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Modeling Of The Biomass Power Generation And Techno-Economic Analysis

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MODELING OF THE BIOMASS POWER GENERATION AND TECHNO-ECONOMIC ANALYSIS

By

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Biomass is one of the renewable energy sources being used widely for power generation. This research work includes developing a comprehensive model for a biomass based power generation system as well as analyzing the technical, economical, and environmental impacts. The research objectives include modeling of the system, stability studies, and sensitivity analysis using MATLAB/Simulink. A mathematical model for the gas turbine has been developed and successfully interconnected with the distribution network. Transient stability of the power system has been carried out for four bus and six bus test case systems. Additionally, the sensitivity of the system to the changes of gas turbine parameters has been investigated under balanced and unbalanced fault scenarios. The economical and environmental impacts of the biomass have been analyzed using HOMER software developed by the National Renewable Energy Laboratory (NREL).

DEDICATION

I would like to dedicate this thesis to my husband, parents, and brothers who have been my continual support.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

There have been considerable technological changes in the generation of electric power over the past few decades. As fossil fuels are not renewable and have harmful effects on the environment, the focus has been transferred to the renewable and sustainable energy sources. Biomass is one of the widely used renewable energy source (RES) because of its certain advantages. In 2007, 7% of the United States' energy was generated from the renewable energy sources of which 53% is produced by the biomass [1]. The main difference between biomass and other RES is its storability. Unlike solar and wind, biomass can produce a near constant, non-fluctuating supply of electricity. Both power and biofuels can be produced by using the biomass. Energy from biomass can be extracted through various ways like solid fuel combustion, gasification, digestion, and fermentation [2]. After the extracting stage, a gas turbine will convert the energy from the gas to the mechanical energy.

Developing the comprehensive model for the biomass generation includes building the mathematical model of a gasifier, a gas turbine, and connecting these components to the generator. The transient stability studies include the response of the biomass generation system connected with power distribution system to severe disturbances. The economic and environmental analysis of the biomass products includes the overall cost and emissions with different biomass resources over the project's life time. This chapter explains in detail the motivation and the objectives of the research. It also describes how the goals have been achieved by performing several simulations. The contributions of the work as well as the organization of the thesis are also given.

1.2 Motivation for Research work

Impact of distributed generator (DG) on electric grid needs to be analyzed before interconnecting to distribution system. Biomass based generation is one of the commonly used DG and quantifying technical impacts and benefits of Biomass Generation will help utilities to plan ahead for necessary upgrade in distribution system. Analyzing the impact requires comprehensive modeling of Biomass Generation system. Modeling efforts require expertise in different fields of engineering. Developing a biomass generation model includes the modeling of a gasifier, modeling of a gas turbine and designing and studying an electrical generator. Developed model can be used for stability analysis, transient simulation, protection studies and fault analysis. Analyzing the economic impacts of various types of biomass will help to come up with most economic available option for given location and size of Biomass Generation. Economic analysis will further help to decide proper size of generation to be connected to grid for most efficient operation. Assessing environmental impact will further help in quantifying benefits and incentive for distributed generation to avoid use of fossil fuels.

1.3 Research work Contributions

Modeling of the biomass generation involves many challenges as it comprises of chemical and biological reactions. This being an interdisciplinary topic, not much research and development has been reported in literature. This research work has contributed towards the development of the biomass generation model including all parts from the biomass input to the consumer loads in one system. The work includes modeling of the components and interconnecting them together as well as studying the transient stability using the stability indicators. The research also aims to find the economical and environmental impact of using the biomass resources to generate the power.

1.4 Objectives of the Research

The objectives of the research have been divided into two categories: the first is modeling and the second is analysis. The modeling part of the work includes developing a model for the turbine and a power system. The analysis part includes the stability and sensitivity studies as well as economic and environmental impacts. The objectives and the steps followed to achieve the goals are as follows.

Modeling:

- Comprehensive modeling of the gas turbine in MATLAB/Simulink.
- Modeling of the power system test cases and other components of biomass generation system.

Stability and Sensitivity Analysis:

- Testing the gas turbine with a small power system (single machine infinite bus system) using SimPowerSystem tool box available in MATLAB/Simulink.
- Interconnecting the validated tested gas turbine model with the four bus system and observing the system response.
- Applying balanced and unbalanced faults and studying the transient stability.
- Sensitive analysis on stability by varying the parameters of the gas turbine.
- Studying the stability analysis for the 6 bus system including asynchronous generator and observing the impact of the induction machine.

Economic and Environmental Analysis:

- Modeling a simple biomass and diesel based power systems in HOMER software.
- Collecting the data on the installation and operating costs as well as the carbon emissions of different biomass fuels.
- Calculating the economics of the different biomass fuels and comparing them with the conventional fuel (diesel).
- Estimating the environmental impact (Carbon dioxide emissions) of different biomass fuels and comparing the results with the diesel fuel.

1.5 Thesis Organization

This thesis has been organized in seven chapters as follows.

Chapter 2 gives the background knowledge of the renewable energy sources, biomass energy, and biomass power plants. It also gives the information about the simulation tools used and the test case systems. Chapter 3 gives the details of the gas turbine including the related work in the literature for the gas turbine. Chapter 4 explains the gasification process and types of the gasifiers. It also explains the economics of the gasifiers based on the amount of power that is generated using the gasification process. Chapter 5 presents all the results for the gas turbine and the integrated power system. It gives the details of stability analysis and the sensitivity. Chapter 6 gives the detailed view of the power system modeling in HOMER, data collection for the different inputs, economic analysis, and the environmental impacts. Results obtained from economic and environmental analysis are presented in this chapter. Chapter 7 gives the conclusions and the future work of the research.

1.6 Summary

Biomass based generation involves converting raw fuel to electricity output and needs to be studied to investigate the impact of biomass based generation on the electric grid. This chapter explained the importance of developing the biomass generation model. The research work done for modeling and the analysis of the biomass generation are described. The objectives of the research are summarized in this chapter and the approach followed to achieve the objectives is explained.

1.7 References

[1] Department of Energy (DOE) renewable energy: http://tonto.eia.doe.gov/energy_in_brief/renewable_energy.cfm

[2] Biomass for Electricity generation, DOE report 2002: www.eia.doe.gov/oiaf/analysispaper/**biomass**/pdf/**biomass**.pdf

CHAPTER 2

BACKGROUND

2.1 Introduction

This chapter gives background knowledge of renewable energy sources and biomass. The renewable energy sources are becoming popular due to their environment friendly nature. This chapter explains different renewable energy sources, their advantages, and their role in present day power generation. Biomass is one of the renewable energy sources that can be used to produce electricity. The types of the biomass and generating power using biomass are explained in detail here. In this research, the test case system has been modeled in MATLAB/Simulink to analyze the stability and sensitivity. HOMER software has been used to study economic feasibility of the biomass resources. This chapter also presents the details of these two software tools and the test case systems that are used for the analysis.

2.2 Renewable Energy Sources (RES)

Renewable energy sources are any sources of energy that can be utilized without depleting their reserves. RES include micro/mini hydro power, wind energy, geothermal, solar energy, and biomass. Hydro power uses the energy of the water flow to produce electricity. Turbines convert the hydraulic energy into mechanical energy and thereby electricity through a generator. Wind turbines use the energy from the wind to rotate turbine blades and produce mechanical power. Geothermal power uses the natural sources of heat inside the Earth to produce heat or electricity. Energy from the sun can be utilized to generate power with the use of different solar collectors. The stored energy in the organic matter (biomass) can be extracted in various ways to produce heat, biofuels, or power.

Why Renewable Sources?

Non renewable energy sources such as coal, natural gas, and oil are hazardous to the environment due to the emissions they produce. As these fuels are non renewable, one may run out of them in future. This led to the increased development of the renewable energy sources. The present technological advances in the renewable energy sources make them more cost-effective and efficient. The advantages of the RES are given below [1, 2].

- *i.* RES emit fewer emissions and thus protect the environment and public health.
- *ii.* RES are more secure than conventional fossil fuels as RES are not affected by geopolitical considerations.
- *iii.* Use of RES creates new competition which helps in restraining fossil fuel price increases and insulates the nation's economy from fossil fuel price spikes and supply shortages or disruptions.
- *iv.* Even small amounts of energy can make a significant difference in remote rural areas and hence higher costs are justifiable.
- *v.* Use of RES diversifies the options to generate power.

vi. Employing RES to produce electricity increases the job opportunities.

vii. Improving the standards of living.

RES in USA

Renewable energy plays an important role in the energy generation of the USA. Biomass is the world's third largest renewable fuel behind hydro and wind. The United States of America is generating approximately 7,000 MW of power from the biomass being in the first place throughout the world. It is estimated that by the year 2020, the world's power production from the biomass can reach 30,000 MW. Figure 2.1 shows the USA states which are rich in different biomass fuels. [3]

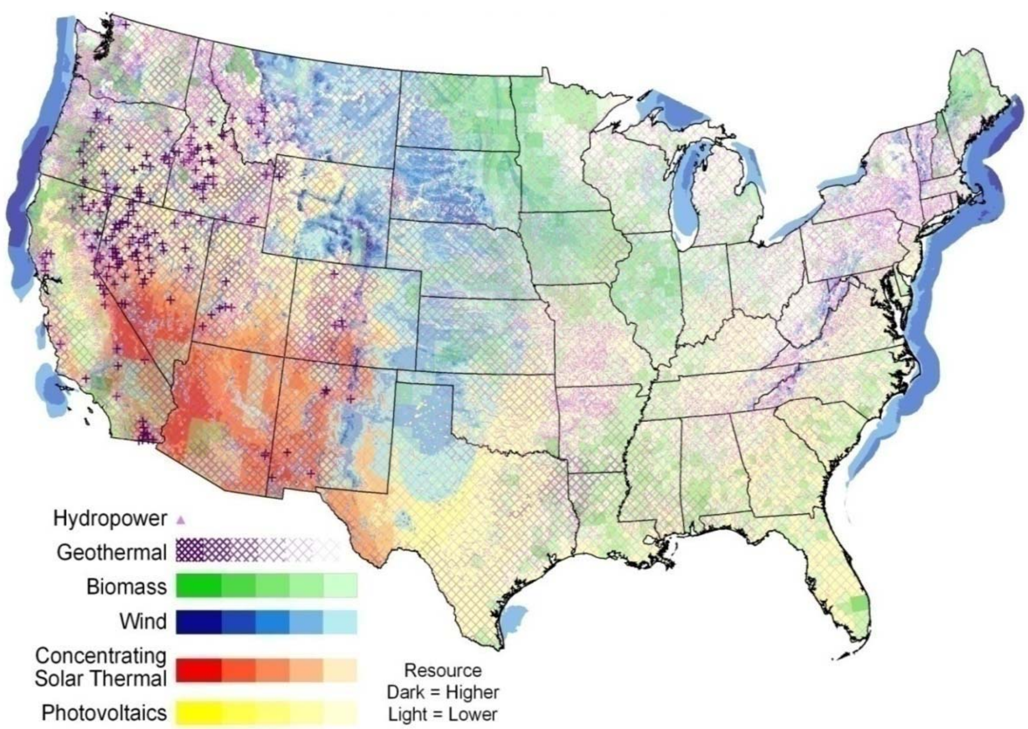


Figure 2.1 Different types of renewable energy sources throughout the nation [4]

Table 2.1 shows the amount of the power that is generated from different biomass fuels in the nation [4].

Table 2.1 Power generated from different renewable energy sources [4]

Resource	Solar PV/CSP)	Wind	Geothermal	Water Power	Biopower
Theoretical Potential	206,000 GW (PV) 11,100GW (CSP)	8,000 GW (onshore) 2,200 GW (offshore to 50 nm)	39 GW (conventional) 520 GW (EGS) 4 GW (co-produced)	140 GW	78 GW

According to reference [4], in the year 2007, 7% of the America's energy is produced by renewable energy out of which 53% is produced by biomass and followed by hydroelectric energy which is 36% (Figure 2.2)

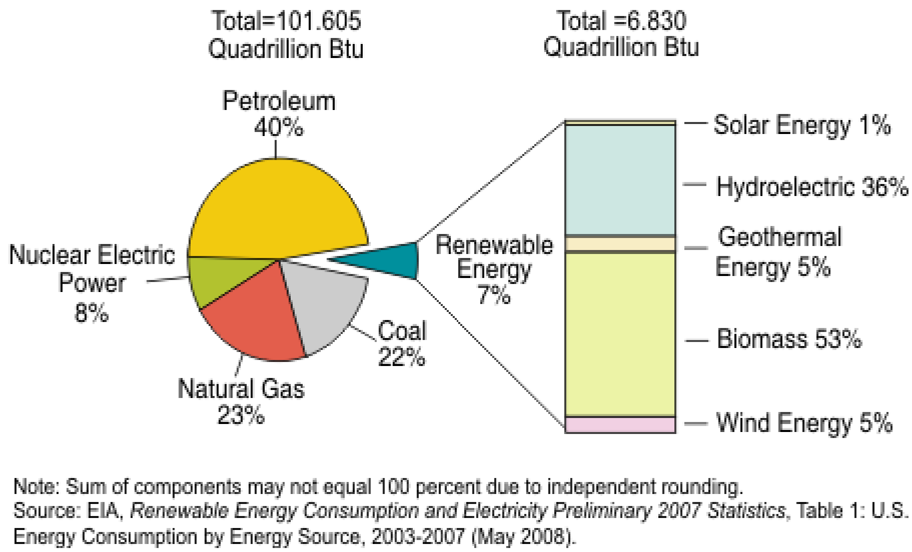


Figure 2.2 Energy released by different renewable sources 2007, USA. [4]

2.3 Biomass

Biomass is the form of the energy stored in any organic matter. Biomass is extensively used to produce biofuels. Due to the advantages of the RES, generating power from the biomass is becoming a challenge issue. Trees utilize the energy from the sun and carbon dioxide from the environment in the process of photosynthesis to produce carbohydrates. When plants die, the process of decay releases the energy stored in carbohydrates and discharges carbon dioxide back into the atmosphere. The reaction that converts biomass into glucose is given by equation 1.1.

$$6H_2O + 6CO2 \quad + \text{Radiant Energy} \rightarrow C_6H_{12}O_6 + 6O_2 \qquad (2.1)$$

(Water) (Carbon Dioxide) (Sunlight) (Glucose) (Oxygen)

When the biomass is burned, the chemical energy is released as heat and this heat can be used for home applications or can be converted into power. The biomass cycle is as shown in Figure 2.3.

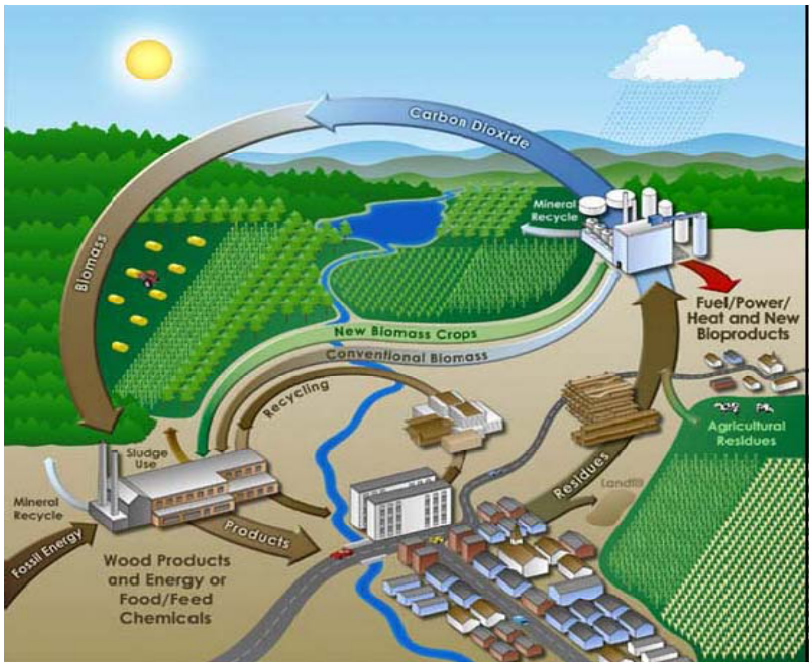


Figure 2.3 Biomass cycle [6]

2.3.1 Types of Biomass

Biomass resources include crops, wood, animal waste, landfill gases, and municipal waste [7].

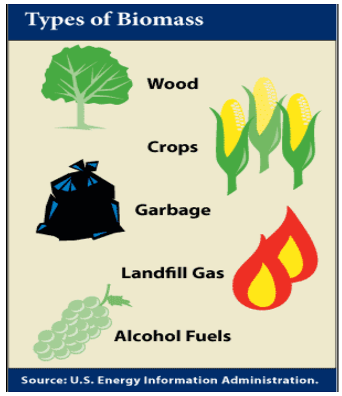


Figure 2.4 Types of biomass [7]

Wood and Crops

Biomass crops include the energy crops such as switchgrass, miscanthus, sweet sorghum, and bamboo; industrial crops such as kenaf, and fiber; agricultural crops such as corn, and vegetable oils; aquatic plants include seaweed, and micro flora. Burning the wood or waste after harvesting the plants produces heat or can be converted into electricity.

Garbage and Animal waste

Garbage includes the waste from the residential areas and industries such as paper waste, and wood waste. Animal waste such as poultry litter, and cow manure can be used in the process of digestion to generate either gases like methane or power. Human waste also can be used to produce energy.

Landfill gases and Alcoholic fuels

When solid waste or garbage are buried in the soil, bacteria eat this dead particles and convert them into landfill gases. Alcoholic fuels like methanol, ethanol, propanol, and butanol can be used as biofuels to run the drives or engines.

2.3.2 Extracting energy from Biomass

Energy from the biomass can be extracted through various ways such as solid fuel combustion, gasification, fermentation, digestion, and fermentation.

Solid Fuel Combustion

It is the simplest technology to transfer energy from the biomass. Biomass particles including agricultural wastes or wood are burned in the combustor to produce the steam. This steam is converted into mechanical energy through a steam turbine which in turn converted into the electricity through a generator. In this direct combustion process, large amounts of ash will be produced which affects the performance of the combustion chamber and reduces the efficiency, so only few types of biomass are used for this combustion process.

Gasification

Gasification is the most adopted technology to convert the raw biomass material into hot gases. Gasification converts the biomass into gases like CO, CO_2, nitrogen, oxygen, and methane. The combination of carbon monoxide and hydrogen is known as synthetic gas (also known as producer gas) which feeds the gas turbine to generate mechanical energy and thereby to produce electricity. Gasification has several advantages over direct combustion. First, the gasification process is easy and methane is a byproduct which can be again used to generate energy. Second, the producer gas which is the output of the gasifier consists of much less impurities and thus fewer pollutants will be released. Third, it is more efficient compared to solid fuel combustion. The gasification concept has been explained more in section 2.4.1. The gasification cycle is as shown in Figure 2.5.

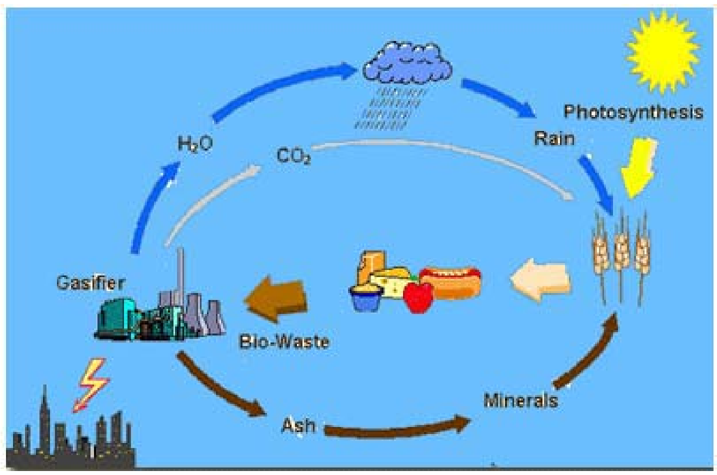


Figure 2.5   Gasification cycle [8]

Digestion

Digestion uses anaerobic bacteria to convert the animal waste into energy. These microorganisms live in the place where there is no air. Organic matter or animal waste can be filled in the tanks called digesters (shown in Figure 2.6) and feeding bacteria in it will produce gases which can be converted into energy.   This process is very efficient and two thirds of the fuel energy of the animal manure could be recovered in the form of manure, biogases, or electricity. The digestion cycle is as shown in Figure 2.6.

