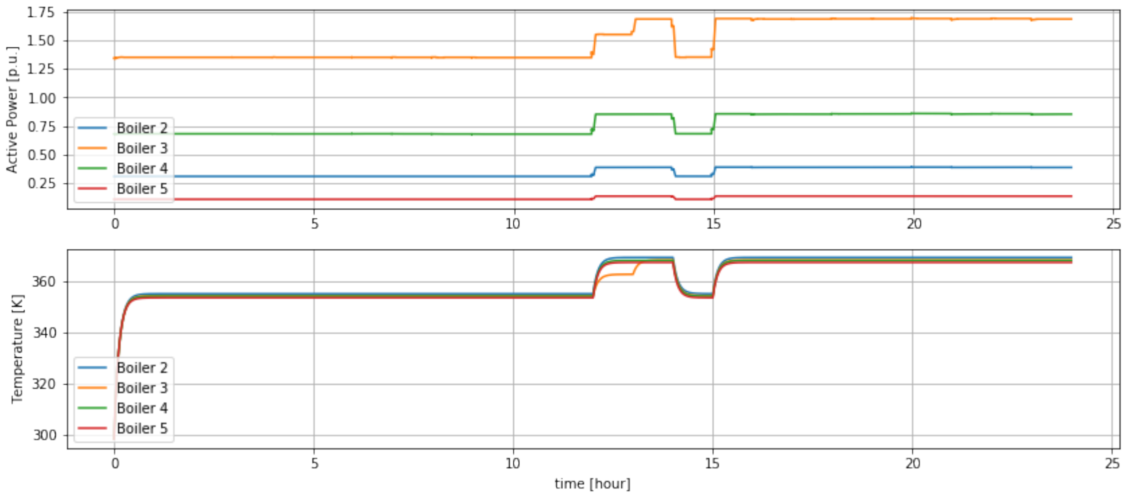

Figure 5.8: The active power and fluid temperature of the boiler in controllable case scenario during Winter season

generators serve as the backup generator and only generate electricity while the electricity generated by the main generator and wind turbine is less than the electricity demand. As can be seen in the figure, in the controllable load scenario, the backup generators generate less electricity compared to the fixed load scenario all the time. In total, in controllable case scenario, the backup generator generate only 671MWh, 54.65% less electricity compared to the fixed load scenario which reach 1480MWh. This significant number is important since it will effectively reduce the fuel cost and the carbon emission.

In the total of energy generation, the flexibility of controllable load capable of reducing energy production around 11.02%. Even though it is a small number, it is a significant number regarding energy saving, especially in Industrial area since most of the daily energy consumption of a single industrial area is in GWh or TWh scale. This number will reduce a large amount of energy generation cost.

Moreover, it is also favorable in terms of environmental sustainability since the generator is mostly fueled by fossil fuel. Therefore, not only reduce the operational cost, but the energy saving also reduce the environmental cost caused by the CO_2 emission.

Furthermore, this number can also be increased. There is two solution to increase energy saving. Those are,

- Increase the thermal storage capacity

  Currently, the boiler that is used in this project is accounted for 40% from the total energy demand. If the number of thermal storage and its flexibility factor is increased, it will increase the energy saving.

- Increase the number of renewable energy sources

  In this project, the electricity is mainly generated by a gas-fueled power plant. The wind turbine only contributes around 28% of the total energy demand. If the wind energy capacity is increased, the variable cost to generate a gas-powered power plant will decrease. Moreover, it is also possible to expand the system with other forms of renewable energy sources such as PV, or biomass power plant.

5.4. SUMMER CASE SCENARIO

Figure 5.10 shows the active power and fluid temperature of the boiler in fixed and controllable load scenario during Summer season. The wind energy production is low in the morning, therefore, the generators are turned on and produce electricity to satisfy the electricity demand. However, as the wind production increase steadily around 5.00, the generator start to decrease the electricity production and reach its lowest production when wind turbine reach its peak at 17.00. However, in the evening, as the wind energy production decrease drastically, the generators start to operate to satisfy the elctricity demand.