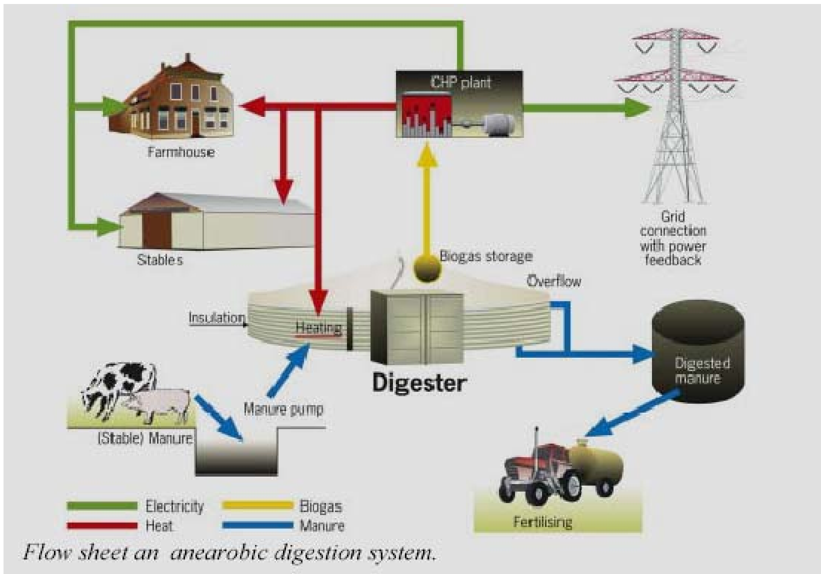


Figure 2.6 Digestion cycle [9]

Fermentation

Yeasts can be used to ferment the sugars of various plants into ethanol. Typical examples of fermentation products are ethanol, lactic acid, and hydrogen. The fermentation process produces more exotic compounds such as butyric acid and acetone. Fermentation cycle is shown in Figure 2.7.

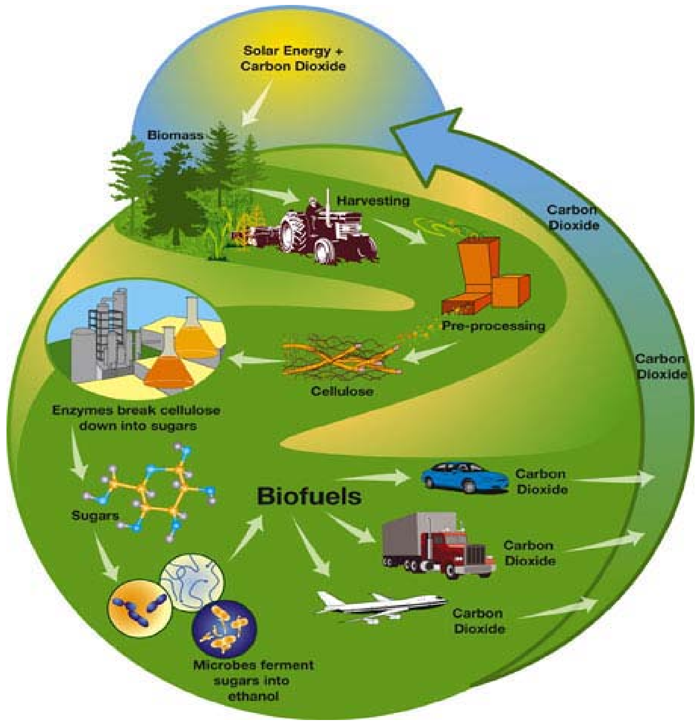


Figure 2.7 Fermentation cycle [10]

2.4 Biomass Power Plants

Biomass power plants include several components that convert the raw biomass into the electricity. This section explains different apparatus that are present in the plant and their operation. Though the components vary from one to the other, a general biomass power plant based on the gasification technology is presented here. Dried biomass is the input to the gasifier where synthetic gases are released and the gas turbine converts the energy from the gas to the mechanical energy which in turn converted into electrical energy with the help of generator. The details of the gasifier and gas turbine are presented in this section.

2.4.1. Components

2.4.1.1 Gasifier

A gasifier is the chamber where gasification takes place. Gasifiers are of different types: updraft, downdraft, cross draft, and fluidized bed gasifiers. A simple updraft gasifier is shown in Figure 2.8. In the gasification process, the matter flows in gasifier through different stages: combustion, reduction, and pyrolysis.

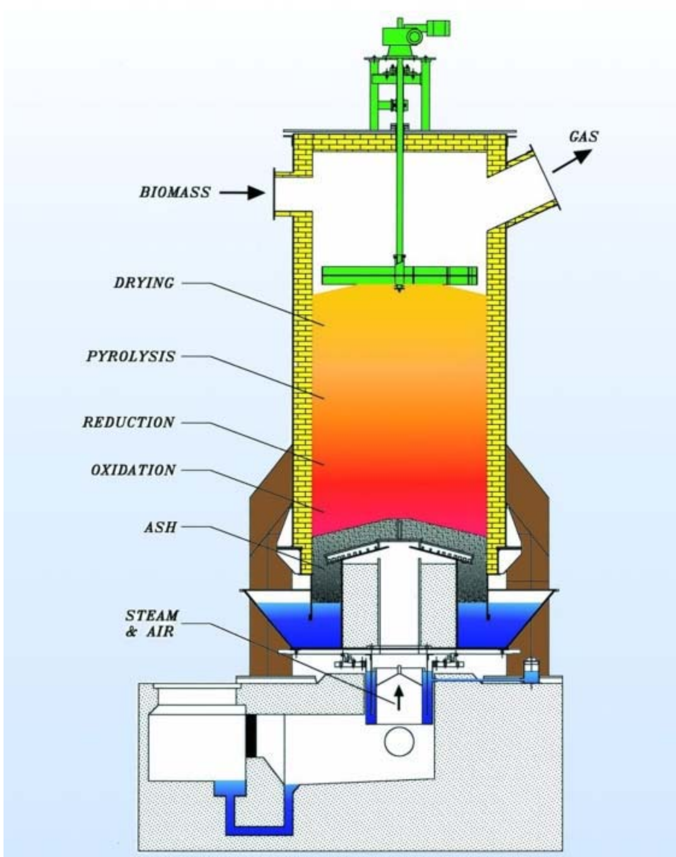


Figure 2.8 Updraft gasifier [11]

Pyrolysis: In the pyrolysis, the dried biomass is burned to produce volatile gases such as carbon monoxide, methane, and hydrogen at around 700ºC.

$$Biomass \xrightarrow{heated} CO_2 + H_2O + H_2 + CH_4 + charcoal \quad (2.2)$$

Combustion: Activated carbon reacts with water vapor and carbon dioxide to form combustible gases such as hydrogen and carbon oxide.

$$C+O_2 \rightarrow CO_2 + heat. \quad (2.3)$$

Reduction: The main reaction here is CO being formed from CO_2 molecules and charcoal.

$$C+CO_2 \rightarrow 2CO \quad (2.4)$$

The combination of carbon monoxide and hydrogen is known as the producer gas which is the final output of the gasifier and input to the gas turbine.

2.4.1.2 Gas Turbine

Gas turbines operate on the Brayton cycle. It consists of a compressor, a combustor, and a turbine. The compressor compresses the air and along with the fuel, and it enters into the combustor where the fuel gets burned and high temperature gases are released. These gases expand in the turbine by releasing mechanical energy. The mechanical energy feeds the generator to produce electricity. More details of the gas turbine are presented in chapter 5.

2.4.1.3. Generator

The final stage of the producing electricity is the generator. The mechanical power from the turbine is converted into electrical energy. The generator can be either synchronous or induction type.

2.4.2 Types of Generation

Co-Generation

Cogeneration, also known as Combined Heating and Power (CHP), is an energy efficient and environmental friendly method. Both electricity and heat can be simultaneously produced by using this technique. The fuels used in cogeneration include natural gas, heating oil, propane, and biomass. When a fuel, such as coal or natural gas, is burned only about 33% of the energy released can be converted into electricity with present day technology. The remaining 67% of energy released is wasted as heat unless captured in another way. With the installation of cogeneration, large proportion of the waste heat can be captured and used as steam or hot water. As a result, cogeneration can utilize 75% or more of the fuel's energy. This is significantly higher than the efficiency of conventional systems generating electricity and heat separately. Hence, cogeneration produces much lower emissions for each unit of energy produced. The other important advantage of CHP is economy compared to individual power and heat generations [12].

Distributed Generation

Distributed Generation is the small scale power generation (usually ranges from 10kW to 50 MW [13]) at or near the load centers. By installing smaller, more fuel-flexible systems near the energy consumer, transmission and distribution power losses can be reduced, thus it is more reliable and economic to install DGs. Distributed generation is especially beneficial when RES are used, it is a great opportunity to exploit the renewable energies around the world and expanding the energy options. The costs can be reduced and reliability can be improved through the installation of DG. The use of renewables as DG, provides clean and environmental friendly energy which has reduced emissions. The employment of DGs in the network need new power flow techniques and protection strategies as DGs bring many changes in the network [13].

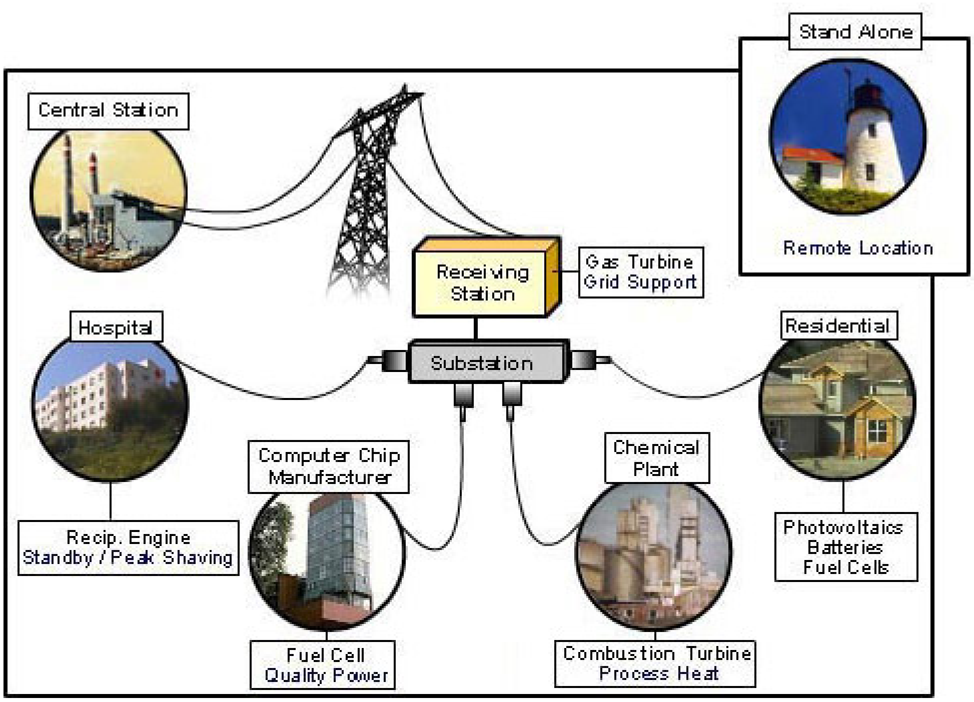


Figure 2.9 Distributed generation [14]

2.5 Previous and Current Research on RES

Many research efforts are being conducted in the area of power systems related to the modeling and analysis of the renewable energy sources including hydro, photovoltaic cells, wind, biomass, and hybrid power systems. The modeling and simulation of different renewable energy sources have been carried out from several years. The transient and small signal stability studies and modeling of the hybrid power plants as well as the fuzzy and neurofuzzy approach have also been proposed in the past. Distribution generation using renewable energy sources and the new technologies to add DG in the network have been recommended.

Much of the research has been done on the hydro power plants in the past. The modeling and simulation of different hydro turbine models, hydro power plants, and the power system studies including stability are presented in [15 - 17]. Different modeling techniques including generic hydro power plants and advanced technologies including the fuzzy and neural approaches to model and to study the dynamics of the hydro power plants are presented in [18 - 21]. The authors also examined the accuracy of the models by comparing different techniques. Different optimization techniques for the hydro power plants included particle swalm optimization and neural approach are discussed in [22 - 26]. Research related to the development of the wind turbines, wind integration to the power system, validation of the wind power systems, interconnecting the wind turbine to an induction machine, power electronic interfaces for the wind generation, and stability studies of the wind generation, are presented in [27 - 32]. Research work related to the area of photovoltaic cells is presented in [33 - 36]. The authors describe the modeling of the PV cells, interconnecting the models with the grid, and the advanced technologies including fuzzy controller. The optimization of the PV cells using fuzzy logic controller, HOMER are presented in [37 - 39].

As biomass is an interdisciplinary area, not much research has been done related to the biomass generation compared to other renewable energy sources. The modeling of the gas turbine is presented in [40 - 43]. Validating the developed gas turbines using the industrial data is presented in [44 - 47]. Different gas turbine models and the comparison of them with the power system studies are presented in [48]. Research work related to the optimization of the hybrid plants which also includes the biomass generator as one of the sources are presented in [49 - 51]. Optimal location of the biomass generation plants is presented in [52]. This research aims on modeling of the gasification based biomass generation, and studying the technical impacts including stability, sensitivity analysis as well as analyzing the economical and environmental impacts.

2.6 Simulation Tools Used

Modeling the gas turbine, integrating it with the distribution network, and analyzing the stability as well as sensitivity have been done using MATLAB/Simulink (commercial software) [53]. Modeling of the power system for economic and environmental studies has been performed using HOMER (freely available) software [54]. This section provides a brief discussion about these two software program.

2.6.1 MATLAB/Simulink

MATLAB/Simulink R2007a has been used in this research. Simulink is simulation tool to model and analyze the dynamic systems. Simulink has extensive built in models in its library which enables the users to easily model and simulate the systems. Powerful GUI in the Simulink allows the users to simulate the systems by using different solvers like Euler, Ranga-Kutta forth order and sixth order algorithms. It even allows the users to develop their own models and to add them to the libraries [53]. Various components in the Simulink library are used to model the gas turbine. The power system modeling has been done using the SimPowerSystems toolbox available in the Simulink. SimPowerSystems extends Simulink by providing many basic and some advanced power system components which help the user to model and analyze power systems. It has different types of machines, sources, loads, transmission and distribution parameters, voltage, current, active power, and reactive power measurements in its library. The simulink library and the SimPowerSystem toolbox provide much flexibility to the user to model and analyze power systems in Simulink.

2.6.2 HOMER

The economic analysis and the environmental impact studies have been carried out using HOMER. Hybrid Optimization Model for Electric Renewables (HOMER) is freely available software developed by U.S National Renewable Energy Laboratory (NREL). This is a micro- power optimization model through which the user can develop different power system models and compare their economics [54]. HOMER models a power system's physical behavior and its life-cycle cost, which is the total cost of installing and operating the system over its life span. It can solve several thousands of the simulations at a time and ranks different alternatives of the power systems based on the net present cost. The graphical user interface (GUI) for HOMER is as shown in Figure 2.10. HOMER has a powerful GUI which allows the user to add or remove particular components including a generator, load, photovoltaic cells, or converters. The modeled power system is shown on the left top most position. Using the 'add/remove' button, the components for the power system can be either added or removed. HOMER also provides a choice to the user whether to connect the system to the grid or not. Once all the components have been modeled, the input parameters for each component need to be set. After modeling and initializing the system, 'calculate' button can be clicked to get the results. Multiple input parameters can be set for each component to do sensitivity analysis. The right side window shows the results. Apart from the cost analysis, the emissions that are released by using specific source also can be determined using HOMER. The details of the economic and environmental analysis are presented in Chapter 6.

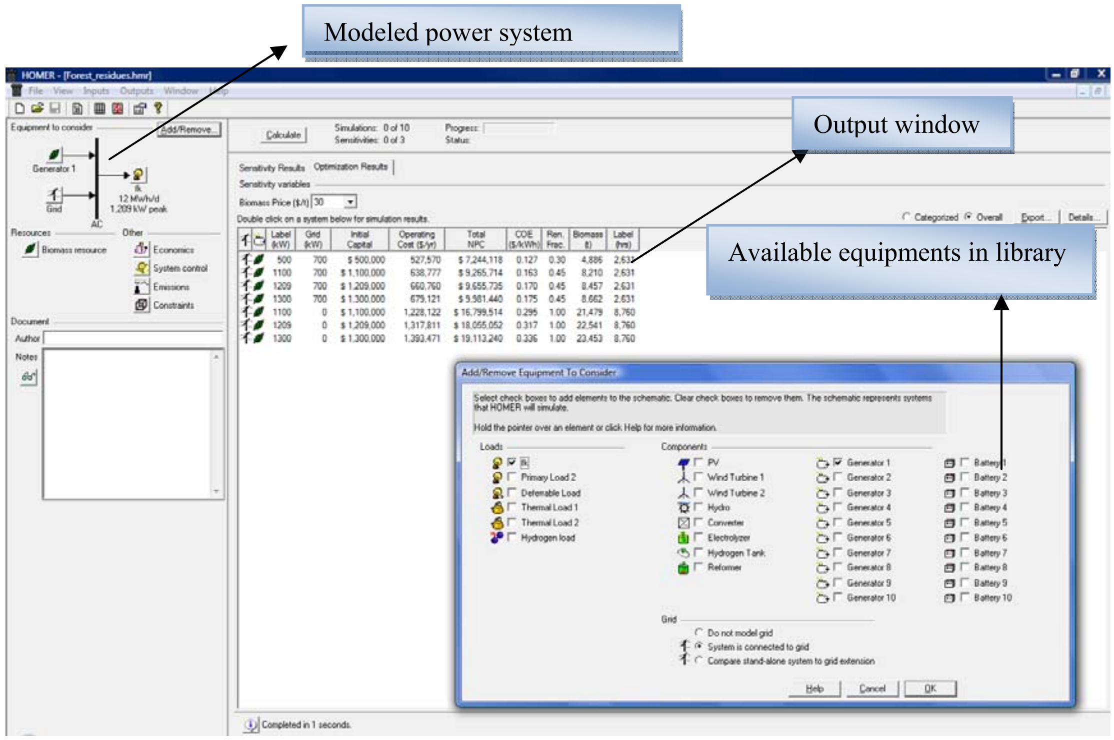


Figure 2.10 Snapshot of HOMER

2.7 Test case systems

A simple four bus system with one machine and an extended six bus system with two machines have been taken as the test case systems in this research.

2.7.1 Four bus System

A single line diagram of a four bus system is shown in Figure 2.11. The system consists of a distribution network of 12.47 kV and a Y-Y transformer which is stepping down the voltage from 12.47kV to 4.157kV and a synchronous machine of salient pole type of 4.157 kV and 6 MVA which is driven by a gas turbine of 5.2 MW. The system feeds the power to the three RL loads of 3000kVA each.

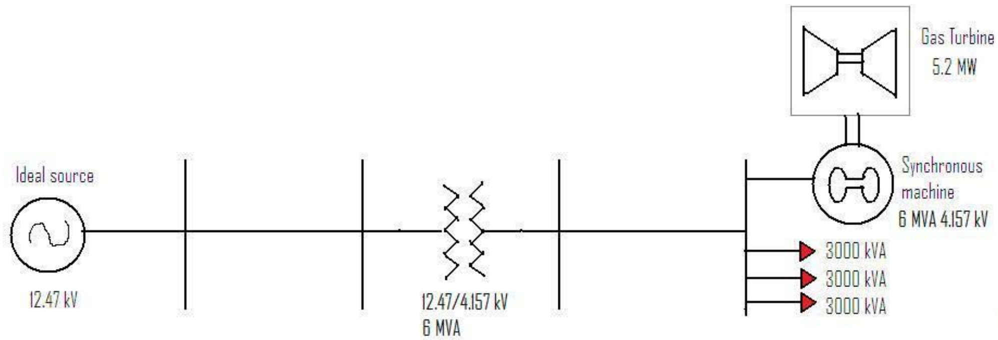


Figure 2.11 Single line diagram of a four bus system

The Simulink model of a four bus system is given in Figure 2.12.