As can be seen in the figure, the presence of a boiler as a controllable loads give significant difference to the energy production and consumption. In total, the controllable load scenario saves 12.39% of energy consumption during low energy production. As the back up generator, Generator 3 and 6 produce much less electricity, and even generator 6 does not operate at all. It occurs since when wind production is low, the electricity demand also not that much and when the electricity demand getting higher, the wind energy reach its peak production, and the electricity production can be handled by the remaining generators. The back up generator produce 63.79% less electricity compared to the fixed load scenario. This significant number is important since it will significantly reduce the fuel cost and the carbon emission.

5.4.1. SUMMER AND WINTER COMPARISON ANALYSIS

The parameter for wind power ratio for winter and summer are different. Therefore, the effect of wind power ratio will be observed in this section. Figure 5.11 shows the active power curves of the generators, Wind turbine, Loads, and boilers. As can be seen in the figure, the wind power generated is different in both seasons. In the summer, wind power starts to generate abundant electricity from around 8.00, four hours earlier compared to the winter period. However, in the evening, the wind energy production decreases continuously. In contrast, during winter, the wind turbine still continues to generate electricity in the evening. Moreover, the total energy generated by the wind turbine in the winter is 30.68% larger compared to the summer period.

Since the optimization algorithm follows the wind energy profile, the electricity generated by the generator and saved by the boilers are also different in winter and summer. In the summer, since the electricity generated by the wind turbine start earlier, the reduction of generator power and the boilers are also starting earlier. However, as the wind power started to decrease in the evening, the boilers power are also reduced, and the generator starts to supply the electricity demand.

However, the total energy production by the generator in the summer season is only 4.08% less compared to the winter period. Even with much lower wind energy production, the difference in generator's electricity production is not that much. It shows that the controllable load gives significant energy saving contribution. This number can also be increased by utilization of PV as renewable energy sources. In the summer, there is abundant sunlight. Therefore, the electricity generated by PV will reduce much more variable cost from a fossil-fueled generator and more environmentally friendly.

5.5. CONCLUSION

A co-simulation of Network model, boiler model, and Optimal Power Flow is performed based on the literature study, and the methodology explained in the previous chapter. The co-simulation scheme performs well as shown by the stability of the network element. Energy efficiency is critical in the industrial area since it will reduce the operational and environmental cost. The simulation shows the significant impact of the boiler as controllable loads which effectively reduce energy consumption. Moreover, seasonal variation result in a different amount of energy saving as winter period has more energy saving compared to the summer period. The amount of energy saving can be increased by increasing the number and flexibility factor of the thermal load.

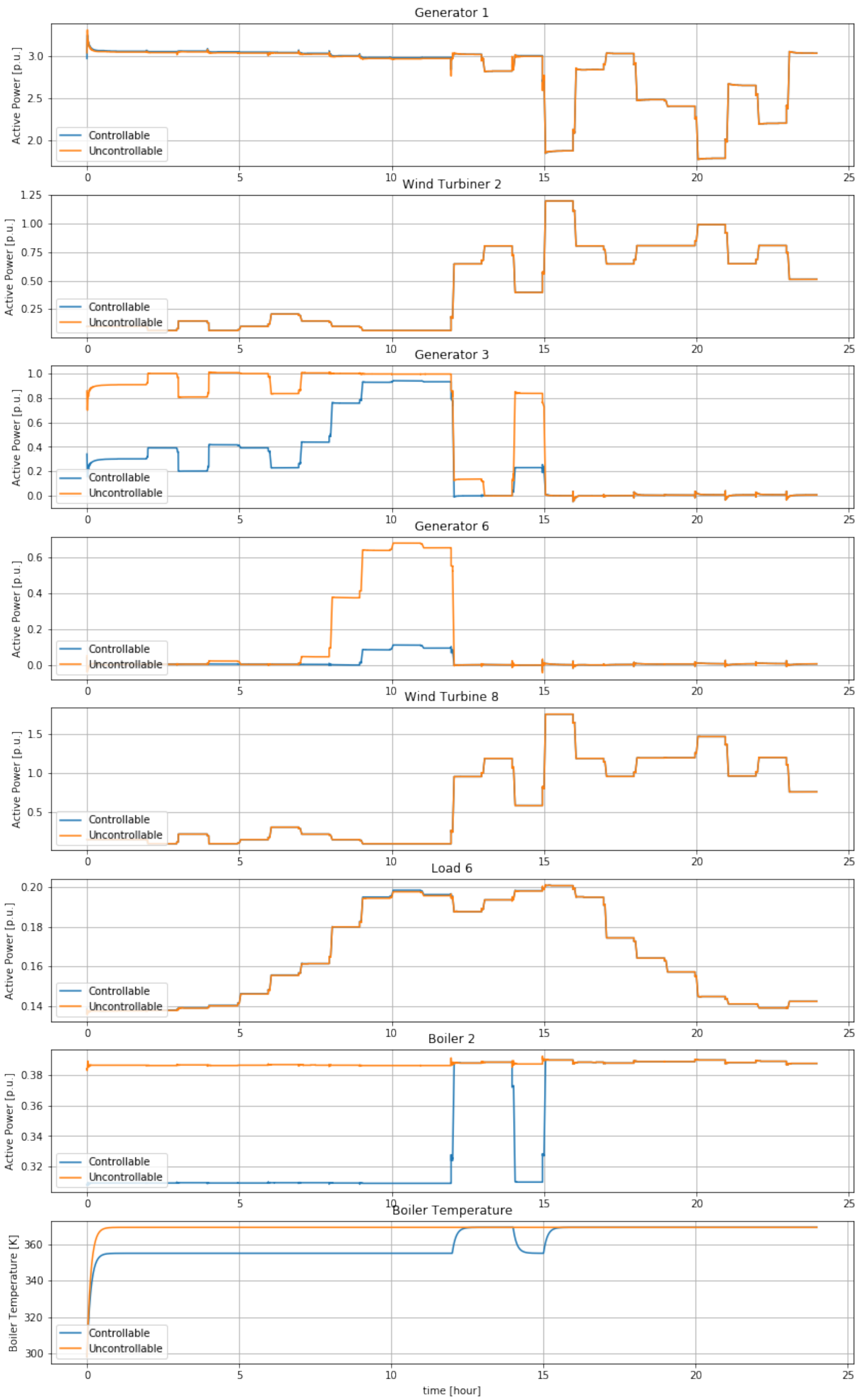

Figure 5.9: The active power and fluid temperature of the boiler in fixed and controllable load scenario during Winter season