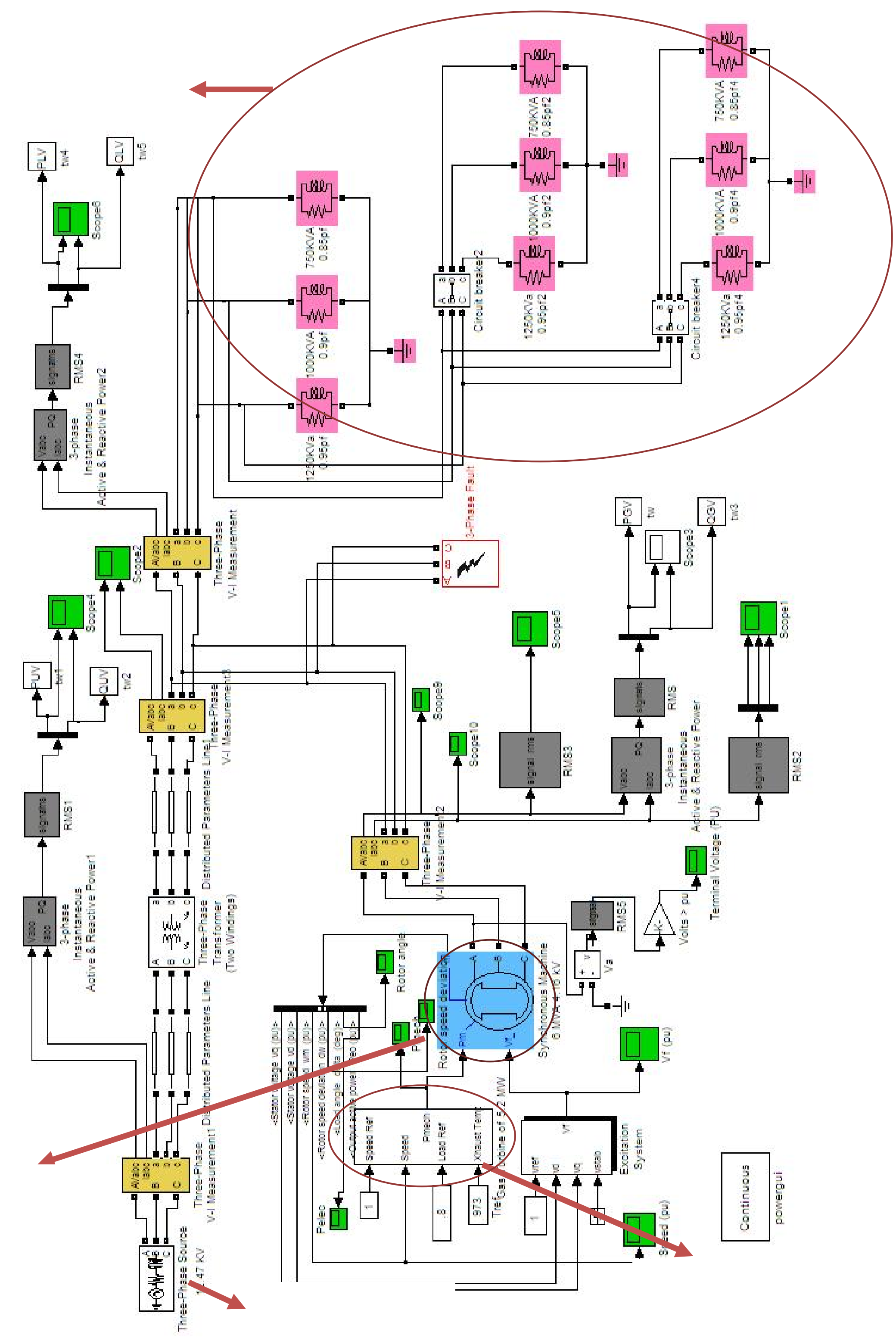


Figure 2.12   Simulink model of a four bus system

2.7.2 Six bus System

The four bus system has been extended to a six bus system by including additional loads and an asynchronous machine. An asynchronous machine of 6 MVA and 4.175 kV has been included in the system and the loads in the four bus system have been split at different buses with an additional 3000kVA added in the system. The single line diagram of a six bus system is shown in Figure 2.13.

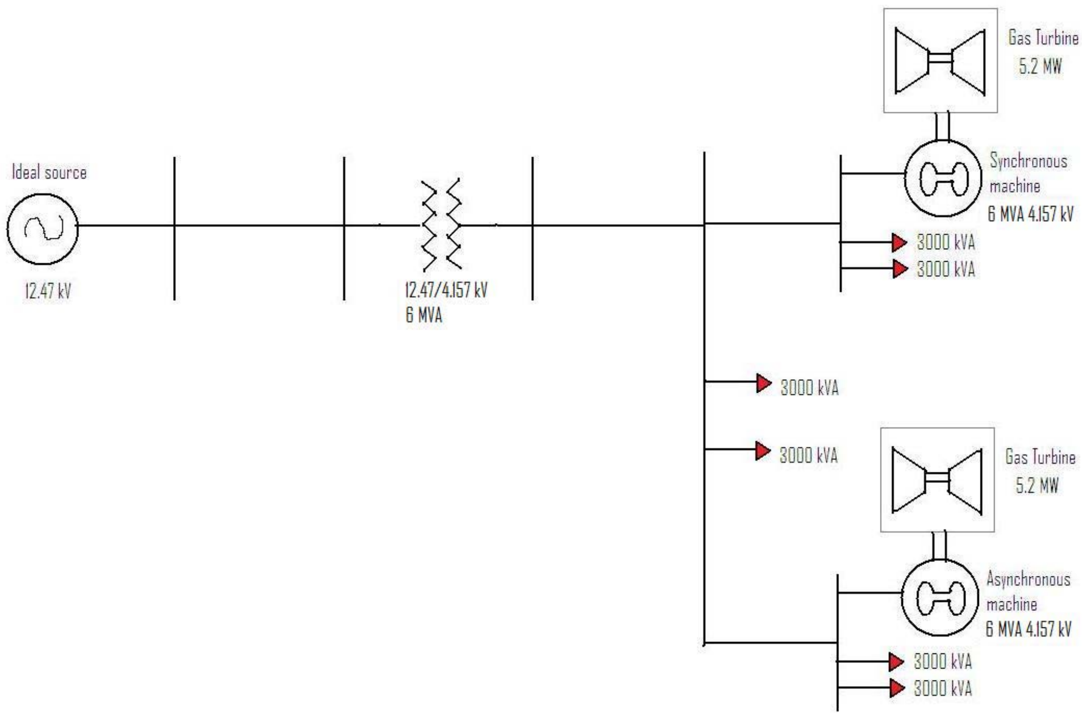


Figure 2.13 Single line diagram of a six bus system

The transformer used is of Y-Y type and the synchronous machine is a salient pole machine having 32 pole pairs. A squirrel cage induction machine is used for the study. The induction machine acts as a generator if the mechanical torque supplied to it is negative. If the torque input to the machine is positive, then it acts as a motor. Table 2.2 shows the summary of the different components and their ratings.

Table 2.2 Components and their ratings in the six bus system

Component	Value
Ideal source	12.47 kV, Feeder
Synchronous machine	6 MVA, 4.175 kV
Asynchronous machine	6 MVA, 4.175 kV
Gas Turbine	5.2 MW
Transformer	12.47 kV/4.175kV

The Simulink model of the six bus system is as shown in Figure 2.14.

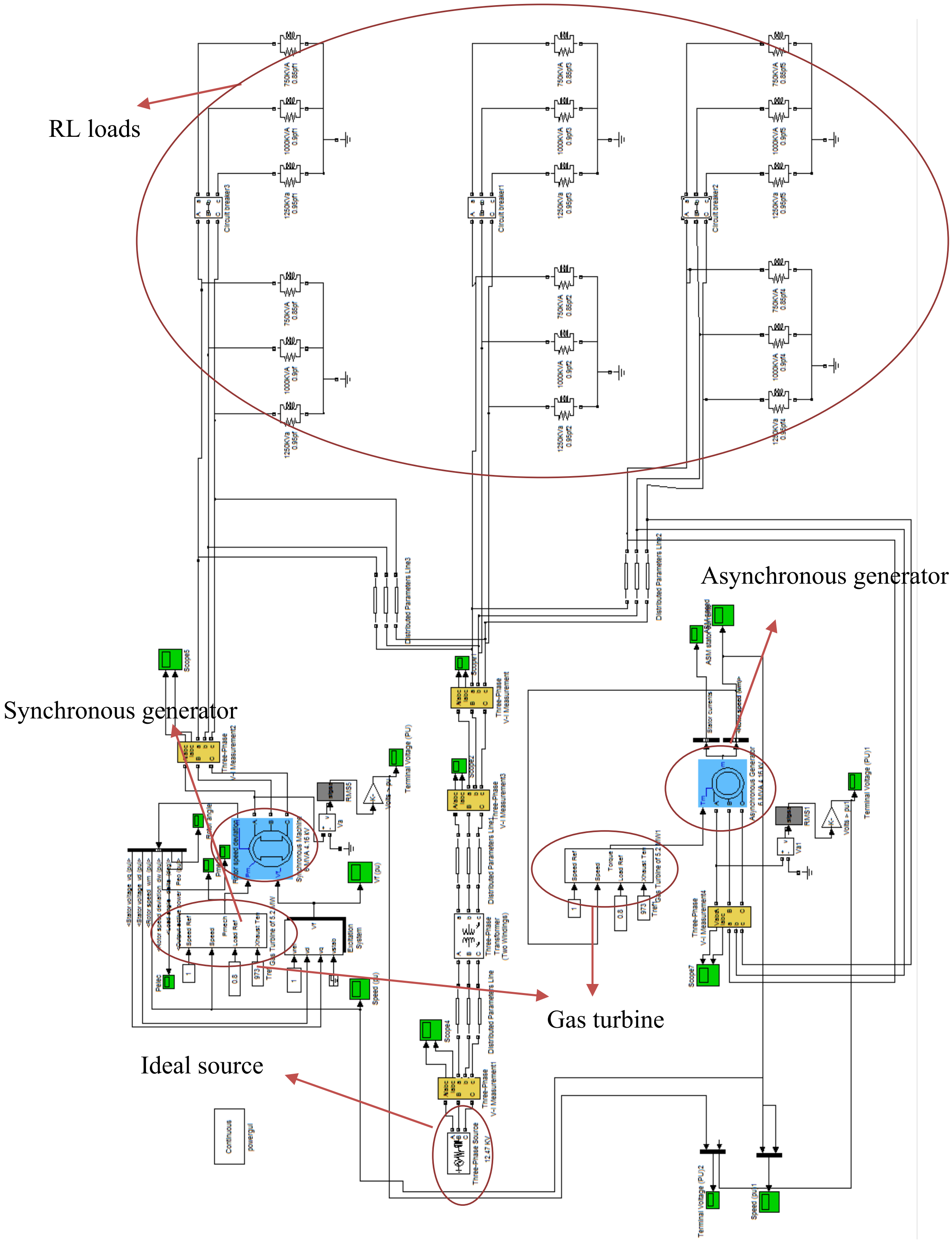


Figure 2.14 Simulink model of six bus power system

2.8 Summary

Biomass is one of the renewable energy sources which are being used widely. This chapter gave the overview of the renewable energy sources and the biomass by explaining its types and the present research. It also described process of converting the energy from the biomass into useful heat, biogases, or electricity. The gasification process which is very important in converting biomass into producer gas is explained. For modeling and analysis of power system, MATLAB/Simulink and HOMER have been used. This chapter presented the basic overview of these two software tools. Finally the test case systems which are used for the research has been explained. Finally, part of the modeling and the analysis has been presented in this chapter by the detailed analysis of the test case systems.

2.9 References

[1] J Cart, "Clean energy for America" accessed: 12-12-2008, available at: http://www.environmentmichigan.org/energy/a-national-strategy

[2] Union of Concerned Scientists, "Why is Renewable energy important?", accessed: 12-12-2008, available at: http://www.ucsusa.org/clean_energy/res/aboutwhy.html

[3] S Rahman.; "Green power: What is it and where can we find it?", *Power and Energy Magazine, IEEE*,Volume1, Issue1, Jan-Feb 2003, pp:30-37.

[4] Department of Energy: http://www.energy.gov/

[5] G. Morris, "The Value of the Benefits of U.S. Biomass Power", Nov 1999, accessed: 12-12-2008, available at: http://www.nrel.gov/docs/fy00osti/27541.pdf

[6] N Sriram, M Shahidehpour, "Renewable biomass energy", IEEE *Power Engineering Society General Meeting, 2005. IEEE,* Vol.1,pp: 612 – 617.

[7] L Minton, T Currah, "Biomass Overview" accessed: 12-12-2008, available at: http://www.window.state.tx.us/specialrpt/energy/renewable/biomass.php

[8] A D. Loganathan, "What is Biomass?", Karnataka Renewable Energy Development Limited, accessed: 12-12-2008, available at: http://kredl.kar.nic.in/BiomassandCogen.htm

[9] http://media.photobucket.com/image/anaerobic%20digestion%20cycle/biopact4/biopact_biogas_pipeline_US.jpg

[10] Green Tech, "Bioenergy fermentation genome sequenced", accessed: 12-12-2008, available at: http://www.greentechnolog.com/2007/03/bioenergy_fermentation_genome_sequenced.html

[11] Babcock & Wilcox Vølund, "The gasification process, accessed: 12-12-2008, available at: http://www.volund.dk/technologies_products/gasification/the_gasification_process

[12] N Elliott, "Combined heat and power": accessed: 12-15-2008, available at: http://www.aceee.org/chp

[13] Abhilash R Masannagari, Master's Thesis, "Optimizing the size and location of distributed generators to maximize the grid stability" ", Electrical and Computer Engineering, Mississippi State University 2008.

[14] B L. Capehart,"Distributed Energy Resources", accessed: 12-15-2008, available at: http://www.wbdg.org/resources/der.php?r=func_oper

[15] Huimin Gao and Chao Wang; "Effect of Detailed Hydro Turbine Models on Power System Analysis", Power Systems Conference and Exposition, 2006. PSCE '06. 2006 IEEE PES Oct. 29 2006-Nov. 1 2006 pp:1577 – 1581.

[16] S. Jadid; Salami, A.;"Accurate model of hydroelectric power plant for load pickup during power system restoration", TENCON 2004. 2004 IEEE Region 10 Conference, Volume C, 21-24 Nov. 2004 pp:307 - 310 Vol. 3.

[17] Yongjun Xia; Xianggen Yin; Deshu Chen; Zhe Zhang; Wei Chen; "Transient Simulation Model and Its Simplified Method Validation for Huge Hydro Generator Internal Short Circuit Faults", International Conference on Power System Technology, 2006. PowerCon 2006. , 22-26 Oct. 2006 pp:1 – 5.

[18] T Stokelj, R Golob, F Gubina, "Accuracy assessment of hydro power plants models", International Conference on Electric Power Engineering, 1999. PowerTech Budapest 99. 29 Aug.-2 Sept. 1999 pp:47.

[19] N Kishor, S P. Singh, A S. Raghuvanshi, P R. Sharma, "Fuzzy Models for the Study of Hydro Power Plant Dynamics", Evolving Fuzzy Systems, 2006 International Symposium on Sept. 2006 pp:235 – 240.

[20] N Kishor, M Singh,A S. Raghuvanshi, "Particle swarm optimization based neural-network model for hydro power plant dynamics", Evolutionary Computation, 2007. CEC 2007. IEEE Congress on 25-28 Sept. 2007 pp:2725 – 2731.

[21] C G S Gunasekara, Udawatta, Lanka, Witharana, Sanjeewa; "Neural Network Based Optimum Model for Cascaded Hydro Power Generating System", Information and Automation, 2006. ICIA 2006. International Conference on 15-17 Dec. 2006 pp:51 - 56 .

[22] V R. Sherkat, R Campo, K Moslehi, E O. Lo, "Stochastic Long-Term Hydrothermal Optimization for a Multireservoir System", IEEE Transactions on Power Apparatus and Systems,Volume PAS-104, Issue 8, Aug. 1985 pp:2040 – 2050.

[23] Ni Jiayan; Wuang Daguang; Cheng Shutang; "The optimization model of hydroelectric generation in the electricity market", Power System Technology, 2002. Proceedings. PowerCon 2002. International Conference onVolume 3, 13-17 Oct. 2002 pp:1344 - 1348 vol.3.

[24] Guozhong Liu; Fushuan Wen; “A chance-constrained programming based approach to optimal hydro energy allocation”, Power and Energy Conference, 2008. PECon 2008. IEEE 2nd International 1-3 Dec. 2008 pp:1233 – 1238.

[25] T M. Welte, J Vatn, J Heggest, “Markov State Model for Optimization of Maintenance and Renewal of Hydro Power Components”, Probabilistic Methods Applied to Power Systems, 2006. PMAPS 2006. International Conference on 11-15 June 2006 pp:1 – 7.

[26] C G S. Gunasekara, Udawatta, Lanka; Witharana, Sanjeewa; “Neural Network Based Optimum Model for Cascaded Hydro Power Generating System”, Information and Automation, 2006. ICIA 2006. International Conference on 15-17 Dec. 2006 pp:51 – 56.

[27] Xinyan Zhang; Weiqing Wang; “Wind farm and wake effect modeling for simulation of a studied power system”, Power Systems Conference and Exposition, 2009. PES '09, IEEE/PES, 15-18 March 2009 pp:1 – 6.

[28] C G. Brown, P E. Johnson, S L. Richards, D G. Long “Wind field models and model order selection for wind estimation”, Geoscience and Remote Sensing, 1997, IEEE International Volume 4, 3-8 Aug. 1997 pp:1847 - 1849 vol.4

[29] W Gawronski, “Modeling wind-gust disturbances for the analysis of antenna pointing accuracy”, Antennas and Propagation Magazine, IEEE Volume 46, Issue 1, Feb 2004 pp:50 – 58.

[30] A D. Hansen, P Sorensen, L Janosi, J Bech, “Wind farm modelling for power quality”, Industrial Electronics Society, 2001. IECON '01, IEEE Volume 3, 29 Nov.-2 Dec. 2001 pp:1959 – 1964.

[31] Ming Yin; Gengyin Li; Ming Zhou; Chengyong Zhao; “Modeling of the Wind Turbine with a Permanent Magnet Synchronous Generator for Integration”, Power Engineering Society General Meeting, 2007. IEEE 24-28 June 2007 pp:1 – 6.

[32] Wei Qiao; R G. Harley,G K. Venayagamoorthy “Dynamic Modeling of Wind Farms with Fixed-Speed Wind Turbine Generators”, Power Engineering Society General Meeting, 2007. IEEE 24-28 June 2007 pp:1 – 8.

[33] J A. Gow, C D. Manning, “Development of a photovoltaic array model for use in power-electronics simulation studies”, Electric Power Applications, IEE Proceedings -Volume 146, Issue 2, March 1999 pp:193 – 200.

[34] J N. Reddy, M K. Moorthy, D V A. Kumar, "Control of grid connected PV cell distributed generation systems", TENCON 2008. IEEE Region 10 Conference, 19-21 Nov. 2008 pp:1 – 6.

[35] Jinhui Xue; Zhongdong Yin; Bingbing Wu; Ziping Wu; Jun Li; "Technology Research of Novel Energy Storage Control for the PV Generation System", Power and Energy Engineering Conference, 2009. APPEEC 2009. Asia-Pacific 27-31, March 2009 pp:1 – 4.

[36] Y Thiagarajan, T S.Sivakumaran, P Sanjeevikumar, "Design and simulation of fuzzy controller for a grid connected stand alone PV system", Computing, Communication and Networking, 2008. ICCCN 2008. International Conference on 18-20 Dec. 2008 pp:1 – 6.

[37] F Morea, G Viciguerra, D Cucchi, C Valencia,"Life cycle cost evaluation of off-grid PV-wind hybrid power systems", Telecommunications Energy Conference, 2007. INTELEC 2007. 29th International Sept. 30 2007-Oct. 4 2007 pp:439 – 441.

[38] Yingzi Li; Jincang Niu; Ru Luan; Yuntao Yue; "Research of multi-power structure optimization for grid-connected photovoltaic system based on Markov decision-making model", Electrical Machines and Systems, 2008. ICEMS 2008. International Conference on 17-20 Oct. 2008 pp:2607 – 2610.

[39] M Urbina, Zuyi Li; "A Fuzzy Optimization Approach to PV/Battery Scheduling with Uncertainty in PV Generation", Power Symposium, 2006. NAPS 2006. 38th North American 17-19 Sept. 2006 pp:561 – 566.

[40] W. I. Rowen, "Simplified mathematical representations of single shaft gas turbines in mechanical drive service," presented at the Int. Gas Turbine and Aeroengine Congr. and Expo., Cologne, Germany, 1992.

[41] A Cano, F Jurado and J Carpio: "Modelling of Power Plants Based on Gasifier/Gas Turbine Technologies" *IEE African 2002*, pp.797-802.

[42] Working Group, on Prime Mover and Energy Supply Models, "Dynamic models for combined cycle plants in power system studies," *IEEE Trans. Power Syst., vol. 9, no. 3, pp. 1698–1708, Aug. 1994.*

[43] R Lasseter, "Dynamic Models for Micro-Turbines and Fuel Cells" *Power Engineering Society Summer Meeting IEEE,* Vol.2, 15-19 July 2001, pp.761-766.

[44] P. Centeno, I. Egido, C. Domingo, F. Fernandez, L. Rouco, and M.Gonzalez, "Review of gas turbine models for power system stability studies," presented at

the 9th Spanish Portuguese Congress on Electrical Engineering, Marbella, Spain, 2005.

[45] N Louis, Hannett, and James W. Feltes " Testing and Model Validation for Combined-Cycle Power Plants", Power Engineering Society Winter Meeting IEEE, Vol. 2, January 2001, pp.664-670.

[46] A. Bagnasco, B. Delfino, G. B. Denegri, and S. Massucco, "Management and dynamic performance of combined cycle power plants during parallel and islanding operation," *IEEE Trans. Energy Convers., vol.*13, no. 2, pp. 194–201, Jun. 1998.