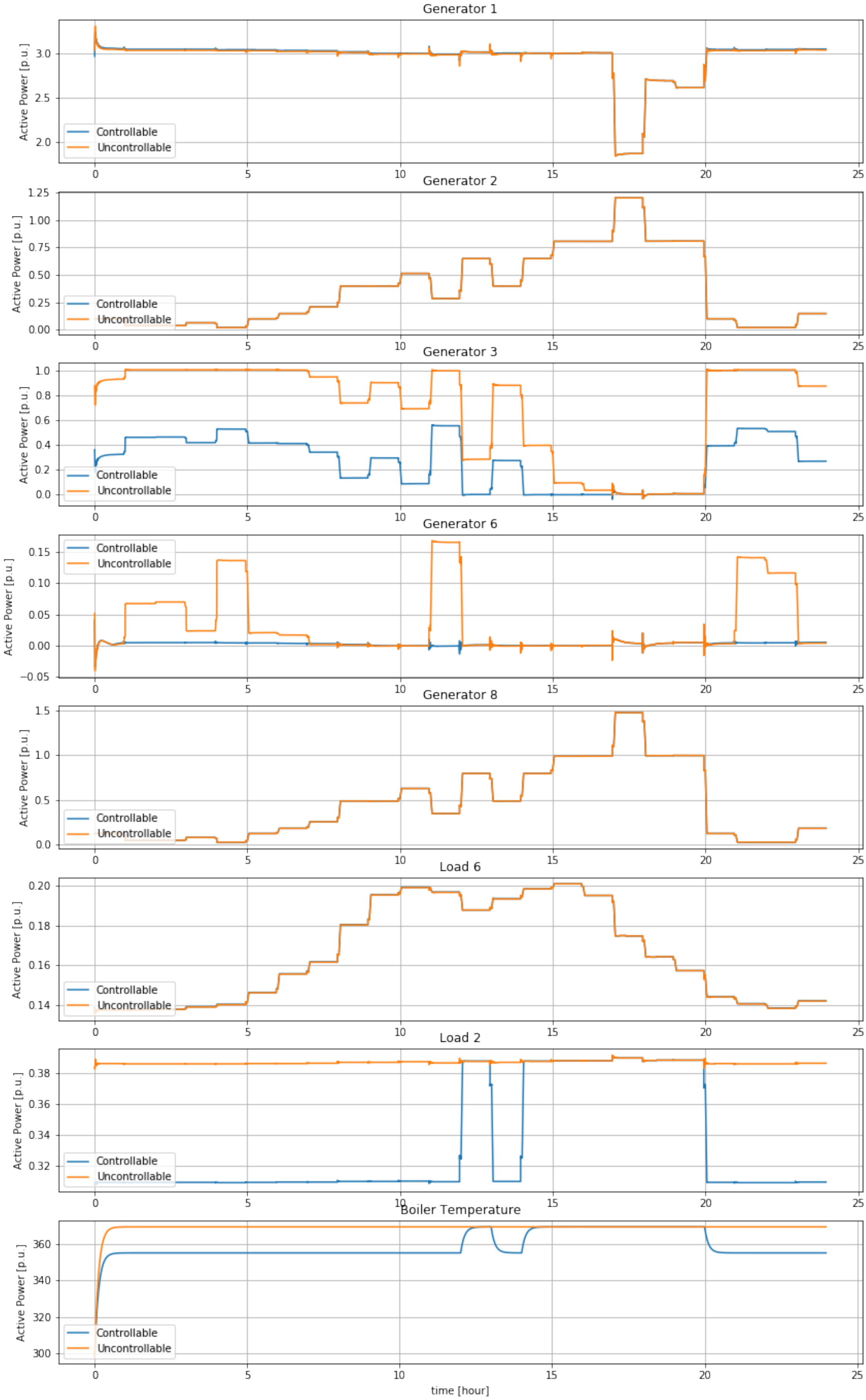

Figure 5.10: The active power and fluid temperature of the boiler in fixed and controllable load scenario during Summer season

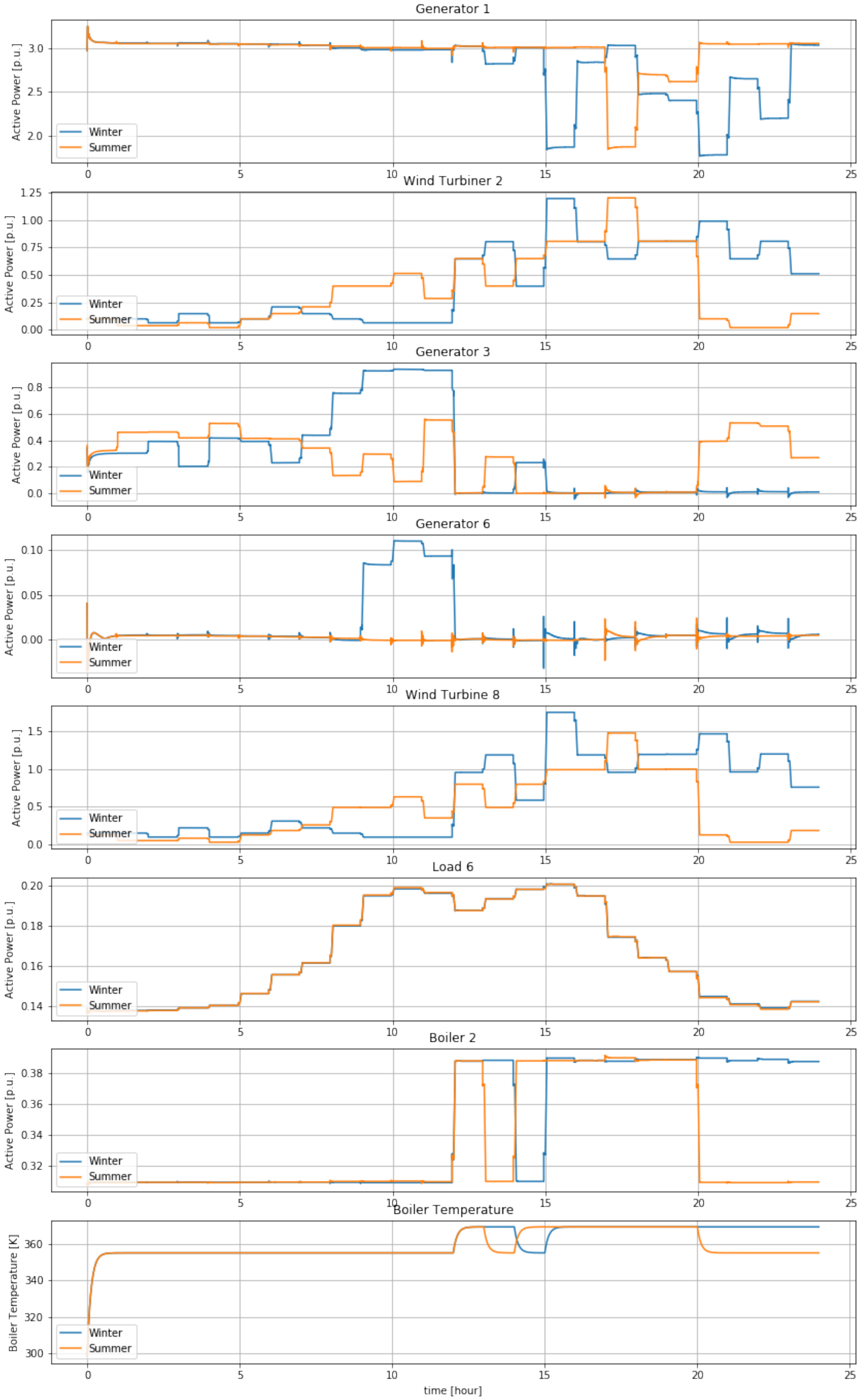

Figure 5.11: The active power and fluid temperature of the boiler in winter and summer period

6

CONCLUSION

This project focuses on designing an industrial microgrid and perform a co-simulation of multi-domain model to represent the elements of an industrial microgrid. Industrial microgrid network is represented by the IEEE 14 bus system with a combination of the various form of power generators and loads. To understand the effect of the flexibility of a boiler as a controllable load, different seasonal input is implemented. In this chapter, the conclusion and research contribution of the project is described. Moreover, several recommendations are made for future study.

6.1. CONCLUSION

There are several key points that are obtained in this project.

- The utilization of Functional Mock-up Interface give the advantage to perform a co-simulation of different model. The network model, boiler model, and the optimal power flow can be simulated together at the same time.
- The utilization of boilers as the controllable load give more energy saving compared as a fixed load. There are around 12% less electricity consumed when the boiler can be controlled.
- The energy saving in the summer is slightly lower compared to the winter. However, this number can be increased by increasing the capacity of controllable loads and the utilization of other forms of renewable energy sources, such as PV and biomass.

6.2. ANSWER TO RESEARCH QUESTION

Several research questions that were formulated previously in this project are answered by the end of this project. The answer of research questions are,

1. **What methodology that can be used to simulate multiple components from different energy domains? Can the power flow models and continuous time models be effectively combined?**

   The utilization of FMI platform grants the flexibility to integrate and simulate the various model. A master program was built in python utilizing FMPy module to perform co-simulation and data exchange between models. The network and boiler model that was built in OpenModelica is exported to FMU. Furthermore, the master code simulates both models in combination with optimal power flow. Optimal Power Flow as a time-discrete simulation is performed first and the results of optimal power flow are transferred to the corresponding models to perform the continuous simulation.

2. **What impact do seasonal variations in wind speed have on network? What are the impacts of boiler as a controllable loads?**

   The presence of the boiler as a controllable loads reduce the a noticeable amount of energy consumption. Due to the different wind energy generation, the energy efficiency is slightly higher in the winter period. However, this number can be increased by increasing the capacity of the controlled load and utilization of other forms of renewable energy sources, such as PV and biomass.

6.3. RESEARCH CONTRIBUTION

There are three main research contribution of this project.