[47] L L. Hannett, A H. Khan, "Combustion Turbine Dynamic Model Validation from Tests" *IEE Trans. on Power Systems*, Vol.8, No. 1, Feb. 1993, pp. 152-158.

[48] Soon Kiat Yee, J V. Milanovic,F M. Hughes, "Overview and Comparative Analysis of Gas Turbine Models for System Stability Studies", Power Systems, IEEE Transactions on Volume 23, Issue 1, Feb. 2008 pp:108 – 118.

[49] N N. Barsoum, P Vacent, **"**Balancing Cost, Operation and Performance in Integrated Hydrogen Hybrid Energy System", *First Asia International Conference on Modeling & Simulation*, pp.14-18.

[50] K Kusakana,J L. Munda, A A. Jimoh, "Economic and environmental analysis of micro hydropower system for rural power supply", *IEEE 2nd International Power ans Energy Conference, 2008*, pp. 441-444.

[51] M.E. Walsh and D. Becker, "Biocost: A Software Program to Estimate the Cost of Producing Bioenergy Crops", *Proc., BIOENERGY '96, Biomass Technologies*, September 15-20, 1996.

[52] G Celli, E Ghiani, M Loddo, F Pilo, S Pani,"Optimal location of biogas and biomass generation plants", Universities Power Engineering Conference, 2008, UPEC 2008, 43rd International 1-4 Sept. 2008 pp:1 – 6.

[53] http://www.mathworks.com/

[54] https://analysis.nrel.gov/homer/

[55] Aarti Asok Kumar, Master's Thesis, "Technical and Economic Impacts of Distributed Generators and Energy storage devices on the Electric grid", Electrical and Computer Engineering, Mississippi State University 2008.

CHAPTER 3

MODELING OF GAS TURBINE

3.1. Introduction

Gas turbines convert the energy of the gases to mechanical energy. In the biomass generation plant model, the biomass will be fed to the gasifier where gases are generated and these gases are input to the gas turbine which consists of the three components: compressor, combustor, and a turbine. This chapter explains the gas turbine history, operating principle, its components, applications, and the modeling of the gas turbine in the MATLAB/Simulink.

3.2. Gas Turbine History and Development

There is a vast development in the gas turbine technologies during past few decades because of its applications and advantages. The gas turbine technology concept was first introduced by Whittle through his patent on jet engines in 1930 and later Brown Boveri Company introduced the first practical gas turbine of 4 MW to generate the electricity at Neuchatel, Switzerland in 1939 [1]. The first gas turbine for an electric utility was installed in 1949 in Oklahoma by General Electric and it produced 3.5 MW of power. During the starting stages of its development, the efficiencies of gas turbine were about 17% due to the less efficiency of the compressor and turbine, but with the present day technologies, it is possible to design these components with less losses [2]. A cutaway of a gas turbine jet engine is shown in Figure 2.1.

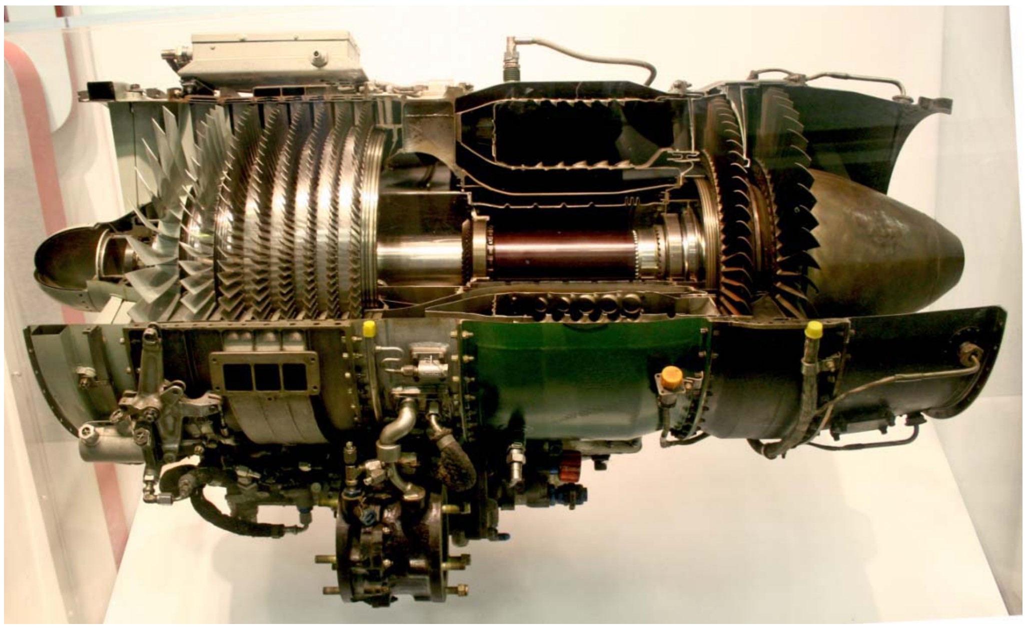


Figure 3.1 Sectioned gas turbine turbojet [2]

Gas turbines can be used in a variety of configurations [4]: (1) simple cycle operation which is a single gas turbine producing power only, (2) combined heat and power (CHP) operation which is a simple cycle gas turbine with a heat recovery heat exchanger which recovers the heat in the turbine exhaust and converts it to useful thermal energy usually in the form of steam or hot water, and (3) combined cycle operation in which high pressure steam is generated from recovered exhaust heat and used to create additional power using a steam turbine. Now-a-days different applications use simple-cycle gas turbine based CHP systems. Several applications which use gas turbine technologies and their ratings are shown in Figure 3.2.

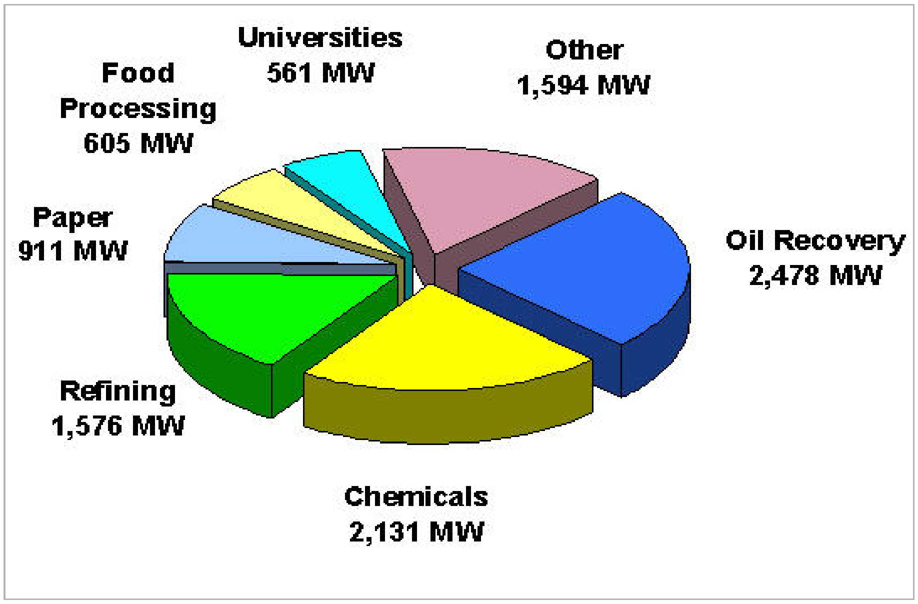


Figure 3.2 Existing Simple Cycle Gas Turbine CHP - 9,854 MW at 359 sites (EEA 2000 report [5])

3.3. Gas Turbine

3.3.1. Gas Turbine Components

Compressor

A compressor is a chamber where compression of air takes place. It is connected to the turbine by a shaft in order to allow the turbine to turn the compressor. If both are connected through a single shaft, then it is known as single shaft gas turbine. A twin pool gas turbine has two connecting shafts. Gas turbine compressors are either centrifugal or axial, or can be combination of both [3]. Centrifugal compressors have compressed air output around the outer perimeter of the machine and these are robust and cheap. These are limits to the pressure ratios of 6 or 7 to 1. Axial flow compressors have compressed air output directed along the center line of the machine and are most widely used in the gas turbines.

Combustor

Combustion chamber is the place where burning of the fuel takes place. Design of a combustor should satisfy many requirements and some principle requirements are given below [3].

i. It should be designed such that it supports multiple fuels, such as natural gas and diesel fuel for industrial applications and kerosene for aircraft high combustion efficiency at all operating conditions.

ii. The combustion process should be without pulsations and stable under all operating conditions.

iii. For good life requirements, the combustor should be designed for a low temperature variation and low pressure drop.

iv. For industrial applications, the combustor should be designed such that it attains long life time.

v. The diameter and length of the combustor should be compatible with engine outside dimensions.

vi. The combustor should be designed for minimum cost, repair, and maintenance and should be lightweight for aircraft applications.

A combustor consists of at least three basic parts: a casing, a flame tube, and a fuel injection system.

Turbine

The turbine uses the energy of high temperature gases to convert to the mechanical energy. The design and manufacturing of the turbines is complicated because of its operation with hot gases. Special materials and elaborate cooling schemes must be used to withstand high temperatures. Axial flow turbines are easier to manufacture compared to axial compressors because the turbine requires less stages compared to the compressor. Some gas turbines of lower ratings use radial inflow, but most of the turbines are of axial type. A gas turbine showing its compressor, combustor, and turbine is shown in Figure 3.3.

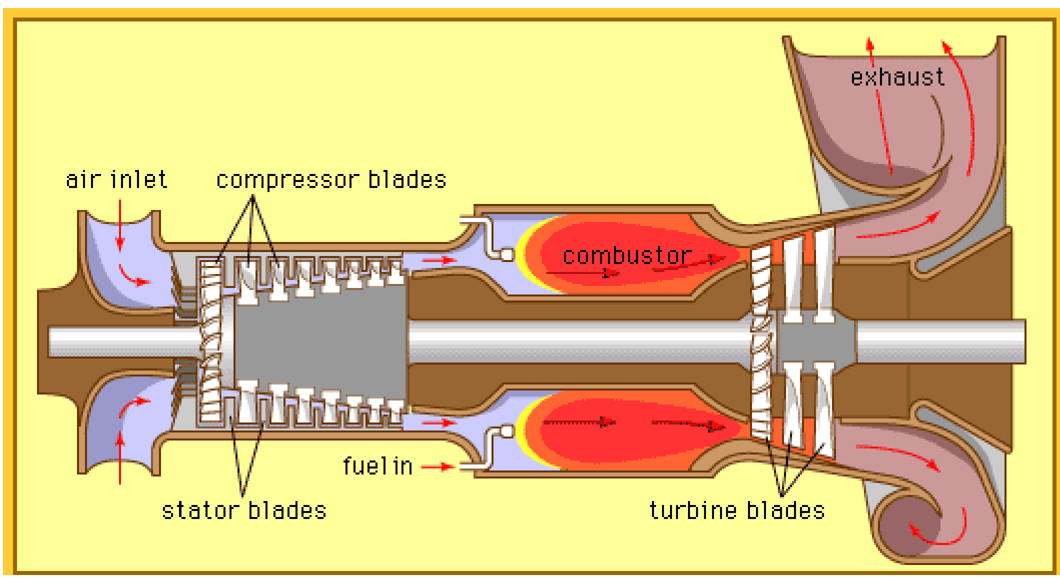


Figure 3.3 Cutaway of the gas turbine showing its components [10]

3.3.2 Gas Turbine Advantages

The two main applications of gas turbines are in aircrafts and in power generation. They also can be used in cruise missiles and unmanned aerial vehicles. Some of the principal advantages of the gas turbine are as follows.

i. Having less size and weight, gas turbine can deliver large amount of power.

ii. Less maintenance cost and long life time.

iii. Though it must be started by some external source, once started it can be brought up to full load conditions in minutes which can be observed in aircrafts.

iv. Gas turbine can work with a wide variety of fuels.

v. It can provide high operating speeds with low operating pressures.

vi. The gas turbine requires no coolant such as water.

3.3.3. Gas Turbine Disadvantages

Though it has several advantages, it suffers from the following disadvantages.

i. Cost is much greater than for a similar-sized reciprocating engine as the materials must be stronger and more heat resistant.

ii. Connecting and operating requires expertise.

iii. Gas turbines are usually less efficient than reciprocating engines.

iv. It produces delayed response to the variation in power settings.

3.4. Brayton Cycle

Gas turbines operate under the Brayton cycle, which is named after George Brayton. An open loop Brayton cycle is shown in Figure 3.4 [10]. Open loop can be converted into a closed loop by adding a heat exchanger (see Figure 3.5). A physical gas turbine consists of a compressor, a combustion chamber, and a turbine. Air enters into the compressor at temperature T_1 and pressure P_1 where it gets compressed and fed to the combustion chamber. Fuel which is the other input to the combustor burns in the combustion chamber under constant pressure and delivers high temperature gases. These gases flow to the turbine where expansion takes place and mechanical energy gets released.

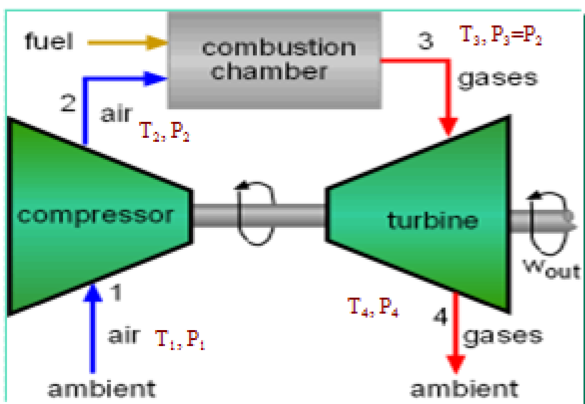


Figure 3.4 Open loop Brayton cycle [10]

The P-V and T-S curves clearly explain the Brayton cycle (shown in Figure 3.6). In the P-V curve, as the air is compressed in the compressor, the pressure is increased and in the combustor, the fuel is burnt at constant pressure, hence a straight line in the graph. Next as the turbine expands the fuels, the pressure will decrease. In the T-S curve, the temperature increases a little bit in the compressor, more in the combustor, so increasing trend in the T-S curve. As the turbine expands the gases, the temperature decreases.

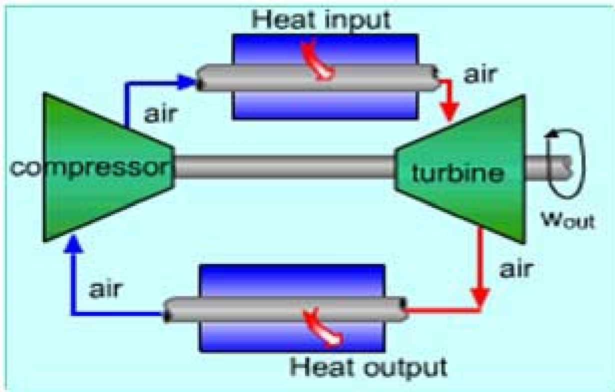


Figure 3.5 Closed loop Brayton cycle [10]

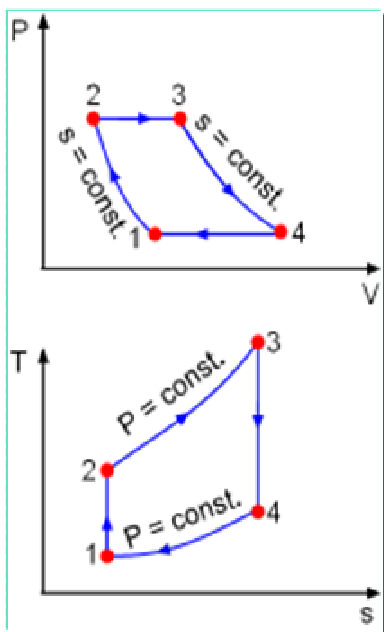


Figure 3.6 P-V and T-S curves of the Brayton cycle [10]

The efficiency of the gas turbine is calculated by comparing the input power to the output power as measured by mechanical energy in the output shaft. Usually turbine efficiency is called as thermal efficiency and can be expressed as follows.

$$\eta_{th,Brayton} = 100 * k * \left[\frac{T_{max} - T_{min}}{T_{max}}\right] \tag{3.1}$$

or

$$\eta_{th,Brayton} = 1 - \frac{1}{r_p^{\frac{(k-1)}{k}}} \tag{3.2}$$

where r_p is the pressure ratio defined as $\frac{P_2}{P_1}$ and k is the specific heat ratio.

3.5 Developed Simulink Model of Gas Turbine

The equivalent mathematical model for the gas turbine is shown in Figure 3.7. In the modeling of the gas turbine, following assumptions were made [7]: i) it is a simple cycle, single shaft, generator drive only; ii) allowable speed range is 95 to 107 percent of the rated speed; iii) it operates at an ambient temperature of 59° and at an ambient pressure of 101.325 kPa. In the modeling, all the values are taken in pu except the temperature.

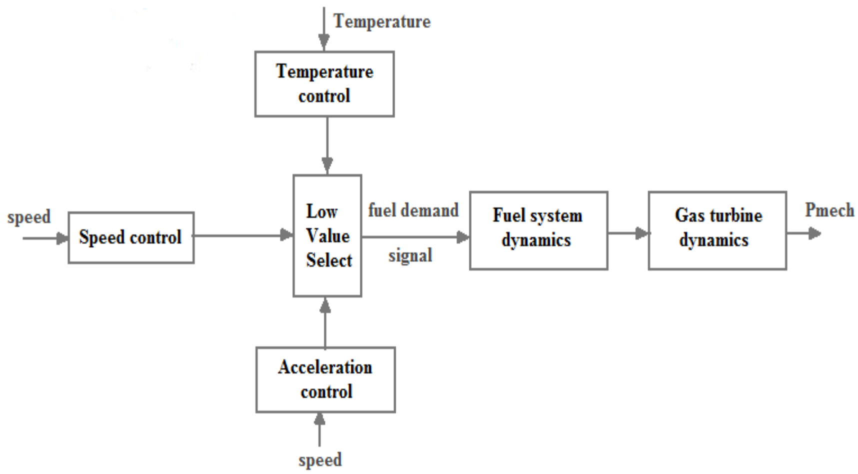


Figure 3.7 Gas turbine model block diagram

Gas turbine has three main control loops: speed control, temperature control, and acceleration control [7, 8]. The outputs of these three controls are the input to the low value select where the minimum of these three inputs will be selected and the control which ever takes less fuel will be active during that time. The fuel request signal from the low value select passes through fuel system and gas turbine dynamics where the turbine torque and exhaust temperature are measured. The model has been developed in Simulink. It is a software tool for modeling, simulating, and analyzing linear, nonlinear, continuous, discrete, and multi-domain time varying systems in interactive graphical environment [9]. GT model in simulink is shown in Figure 3.8.

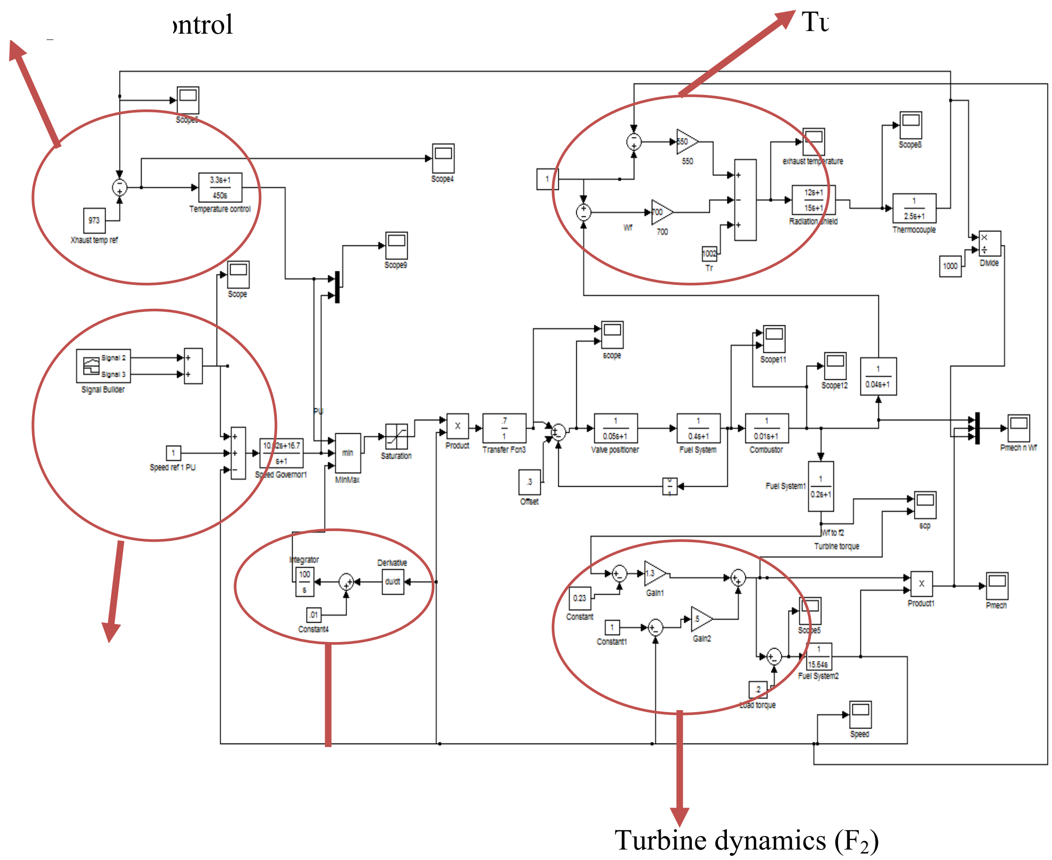


Figure 3.8 Gas turbine model in MATLAB/Simulink

In the modeling, the effect of the inlet guide vanes has been neglected because they are active during only in the startup and shutdown, so their effect on the dynamics of the turbine is almost negligible. The three control blocks are explained in detail below.

Speed Control

Speed control is the major control loop during normal operating conditions. It can be either in droop configuration mode in which output is proportional to the speed error or in isochronous mode in which rate of change of output is proportional to the speed error. These two modes allow the gas turbine to operate when connected to the grid or in an isolated mode. This control block operates on the speed deviation formed between the reference speed and actual speed. The gain of this control is inversely proportional to the droop, which is taken as four percent. This block is shown in the Figure 3.12.

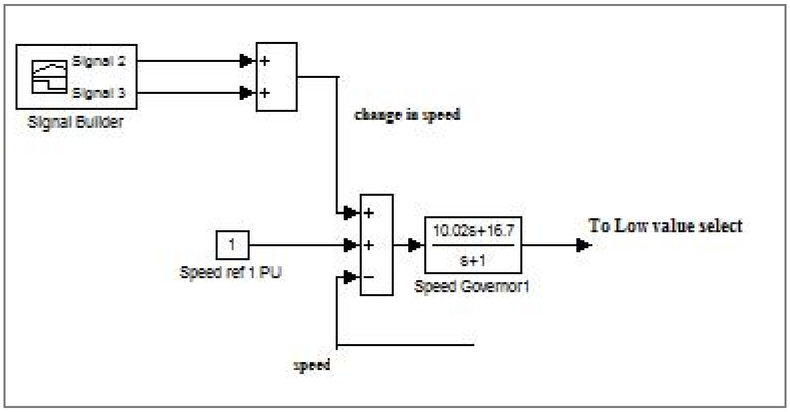


Figure 3.9 Speed control of the Gas Turbine

Temperature Control

Temperature control is the other means of control for the gas turbine which controls the exhaust temperature of the turbine. If the load demanded to the gas turbine increases, the exhaust temperature also rises. If this temperature exceeds a fixed maximum value, the temperature control block will become active. When it is active, the output of the temperature control is less compared to the speed control. Thus reduces the mechanical power and there by the exhaust temperature. This control block is as shown in Figure 3.13. The exhaust temperature is measured in the series of thermocouple and radiation shield. The measured temperature is compared with the reference value, which varies with the rating of the gas turbine, and the error is fed to the temperature control block.

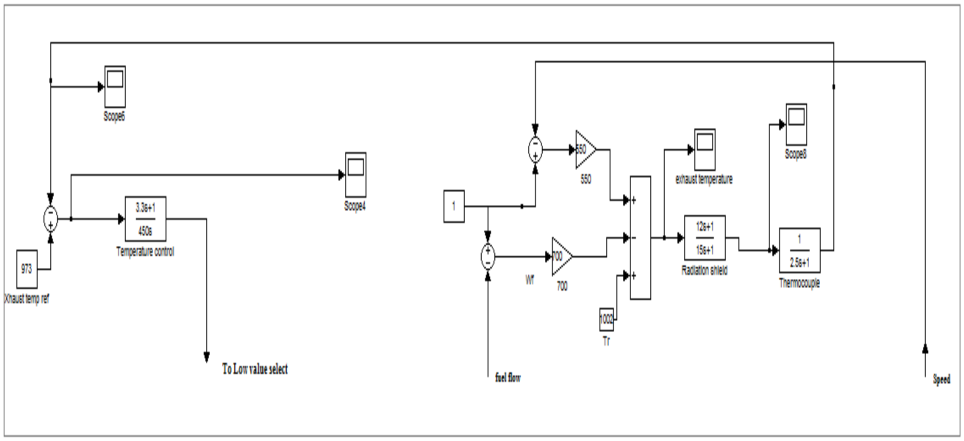


Figure 3.10 Temperature control of the Gas Turbine

Acceleration Control

The third control of the GT is the acceleration control that controls the speed of the turbine. During the startup and in the case of load rejection, the generator accelerates more, and if this exceeds the particular value, the acceleration control will become active and it reduces the high positive acceleration. Acceleration control is shown in Figure 3.14.

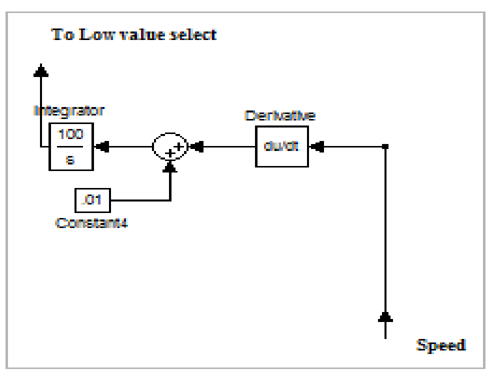


Figure 3.11 Acceleration control of the Gas Turbine

Gas turbine dynamics measure the turbine torque and exhaust temperature by using thermodynamic principles.

The following equation has been used for calculation of the exhaust temperature.

$F_1 = T_r - A_1 (1-W_f) + B_1 (1-N)$ (3.3)

Gas turbine mechanical torque is calculated using equation 3.4.

$F_2 = A_2 (1-W_f) + B_2 (1-N)$ (3.4)

where

W_f – p.u. fuel flow;

T_r – turbine rated exhaust temperature

N – p.u. turbine rotor speed;

A_1, A_2, B_1, and B_2 – coefficients used for calculation of torque and temperature.

The gas turbine developed in MATLAB/Simulink is adopted from reference [7] and the stability and sensitivity studies have been performed to investigate the impact of the biomass on the electric grid.

3.6 Summary

This chapter presented the historical and technical details of gas turbines. Gas turbine components and their operating principles, and the Brayton cycle are explained in detail. The gas turbine model has been developed in MATLAB/Simulink. This chapter explained the model developed for the gas turbine in MATLAB/Simulink and details of the model including the calculation of the mechanical torque and exhausting temperature are described

3.7 References

[1] Kenneth C. Weston, “Energy Conversion”, Electronic book, 2000.

[2] Yunus A. Cengel, and Michael A. Boles, “Thermodynamics-An Engineering Approach”, McGraw-Hill, 2006.

[3] Lee S. Langston and George Opdyke, “Introduction to Gas Turbines for Non-Engineers”, Global Gas Turbine News, Volume 37, 1997, No.2

[4] “Gas Turbine”, accessed: 01-15-2009, available at: http://www.emt-india.net/process/power_plants/Gas_Turbines.htm

[5] Energy Solutions Center, DG Consortium 2004, “Gas Turbine”, accessed: 01-15-2009, available at http://www.energysolutionscenter.org/distgen/AppGuide/Chapters/Chap4/4-3_Gas_Turbines.htm

[6] David Flin, “Gas turbine efficiency: how to maximize it”, ”, accessed: 01-15-2009, available at http://www.cospp.com/display_article/273000/122/ARTCL/none/TECHS/1/Gas-turbine-efficiency/

[7] W. I. Rowen, “Simplified mathematical representations of single shaft gas turbines in mechanical drive service,” Int. Gas Turbine and Aeroengine Congr. and Expo., Cologne, Germany, 1992.

[8] P. Centeno, I. Egido, C. Domingo, F. Fernandez, L. Rouco, and M.Gonzalez, “Review of gas turbine models for power system stability studies,” 9th Spanish Portuguese Congress on Electrical Engineering, Marbella, Spain, 2005.

[9] www.mathworks.com

[10] C R. Russell, “Internal combustion engine”, accessed: 01-15-2009, available at: http://www.britannica.com/EBchecked/topic-art/187279/19424/Open-cycle-constant-pressure-gas-turbine-engine

CHAPTER 4

GASIFICATION AND THE STATISTICAL ANALYSIS

4.1 Introduction

Gasificaiton is an important stage of the biomass generation while generating power. Gasification occurs in a chamber known as a gasifier. Gasifiers are a good alternative for producing heat and power with minimal impact on the environment. The process of gasification includes several biological and chemical reactions forming different stages known as combustion, reduction, and pyrolysis. The reactions that take place in these three zones are described in Chapter II. This chapter explains the gasification process in detail with the factors that affect the gasification. Some of the statistics in the process of the biomass generation are also presented in this chapter. A case study of a Mississippi has been taken into account and the results are presented.

4.2 Factor affecting Gasification

Gasificaiton is a robust proven technology that can be operated either as a simple, low technology system based on a fixed bed gasifier, or as a more sophisticated system using fluidized bed technology [1]. From the gasification process, synthetic gas (known as syn gas) is generated which is considerably clean and convenient to use. Some research has been done in the past with regard to the operating factors that affect the gasification. Here the summary of this analysis from different research efforts are presented. Some of the factors that affect the gasification are given below [1, 2].Temperature

i. Moisture content

ii. Wood diameter

iii. Preheating of air

iv. Pressure

Temperature

In gasification, temperature influences rate constants and equilibrium constants. The compositions of CO and H_2 increase significantly as temperature increases thus increasing the syn gas. The increase in temperature also decreases CH_4 and CO_2 slightly.

Moisture content

Moisture content has a very important influence on the cumulative conversion efficiency and the reactor design requirement. As the moisture content increases, the cumulative conversion efficiency drops. Hence usually drying of the biomass is carried out before processing the gasification.

Size of the particles

Char conversion consists of two processes namely, fast conversion and slow conversion. Fast conversion of char takes place at the entrance of the reduction zone due to the fast reaction rate. Smaller wood diameters are more likely to get converted to gases completely before the slow conversion begins because of their size. Thus gasifiers with shorter reactor lengths need small wood size. For larger particles, because of their size, complete conversion may not be possible. Hence smaller wood size increases the conversion efficiency.

Preheating of air

Gasifiers are generally operated using ambient air temperature at 300 K. Cumulative conversion efficiency increases as the inlet air temperature increases because hot air provides additional enthalpy necessary for reaction thereby decreasing the equivalence ratio.

Pressure

Increased pressure boosts the reaction rate, enhances the yields of the carbon & methane and decreases the CO & H_2.

4.3 Energy from the Gasification

The amount of the biomass utilized to generate the power has been estimated by using cost of energy calculator [3]. A simple block diagram of a biomass gasification plant is shown in Figure 4.1.

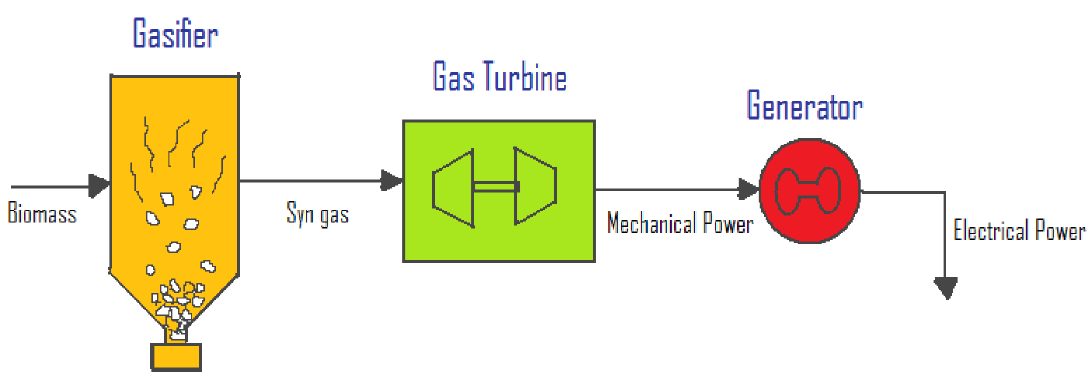


Figure 4.1 Gasification process and power generation

A set of equations in different stages of the power generation has been involved in this study. Based on the factors that affect the gasification, the required biomass feed to generate energy has been formulated. The list of inputs is given in table 4.1. All the input values are taken from [3] and [4] due to the lack of the real plant data.

Table 4.1 List of inputs to calculate the energy from the biomass

Parameter	**Values**
Net electrical capacity (N.E.C)	100 kW
Capacity factor (C.F)	85%
Efficiency of gasification: biomass to clean energy (η)	65%
Clean gas compositions:	
CO	21%
H_2	36%
CH_4	11%
CO_2	14%
O_2	0%
N_2	18%
Higher heating values of	
CO	11, 566 kJ/L
H_2	11, 615 kJ/L
CH_4	36, 316 kJ/L
Lower heating values of	
CO	11, 566 kJ/L

H_2 CH_4	9815 kJ/L 32, 718 kJ/L
Higher heating of biomass feedstock to gasifier	18, 608 kJ/kg
Moisture content of biomass feedstock to gasifier	40 %
Ash content	2 %
Carbon concentration of char	30 %

The parameters associated with the overall plant are calculated in equations 4.1 to 4.16.

$$Annual\ hours\ (A.hrs) = \frac{Capacity\ Factor}{24*365*100} \quad (4.1)$$

$$Annual\ net\ electricity\ generation = N.E.C * A.hrs \quad (4.2)$$

$$Overall\ net\ effeciency = \frac{\eta_{gas}*\eta_{power}}{100}\% \quad (4.3)$$

The parameters involved in the gasification process are calculated by using equations 4.4 to 4.12.

$$Clean\ gas\ molecular\ mass\ \left(\frac{kg}{kMol}\right) = \frac{28A+2B+16C+44D+32E+28F}{100} \quad (4.4)$$

$$Clean\ gas\ density 298K, 1\ atom\ \left(\frac{kg}{m^3}\right) = mass * 101325 * \frac{298}{8314} \quad (4.5)$$

$$Clean\ gas\ higher\ heating\ value\ \left(\frac{kJ}{m^3}\right) =$$

$$\frac{A*higher\ heating\ value\ of\ CO+B*H_2\ higher\ heating\ value+C*CH_4\ higher\ heating\ value}{100} \quad (4.6)$$

$$Clean\ gas\ lower\ heating\ value\ \left(\frac{kJ}{m^3}\right) =$$

$$\frac{A*lower\ heating\ value\ of\ CO+B*H_2\ lower\ heating\ value+C*CH_4\ lower\ heating\ value}{100} \quad (4.7)$$

$$Clean\ gas\ flow\ rate\ \left(\frac{m^3}{h}\right) = \frac{Clean\ gas\ power\ input}{Clean\ gas\ higher\ heating\ value} * 3600 \quad (4.8)$$

$$Clean\ gas\ flow\ rate\ \left(\frac{kg}{h}\right) = Clean\ gas\ flow\ rate * density \quad (4.9)$$

$$Annural\ clean\ gas\ consumption = Clean\ gas\ flow\ rate * Annual\ hours \quad (4.10)$$

$$Char\ production\ rate, dry\left(\frac{kg}{h}\right) = \frac{Ash\ content}{100*dry\ biomass/(1-Carbon\ concentration\ of\ char/100)} \quad (4.11)$$

$$Annual\ char\ production\ \left(\frac{t}{yr}\right) = \frac{Char\ production\ rate*Annual\ hours}{1000} \quad (4.12)$$

The parameters of biomass feed are calculated below.

$$Total\ fuel\ power\ input\ (kW) = \frac{NPC}{\eta_{power}} * 100 \quad (4.13)$$

$$Biomass\ feed\ rate\ \left(\frac{kg}{h}\right) = \frac{Clean\ gas\ power\ input}{\frac{\frac{\eta_{gas}}{100}}{\text{higher heating of biomass}*3600}} \quad (4.14)$$

$$Annual\ biomass\ consumption, dry\ \left(\frac{t}{yr}\right) = \frac{Biomass\ feed\ rate*Annual\ hours}{1000} \quad (4.15)$$

$$Annual\ biomass\ consumption, wet\ \left(\frac{t}{yr}\right) = \frac{Dry\ tonns}{(1-moist/100)} \quad (4.16)$$

By using the these formulas, the biomass feedstock that is required to generate a certain amount of power can be calculated. By using the input values and the equations, biomass consumption to generate 100 kW is obtained and are shown in Table 4.2.

Table 4.2 Results of the biomass power plant

Values of different Parameters to generate 100 kW	**Value**
Total fuel power input	435 kW
Biomass feed rate	129 kg/hr
Annual biomass consumption (dry)	964 tons/yr
Wet annual biomass consumption	1606 tons/yr
Char production rate	4 kg/hr
Annual char production	28 tons/yr

Thus in order to generate 100 kW from the biomass, the required biomass is 2570 (=964+1606) tons per year. This may not be true in reality because of the some of the input values are assumed and not takes from the plants. By considering 2% ash content generated in the gasification process, the annual char production rate is 28 tons.

4.4 Summary

Gasification is the process where the biomass is converted into synthetic gas. The gasification process depends on several parameters. This chapter described the major parameters that affect the gasification process. It also gave the formulation to calculate the specific biomass needed to generate given power in the biomass generation plant using [3].

4.5 References

[1] S. S. Kumar, K. Pitchandi, and E. Natarajan, “Modeling and Simulation of Downdraft wood gasifier”, *Journal of Applied Sciences,* 2008, pp: 271-279.

[2] Y. Wang and C.M. Kinoshita, “Kinetic model of biomass gasificaiton”, *Solar Energy,* Vol. 51, No. 1, 1993, pp: 19-25.

[3] Bryan Jenkins, “Cost of energy calculator”, accessed: 02-01-2009, available at: http://faculty.engineering.ucdavis.edu/jenkins/CBC/Calculator/index.html

[4] J Zhou and S. M. Masutani, “Simulation of Fuel-Bound Nitrogen Evolution in Biomass Gasificaiton”, *Energy Conversion Engineering Conference, IECEC-97,* Vol.3, pp: 1791-1796.

CHAPTER 5

STABILITY ANALYSIS AND SIMULATION RESULTS

5.1 Introduction

This chapter deals with the stability analysis of biomass power generation connected to power distribution system. Different types of stability and the stability indicators that are considered for the research have been discussed. The modeled gas turbine is validated individually and then connected to the power system to study the stability. The sensitiveness of the electrical parameters to the gas turbine variables has been investigated. All the simulated results are presented in this chapter.

5.2 Gas turbine simulation results

The gas turbine presented in Chapter III is validated and the results are presented in this section. To test the gas turbine, it is assumed that the speed of the gas turbine is ramping up 10% in 20 seconds. The change in speed is shown in Figure 5.1.

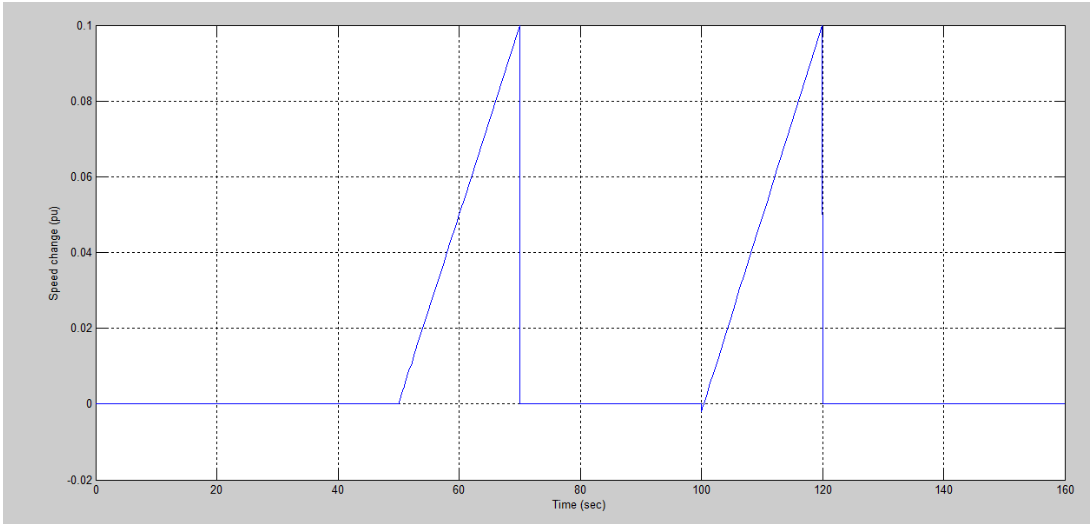


Figure 5.1 Input speed change to the turbine

Mechanical power output of the turbine is shown in Figure 5.2.