1. Multi-energy co-simulation that involves electrical and thermal energy domains. The utilization of FMI standard offer a solution to perform multi-energy co-simulation of models from various energy domains.
2. Interfacing Optimal Power Flow and continuous time domain models. The master code manage the data exchange and simulation time line between the optimal power flow and the network and boiler models.
3. A master code that accommodates the co-simulation and data exchange of various model which can be easily integrated to different models for future works.

6.4. RECOMMENDATION AND FUTURE WORKS

Despite several parameter assumption and simplifications were used in this project, there are several elements to consider for future studies.

- The optimization algorithm can be self-developed in order to accommodate more network detail.
- the network component (wind turbine, generator, and boiler) can be developed in more detail component.
- The inclusion of more microgrid component such as PV, electric vehicle charger, or fuel cell and hydrogen storage is possible due to the flexibility of the FMI platform.

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Appendices

A

NETWORK PARAMETERS

A.1. IEEE 14 BUS PARAMETER

Table A.1: Line Parameters [33]

Line	From Bus	To Bus	R(pu)	X(pu)	B(pu)	G(pu)
Line 1	1	2	0.01938	0.05917	0.0528	0
Line 2	1	5	0.05403	0.22304	0.0492	0
Line 3	2	3	0.04699	0.19797	0.0438	0
Line 4	2	4	0.05811	0.17632	0.034	0
Line 5	2	5	0.05695	0.17388	0.0346	0
Line 6	3	4	0.06701	0.17103	0.0128	0
Line 7	4	5	0.01335	0.04211	0	0
Line 8	4	7	0	0.20912	0	0
Line 9	4	9	0	0.55618	0	0
Line 10	5	6	0	0.25202	0	0
Line 11	6	11	0.09498	0.1989	0	0
Line 12	7	8	0.12291	0.25581	0	0
Line 13	7	9	0.06615	0.13027	0	0
Line 14	9	10	0	0.17615	0	0
Line 15	9	14	0	0.11001	0	0
Line 16	10	11	0.03181	0.0845	0	0
Line 17	12	13	0.12711	0.27038	0	0
Line 18	13	14	0.08205	0.19207	0	0

Table A.2: Transformer Parameters [33]

Name	**LV Bus**	**HV Bus**	**Ratio**	**R(pu)**	**X(pu)**
Trafo 1	6	5	0.932	0	0.2502
Trafo 2	9	4	0.969	0	0.55618
Trafo 3	7	4	0.978	0	0.20912
Trafo 4	7	8	-	0	0.17615

Table A.3: Generator Parameters [33]

Generator	Generator 1	Generator 3	Generator 6
Bus Location	1	3	6
P_0	300	100	100
Q_0	40	40	40
Sn	615	60	25
Td10	7.4	6.1	4.75
Tq10	0.033	0.3	1.5
V_0	1.06	1.01	1.07
V_b	69	69	13.8
Vn	69	69	13.8
angle_0		-14.387	-12.925
ra	0	0.0031	0.0041
xd	0.8979	1.05	1.25
xd1	0.2998	0.1850	0.232
xq	0.646	0.98	1.22
xq1	0.4	0.36	0.715
D	2	2	2

Table A.4: Bus Data [33]

Bus Number	Pd (MW)	Qd (MVAr)	V0(pu)	Angle(deg)	Vmax(pu)	Vmin(pu)
1	0	0	1.06	0	1.06	0.94
2	39.06	22.86	1.045	-4.98	1.06	0.94
3	169.56	34.2	1.01	-12.72	1.06	0.94
4	86.04	-7.02	1.019	-10.33	1.06	0.94
5	13.68	2.88	1.02	-8.78	1.06	0.94
6	20.16	13.5	1.07	-14.22	1.06	0.94
7	0	0	1.062	-13.37	1.06	0.94
8	0	0	1.09	-13.36	1.06	0.94
9	53.1	29.88	1.056	-14.94	1.06	0.94
10	16.2	10.44	1.051	-15.1	1.06	0.94
11	6.3	3.24	1.057	-14.79	1.06	0.94
12	10.98	2.88	1.055	-15.07	1.06	0.94
13	24.3	10.44	1.05	-15.16	1.06	0.94
14	26.82	9	1.036	-16.04	1.06	0.94