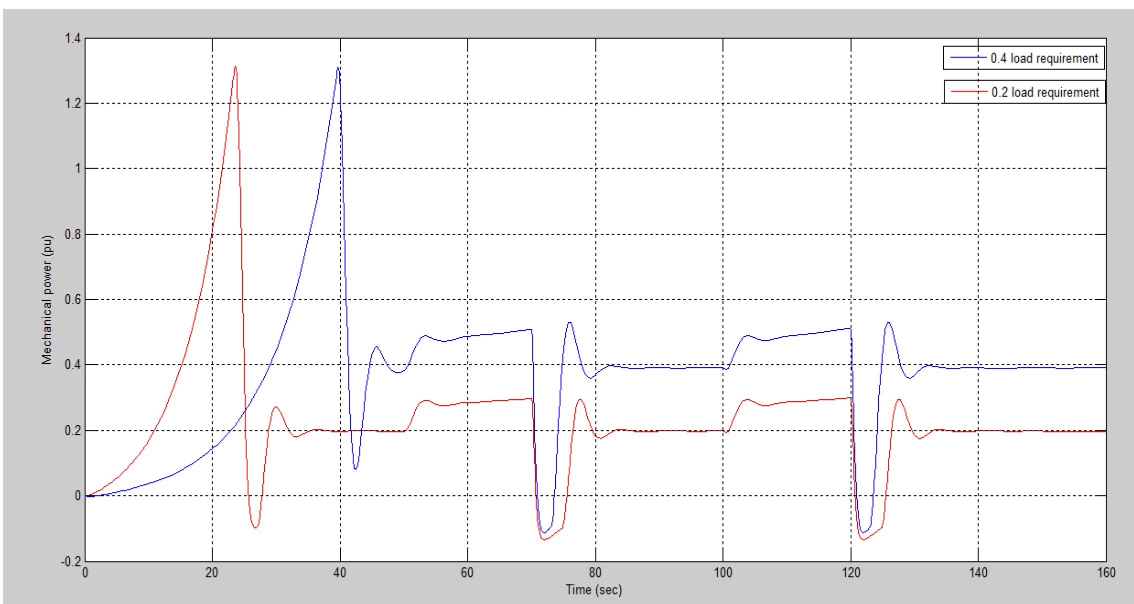


Figure 5.2 Mechanical power output of the turbine

The gas turbine has been tested for different loads and the results with 0.2 and 0.4 pu load requirements are presented in Figure 5.2. As the speed input of the turbine is increasing at 40 seconds, the mechanical power is also increasing at 40 seconds and as the speed is decreasing at 60 seconds, the mechanical power is also decreasing. At 100 seconds, the mechanical power is increasing as the speed is increasing and thereby decreasing following the input. The mechanical power of the gas turbine is satisfying the load requirements.

5.3 Stability Analysis

Power system stability may be broadly defined as the property of a power system that enables it to remain in a state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance [1]. The stability is associated with the behavior of the power system when subjected to a disturbance. The disturbance could be small or large. The small disturbances are in the form of load changes and the system will adjust itself to the load changes and supplied maximum amount of load. A short circuit, loss of generation, or loss of entire load fall under severe disturbances. These disturbances affect the system performance.

5.3.1 Stability Classification

The classification of the stability helps to understand the stability problem clearly. Figure 5.3 shows the classification of the stability.

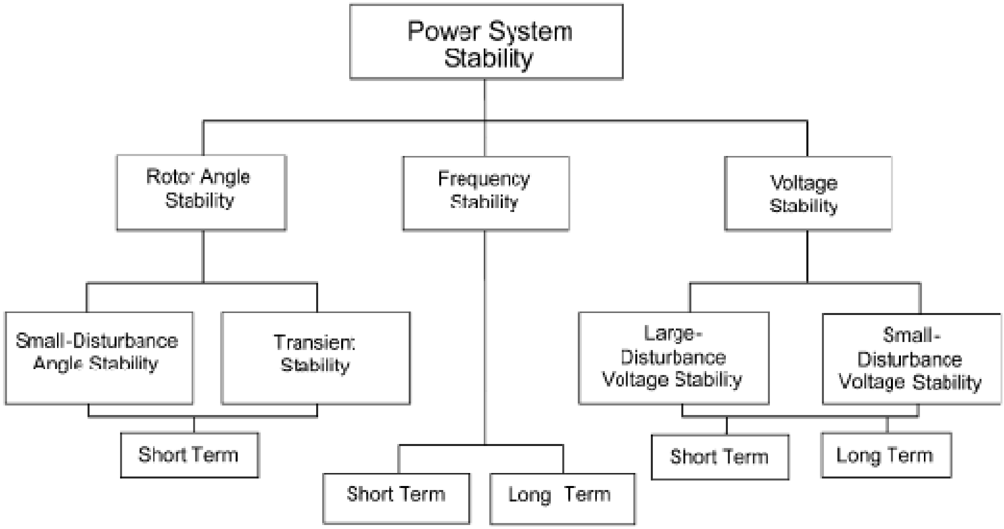


Figure 5.3 Classification of stability [2]

The power system stability has been classified into three main types: rotor angle, frequency, and voltage stabilities. They are again subdivided into different types based on the type of the disturbance and the time period.

Rotor angle stability

It is the ability of the interconnected synchronous machines of a power system to remain in synchronism. This type of stability is associated with the behavior of the power outputs of synchronous machines when their rotors oscillate. Under steady state conditions, there is equilibrium between the input mechanical torque and the output electrical torque of each machine and the speed remains constant. If one generator runs faster than the other due to the disturbance, the angular position of its rotor relative to that of the slower machine will advance. The resulting angular difference transfers part of the load from the slow machine to the fast machine, depending on the power angle relationship.

Small Signal Rotor angle Stability: It is the ability of the power system to maintain in synchronism under small disturbances. Such disturbances occur continually because of the change in load and generation. Eigenvalue analysis is used to study the small signal stability.

Transient Stability: It is the ability of the power system to maintain synchronism when subjected to a severe disturbance. Transient stability depends on both initial operating state of the system and the severity of the disturbance. The contingencies usually include phase-to-ground, phase-to-phase-to-ground, or three phase types of faults.

Voltage Stability

It is the ability of the power system to maintain steady acceptable voltages at all the buses in the system under normal operating conditions and after being subjected to a disturbance. The main factor causing the voltage instability is the inability of the power system to meet the demand for reactive power.

Large disturbance voltage stability: It is concerned with the system's ability to control voltages following large disturbances such as system faults, loss of generation, or circuit contingencies.

Small disturbance voltage stability: It is the system's ability to control voltages following small disturbances such as changes in the load and generation.

Frequency stability

It is the ability of the power system to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. Instability will occur in the form of sustained frequency swings leading to tripping of a generating unit or loads. It is classified into short term and long term frequency stability.

5.3.2 Transient Stability Studies for this Research

The approach for the sensitivity and the stability analysis can be clearly understood by Figure 5.4.

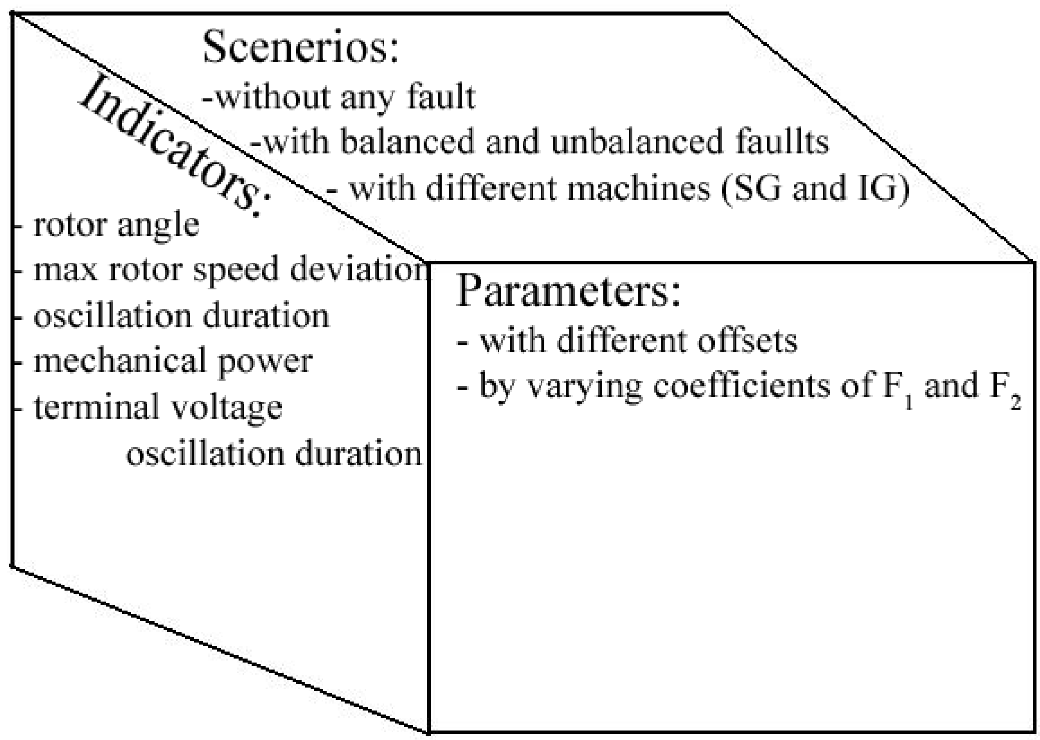


Figure 5.4 Approach for the analysis of transient stability

The stability criterion is carried out under the different scenarios such as with no fault, with different faults, and with different machines. The parameters varied are minimum fuel flow and the coefficients of the turbine. Stability indicators that are taken for the analysis are the mechanical power, oscillation duration, rotor angle, terminal voltage, and rotor speed deviation. Transient stability of the power system is carried out by varying the parameters under different scenarios and measuring different stability indicators that are mentioned. The details of these stability indicators are presented below.

Rotor angle:

Rotor angle of the synchronous machine is a constant value under normal conditions. When fault occurs, the rotor angle increases and after some time, it will come to its normal position. This increase in the rotor angle can be used to assess the stability. If the increase in the rotor angle is more, then the system is less stable and vice versa.

Maximum Rotor Speed deviation:

Rotor speed deviation of the synchronous machine is zero. When a fault occurs, the rotor speed deviation gets disturbed and deviates from zero. The maximum peak that it attains during the fault period is known as the maximum rotor speed deviation. The more the maximum speed deviation, the less stable the system is and vice versa. Maximum rotor speed deviation can be better understood with the help of Figure 5.5.

Oscillation Duration:

For transient stability phenomenon, the post fault behavior of the system is very important. Oscillation duration is the time taken by the system to bring the rotor speed deviation to its normal value which is zero. Oscillation duration is defined in [3] as "equal to the time interval between the application of the fault and the moment after which the rotor speed stays within a bandwidth of $1*10^{-4}$ p.u during a time interval longer than 2.5 seconds." Oscillation duration should be less for the stable system.

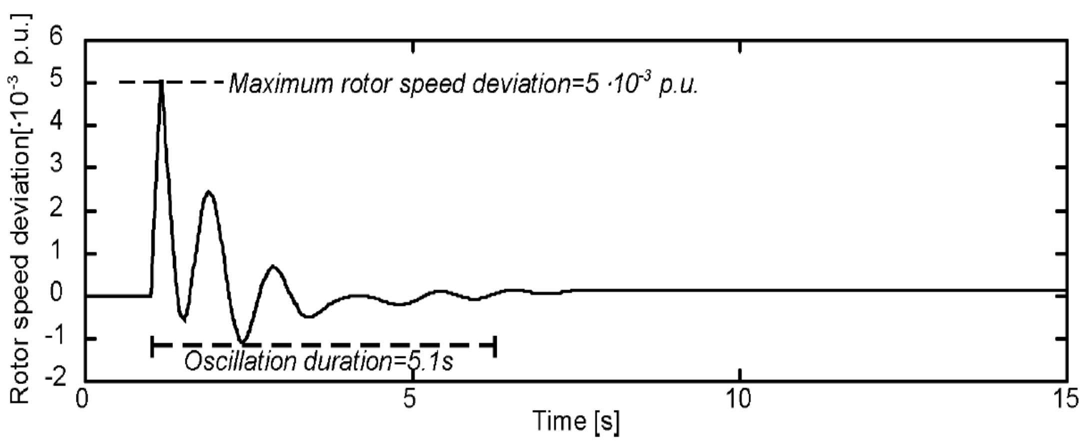


Figure 5.5 Maximum rotor speed deviation and oscillation duration

Terminal Voltage:

When a fault is applied, terminal voltage magnitude or phase will change and after clearing the fault it will settle to normal value. The change in the terminal voltage can be used to assess the stability.

Mechanical Power:

During normal operating conditions, the mechanical power satisfies the load requirement, but when fault occurs, there will be a disturbance followed by oscillation in the mechanical power. Mechanical power varies according to the turbine parameters, so it is used to analyze the sensitivity of the power system stability.

5.4 Sensitivity Analysis

Sensitivity analysis was done to analyze the sensitiveness of the stability to the turbine parameters as well as to verify the performance of the turbine. Turbine dynamics are represented by two functions which calculate the turbine torque and exhaust temperature.

Gas turbine mechanical torque is calculated using the equation (5.1) [4].

$$F_1 = A_1 (1-W_f) + B_1 (1-N) \tag{5.1}$$

Equation (5.2) calculates the exhaust temperature.

$$F_2 = T_r - A_2 (1-W_f) + B_2 (1-N) \tag{5.2}$$

where

W_f – p.u. fuel flow;

T_r – turbine rated exhaust temperature

N – p.u. turbine rotor speed;

A_1, A_2, B_1, and B_2 – coefficients used for calculation of torque and temperature.

F1, F2 – functions that calculate torque and exhaust temperature respectively.

The sensitivity analysis is being carried out by varying

i) minimum fuel flow

ii) coefficients of the F_1.

iii) coefficients of the F_2.

As the speed of the gas turbine is 1 pu, the variation in the associated coefficients B_1 and B_2, is negligible. Hence the analysis is done by varying only A_1 and A_2 coefficients. The results of the sensitivity analysis are presented in next section.

5.5 Simulation Results

5.5.1 Base case Results

The system having a synchronous machine fed by a gas turbine, a distribution network, and loads is run (4 bus test case system presented in Chapter II) and base case results are shown in Figures 5.6 to 5.9.

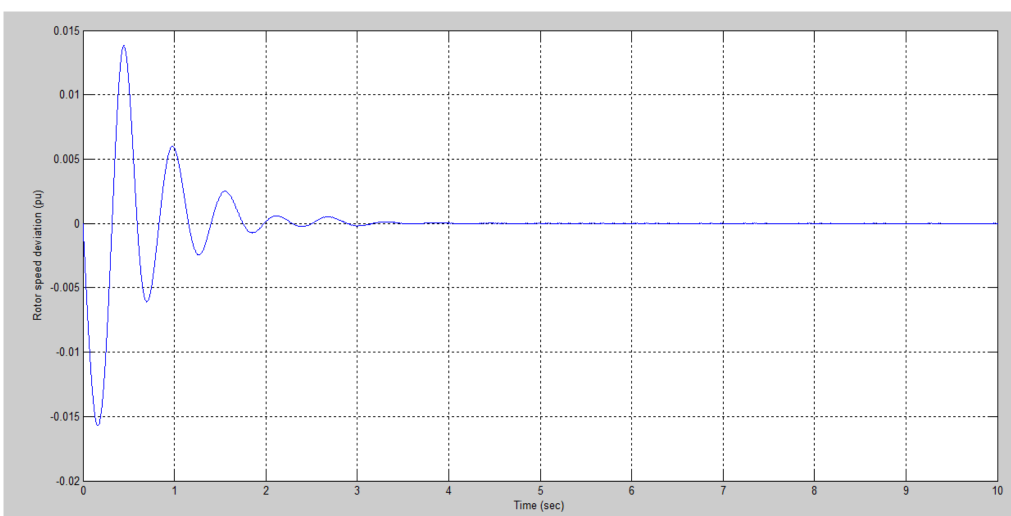


Figure 5.6 Rotor speed deviation under normal operating conditions (no fault)

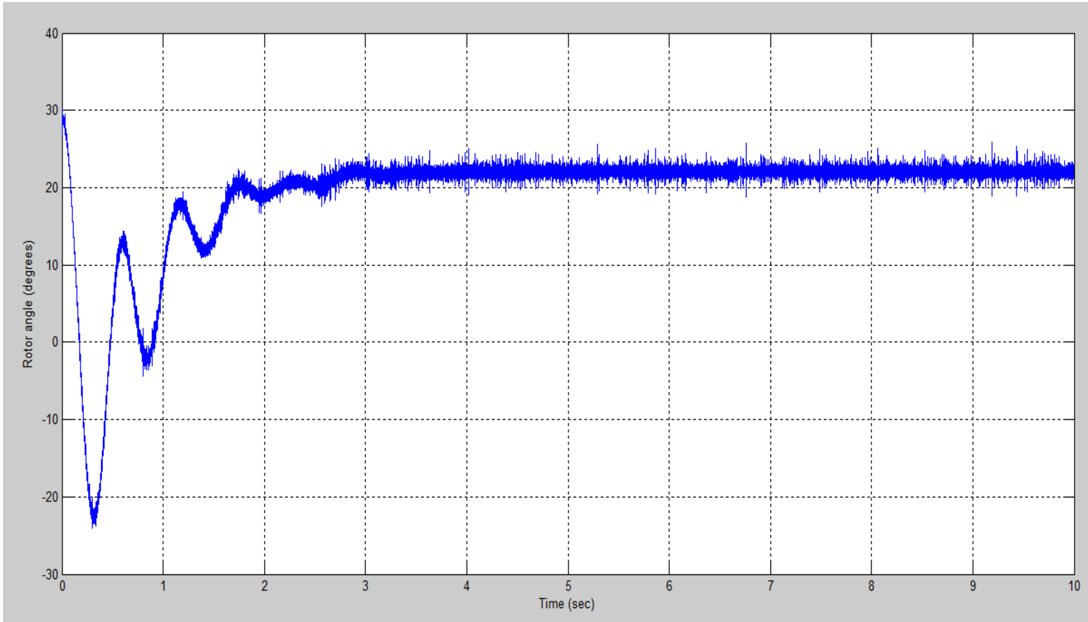


Figure 5.7 Rotor angle under normal operating conditions

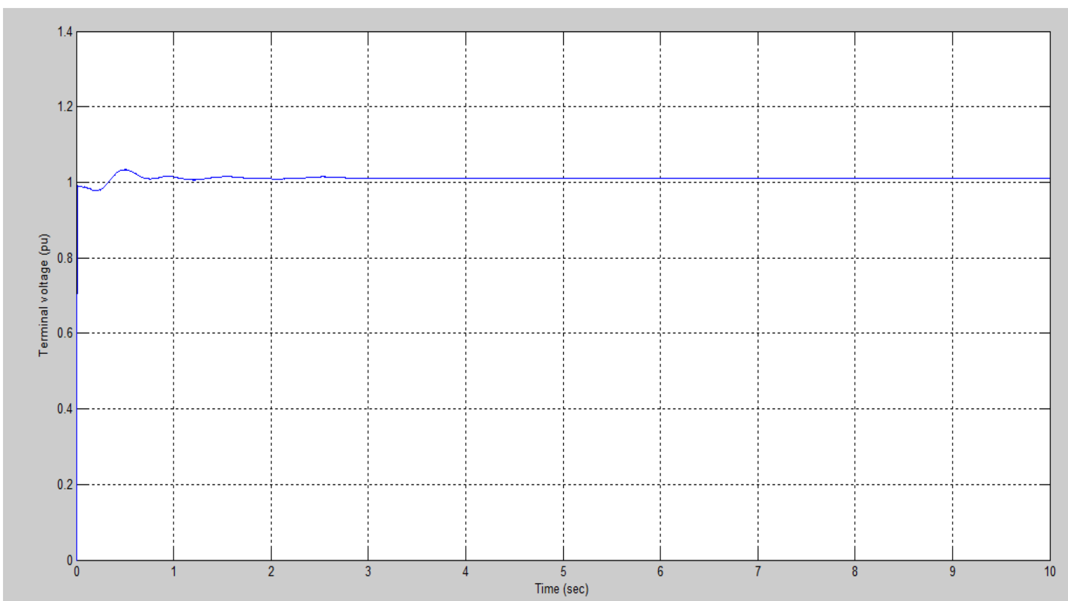


Figure 5.8 Terminal Voltage under normal operating conditions

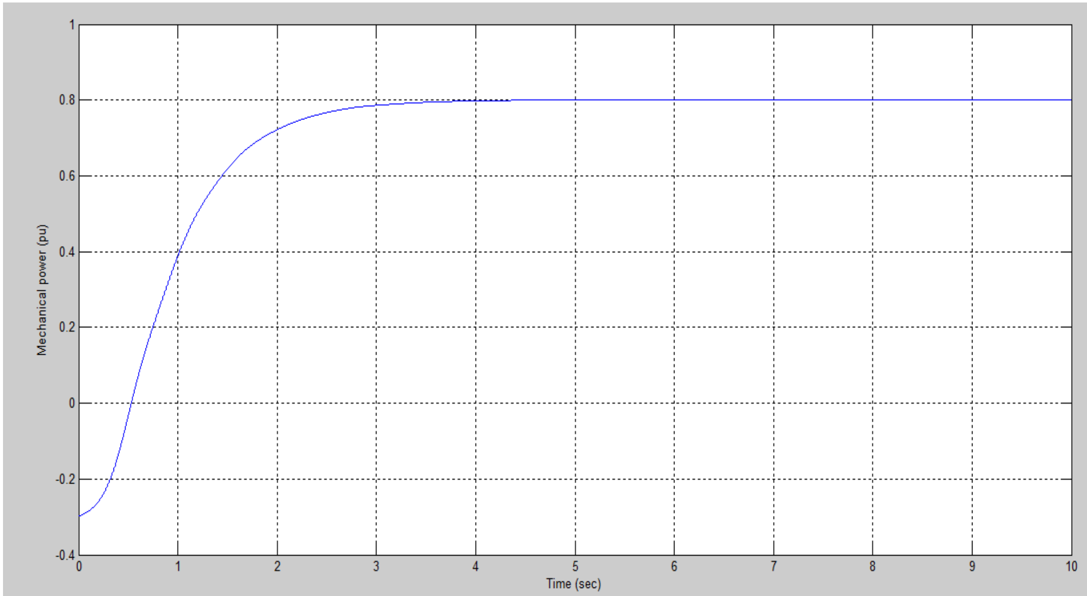


Figure 5.9 Mechanical power under normal operating conditions

After some initial oscillations in the rotor speed deviation (Figure 5.6), it becomes zero. The rotor angle initially oscillates and settles at some stable point. During no fault, it is observed that the terminal voltage is 1 pu and the mechanical power is meeting the load requirement which is taken as 0.8pu.

5.5.2 Results with Three Phase Fault

Three phase fault has been applied near the synchronous generator and the stability indicators were observed. The results are shown in Figures 5.10 to 5.13. Fault is applied at 4 seconds and released at 4.1 seconds, i.e. the fault is cleared approximately after 6 cycles. The mechanical power is settling to 0.8pu which is the load requirement. At 4 seconds, there is a disturbance in mechanical power and is settling to 0.8 again (Figure 5.10). In the similar way, the disturbance in the rotor angle, rotor speed deviation, and the terminal voltage have been observed when a fault is applied and all the indicators are stabilizing after some time of fault clearing.

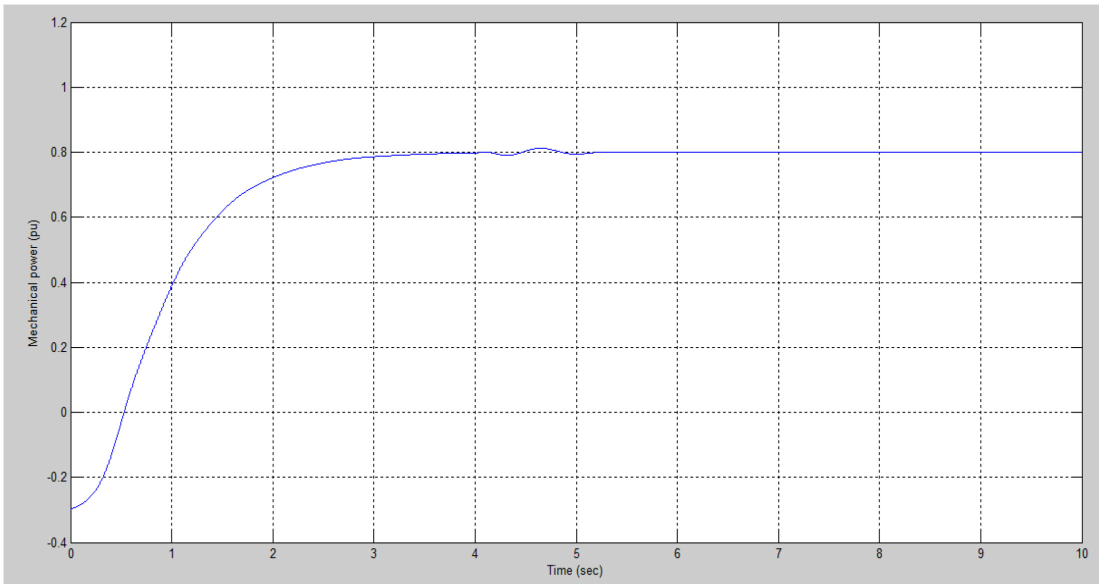


Figure 5.10 Mechanical power during three phase fault

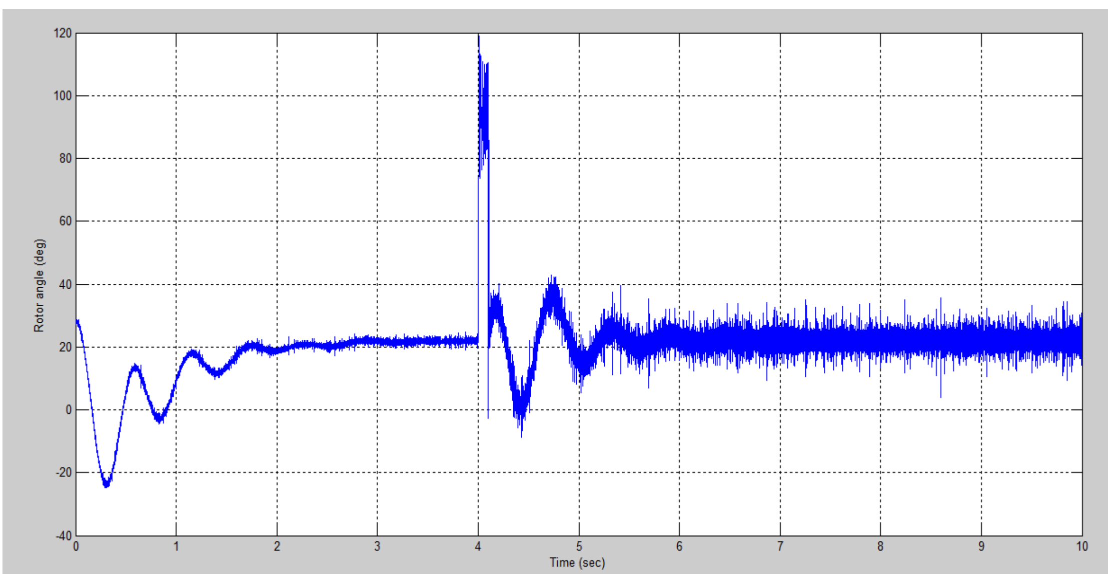


Figure 5.11 Rotor angle during three phase fault

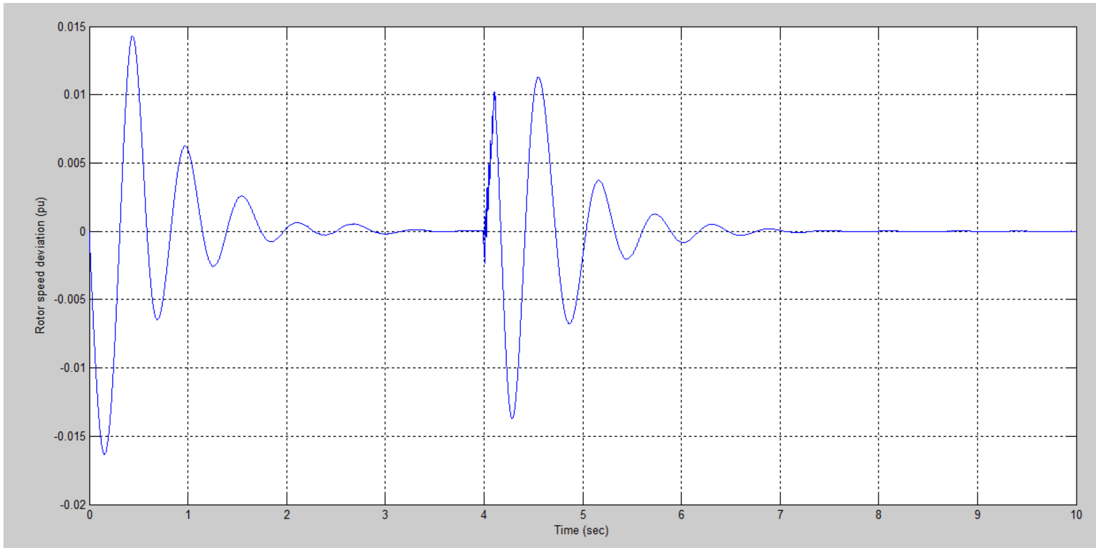


Figure 5.12 Rotor speed deviation during three phase fault

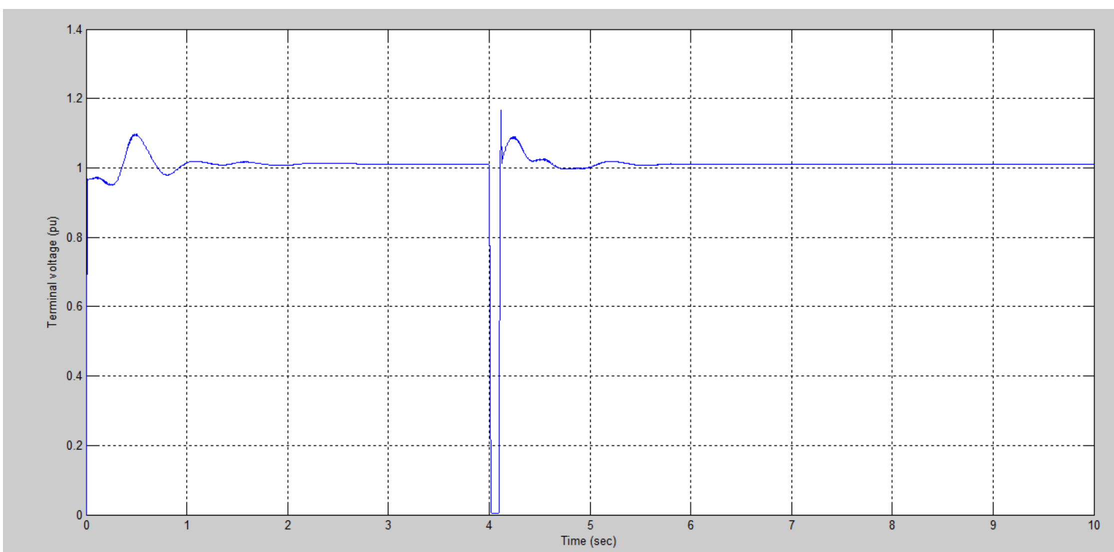


Figure 5.13 Terminal voltage during three phase fault

The rotor angle of the machine is settling to around 10 degrees and the fault at the 4 seconds is disturbing the rotor angle behavior and it is increasing to 90 degrees then after some time, it is settling to the same initial stable value. The increment in the rotor angle is 80 degrees. The rotor speed deviation is increasing to 0.0075 from zero because of the fault and is becoming zero after some time. The measured oscillation duration is 3 seconds. The terminal voltage of the machine is 1 pu and during the fault, the voltage became zero which can be observed from Figure 5.13.

For three phase fault, the analysis has been done by varying the offset, coefficients of F_1 and coefficients of F_2. The results with these three cases are presented in the following sections.

5.5.2.1 With different offsets

The offset is the minimum fuel which is required to start the combustion. It is varied to see the impact on the stability. The offset from [4] is taken as 0.23 pu. In this research, it has been varied from zero to 1 in steps of 0.1 and the stability indicators were observed (see table 5.1)

Table 5.1 Stability indicators with different values of offset for three phase fault

Offset	P_{mech} (pu)	Rotor angle (degree)	Maximum rotor speed deviation (pu)*10^{-3}	Oscillation duration (sec)	Terminal voltage oscillation duration (pu)
0	0.74	97.3	10.3	7.6	5.5
0.1	0.77	97	10.75	7.5	5.5
0.2	0.79	96.6	11.2	7.4	5.5
0.23	0.8	97	11.3	7.2	5.5
0.3	0.82	97	11.6	7.2	5.5
0.4	0.845	97	12.0	7.2	5.5
0.5	0.87	97	12.5	7.5	5.5
0.6	0.897	96.6	13.0	7.5	5.5
0.7	0.923	97.3	13.4	7.5	5.5
0.8	0.949	96.5	13.8	7.5	5.5
0.9	0.975	96.7	14.35	7.5	5.5
1.0	1.0	97.5	15.0	7.5	5.5

As the minimum fuel is increasing, the mechanical power is also increasing, which is obvious. The increase in the offset increases the maximum rotor speed deviation, and thus higher values of the offset lead to the less stable system. Apart from this, the gas turbine should satisfy the load requirement. At 0.23 value of offset, the turbine is satisfying the load requirement of 0.8 pu. The graphical representation of the change in the mechanical power and the maximum rotor speed deviation with different offsets are shown in Figures 5.14 and 5.15.

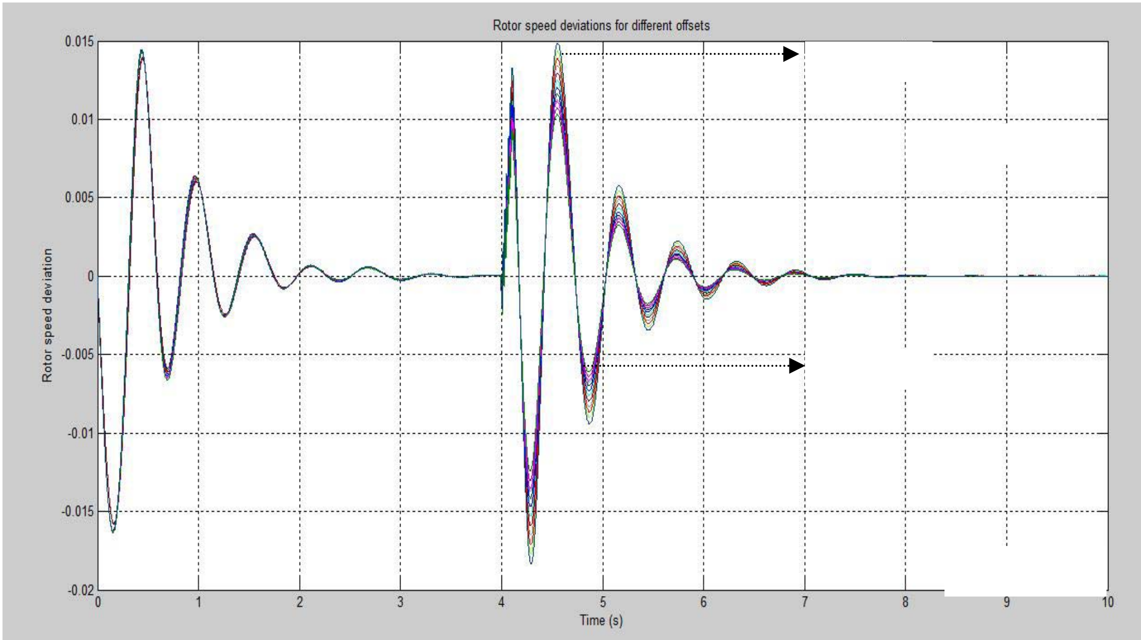


Figure 5.14 Rotor speed deviation with different values of offsets (0-1) for 3 phase fault

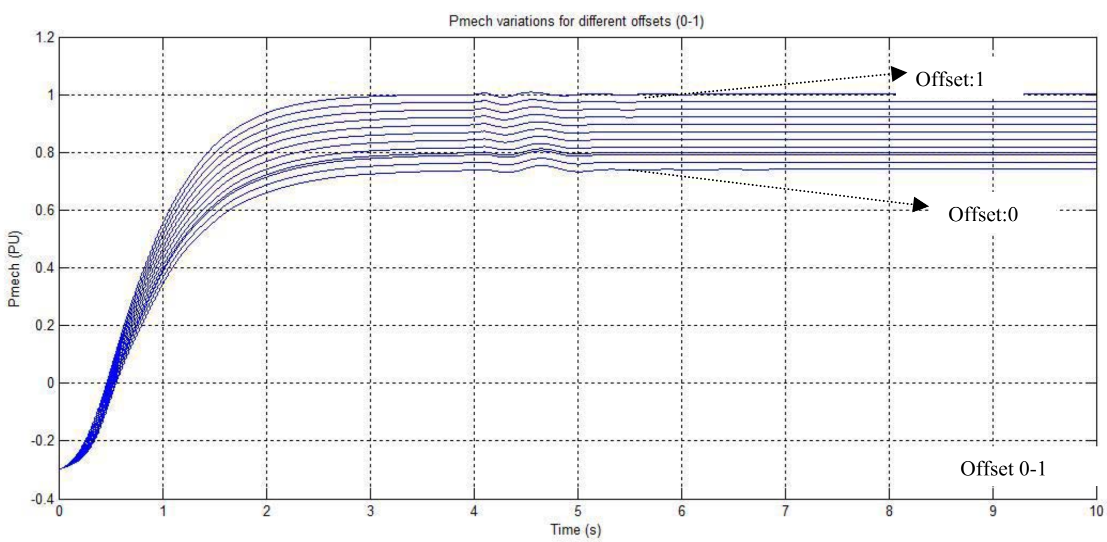


Figure 5.15 Mechanical powers with different values of offset for three phase fault

5.5.2.2 With different coefficients of A_1

The coefficients of the A_1 are varied and effect on the stability indicators was observed as presented in table 5.2.

Table 5.2 Stability indicators with different values of A_1 for three phase fault

A_1	P_{mech} (pu)	Rotor angle Increment (deg)	Max rotor speed deviation (pu)*10^{-3}	Oscillation duration (sec)	Term Voltage Oscillation duration (sec)
0.52	0.321	96.8	3.77	6.4	5.4
0.78	0.48	97.0	6.07	6.5	5.4
1.04	0.641	96.5	8.45	6.8	5.5
1.3	0.8	97	11.3	7.5	5.5
1.56	0.961	96.3	14.18	7.8	5.5
1.82	1.12	96.5	17.38	8.2	5.5
2.08	1.28	96.6	21.2	9.5	5.8

As the A_1 is increasing, the mechanical power, speed deviation, and oscillation duration are increasing. For more stable system, A_1 should be less and as mentioned, the mechanical power should meet the load requirement. The graphical representation of change in the indicators is shown in Figures 5.16, 5.17, and 5.18.

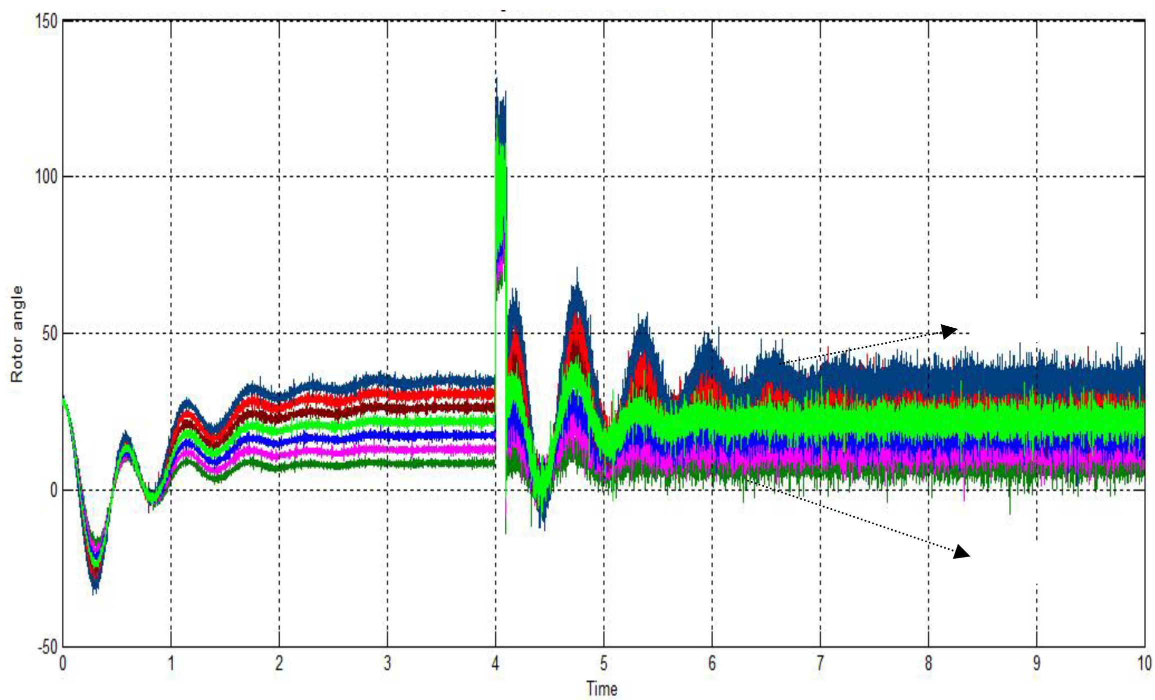


Figure 5.16 Rotor angles with different values of A_1 for three phase fault

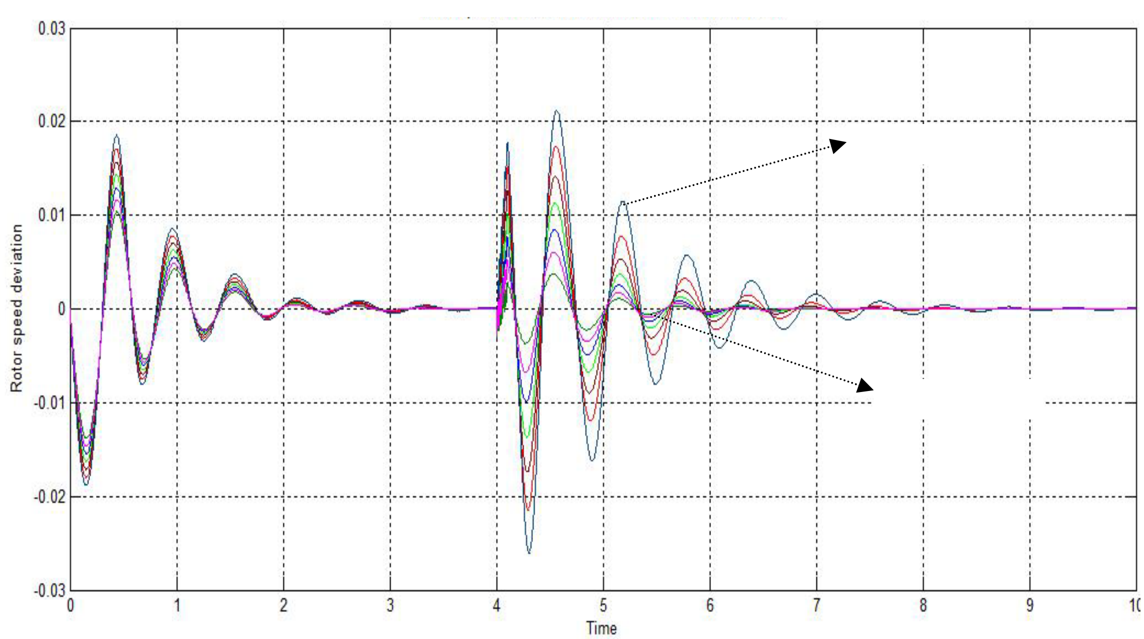


Figure 5.17 Rotor speed deviations with different values of A_1 for three phase fault

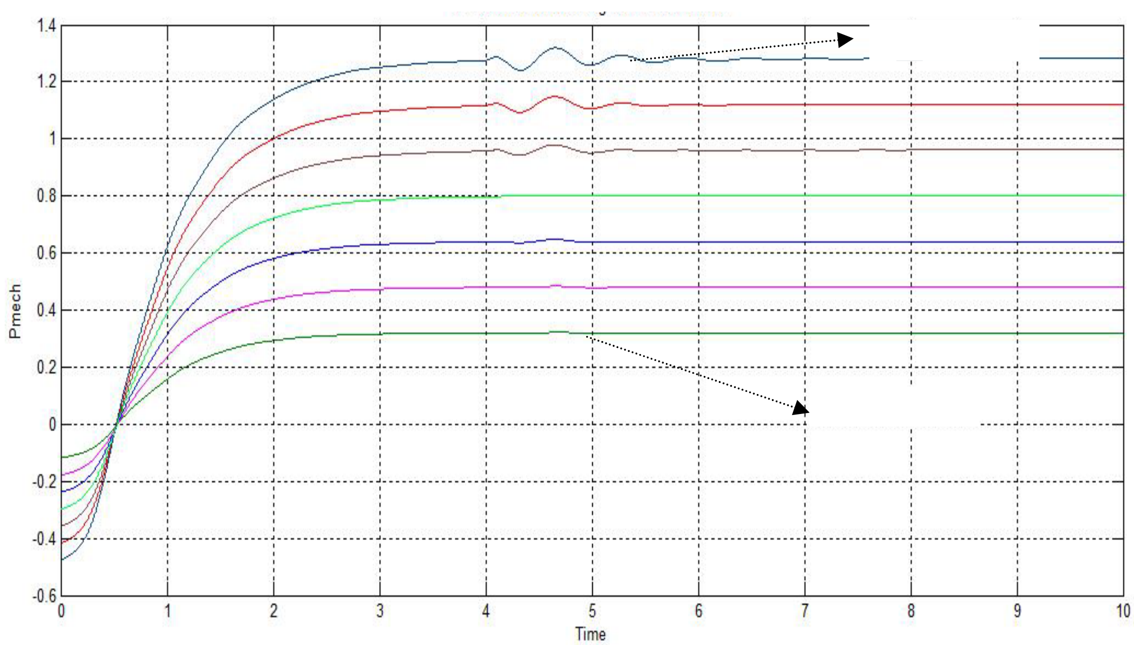


Figure 5.18 Mechanical power with different values of A_1 for three phase fault

5.5.2.3 With different coefficients of A_2

The change in the stability indicators with different values of A_2 are presented in table 5.3.

Table 5.3 Stability indicators with different values of A_2 for three phase fault

A_2	Exhaust temp (F)	P_{mech} (pu)	Max rotor speed deviation (pu)*10^{-3}	Oscillation duration (sec)	Rotor angle (deg)
420	820	0.8	11.3	7.2	97
560	780	0.8	11.3	7.2	97
700	750	0.8	11.25	7.2	97
840	720	0.8	11.26	7.2	97

980	700	0.8	11.2	7.2	97
1120	645	0.8	11.3	7.2	97

The increase in A_2 does not have any impact on the mechanical power, and rotor speed deviation, oscillation duration because A_2 is associated with the exhaust temperature calculation not with the mechanical torque. Though the exhaust temperate is calculated based on the value of the A_2, at low value select, the speed control is active rather than the temperature control.

5.5.3 Results with LG Fault

A phase to ground fault has been applied on phase A and the stability indicators were observed. Fault is applied at 4.0 seconds and released at 4.1 seconds. The increase in the coefficient A_2 decreases the exhaust temperature but there were no changes observed in the stability indicators (see Table 5.2) because at low value select, the speed control is active rather than the temperature control.

5.5.3.1 With different offsets

The offset is again changed between 0 and 1 as in the case of LG fault. The stability indicators with the change in offset are presented in Table 5.4.

Table 5.4 Stability indicators with offset variation for LG fault

Offset	P_{mech} (pu)	Rotor angle (degree)	Maximum rotor speed deviation (pu)*10^{-3}	Oscillation duration (sec)	Terminal voltage oscillation duration (pu)
0	0.741	14.4	4.49	6.5	5.5
0.1	0.767	13.8	4.62	6.5	5.5
0.2	0.793	13.5	4.76	6.5	5.5
0.23	0.8	13.5	4.82	6.5	5.5
0.3	0.819	13.7	4.9	6.5	5.5
0.4	0.845	13.7	5.03	6.5	5.5
0.5	0.871	13.7	5.175	6.5	5.5
0.6	0.897	13.5	5.32	6.5	5.5
0.7	0.923	13.3	5.46	6.5	5.5
0.8	0.949	13.6	5.6	6.5	5.5
0.9	0.975	13.5	5.76	6.5	5.5
1	1.0	13.95	5.9	6.5	5.5

The graphical representation of the change in rotor speed deviation and the mechanical power are shown in Figures 5.19 and 5.20.

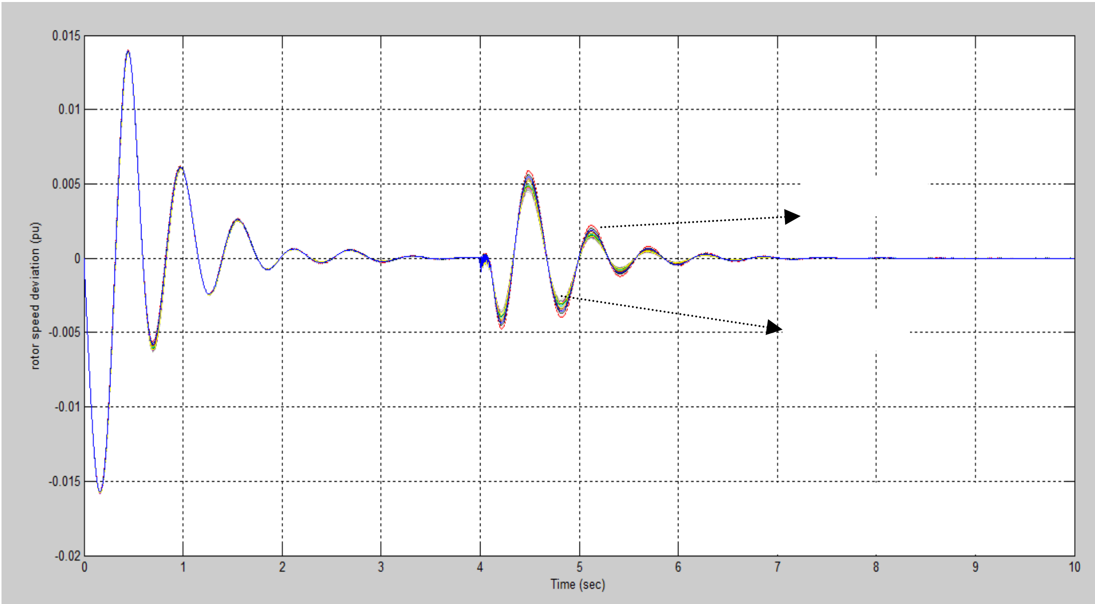


Figure 5.19 Rotor speed deviations with different offsets for LG fault

As the offset is increasing, the mechanical power and the rotor speed deviations are increasing as in the case of three phase fault, but with less effectively. The best offset value could be the one which gives the satisfied load requirements as well as minimum rotor speed deviation.

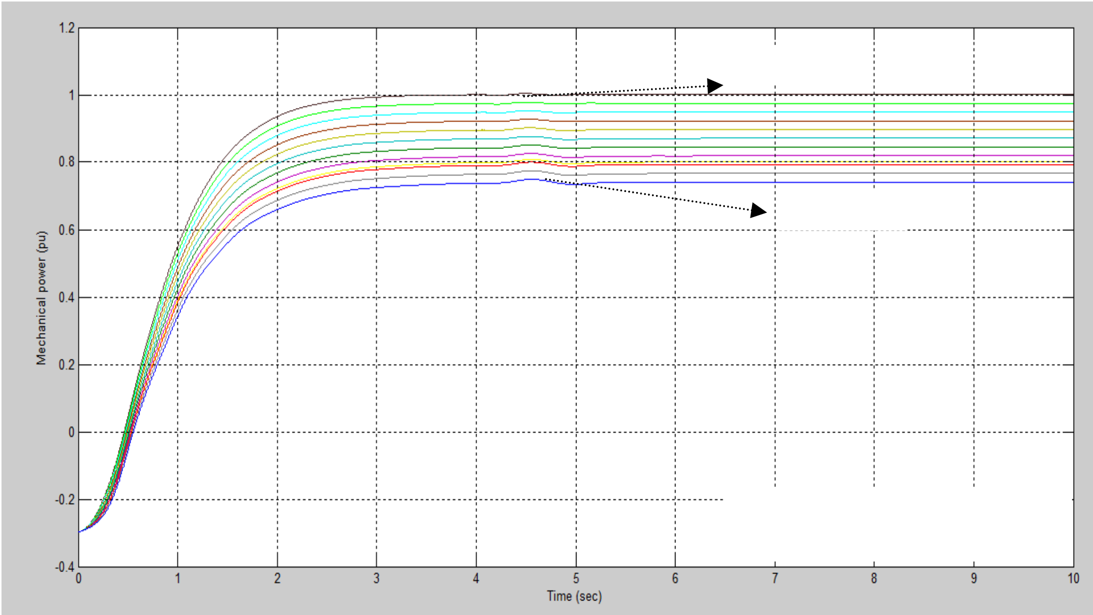


Figure 5.20 Mechanical powers with different offsets for LG fault

5.5.3.2 With different coefficients of A_1

The similar results as the three phase fault were observed. Table 5.5 shows the stability indicators with different values of A_1.

Table 5.5 Stability indicators with different values of A_1 for LG fault

A_1	P_{mech} (pu)	Rotor angle (deg)	Max rotor speed deviation (pu)*10^{-3}	Oscillation duration (sec)	Terminal voltage oscillation duration (sec)
0.52	0.32	13.7	2.24	6.5	5.5
0.78	0.48	13.44	3.05	6.5	5.5
1.04	0.64	13.6	3.92	6.5	5.5
1.3	0.8	13.8	4.8	6.5	5.5
1.56	0.961	13.4	5.75	6.5	5.5
1.82	1.12	13.5	6.71	6.5	5.5
2.08	1.28	13.6	7.74	6.5	5.5

The graphical representation of the variation is as shown in Figures 5.21, 5.22, and 5.23.

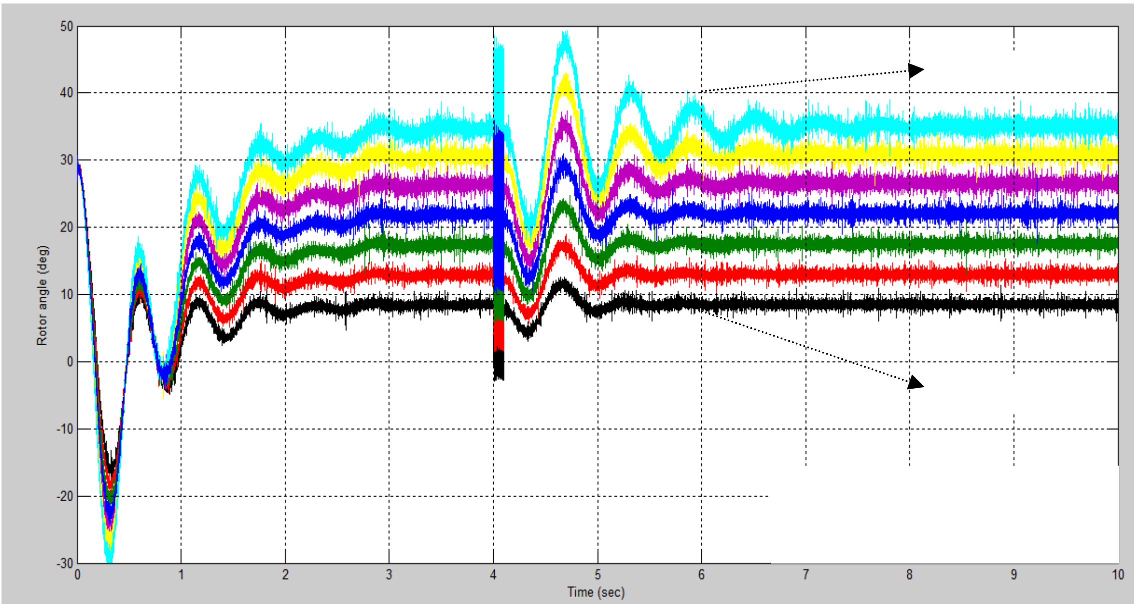


Figure 5.21 Different rotor angles with different values of A_1 for LG fault

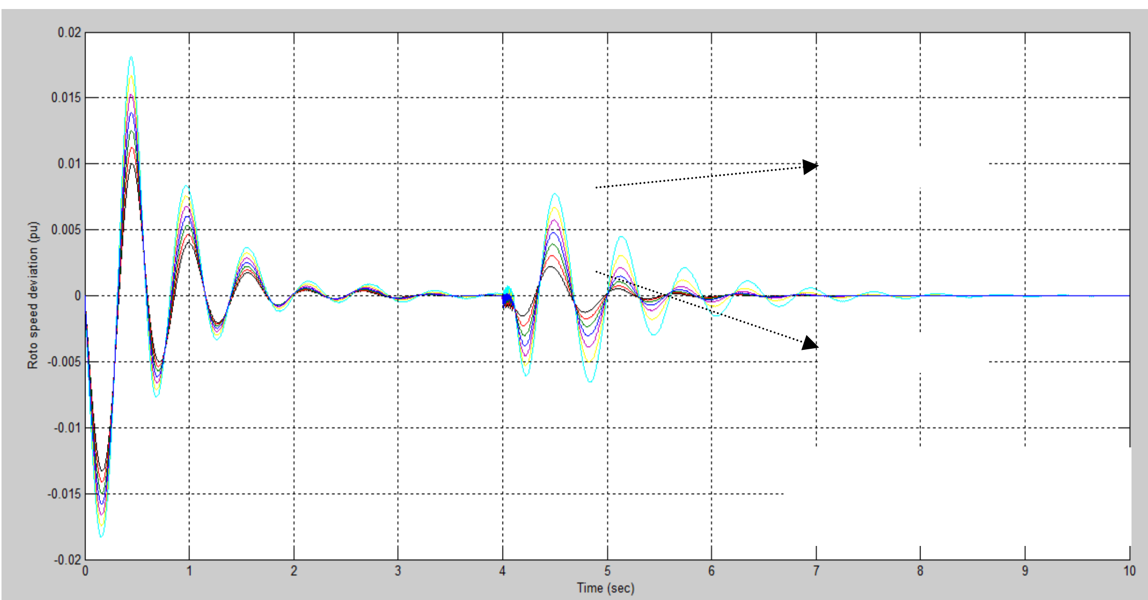


Figure 5.22 Different rotor speed deviations with different values of A_1 for LG fault

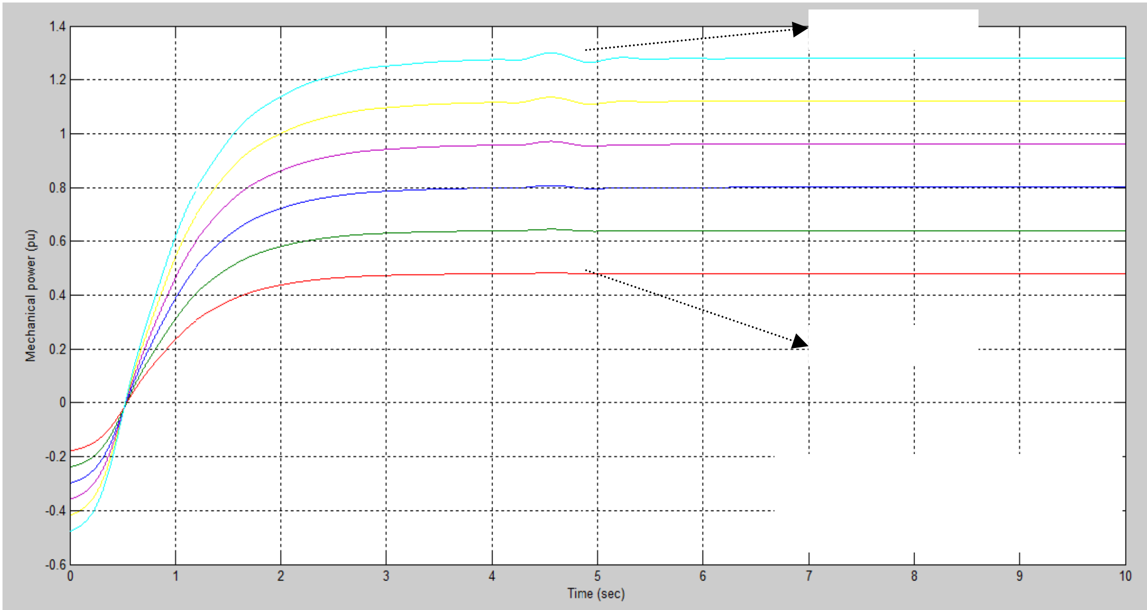


Figure 5.23 Different mechanical powers with different values of A_1 for LG fault

5.5.3.3 With different coefficients of A_2

Table 5.6 Stability indicators with different values of A_2 for LG fault

A_2	Exhaust temp (F)	P_{mech} (pu)	Max rotorspeed deviation (pu)*10^{-3}	Oscillation duration (sec)	Rotor angle (deg)
420	820	0.8	4.8	6.5	13.8
560	778	0.8	4.8	6.5	13.8
700	750	0.8	4.8	6.5	13.8
840	737	0.8	4.8	6.5	13.8
980	720	0.8	4.8	6.5	13.8
1120	700	0.8	4.8	6.5	13.8

The simulation results with different values of A_2 are presented in Table 5.6. The simulation results with LG fault are similar to those of three phase fault except the effect on the indicators due to LG fault is less compared to those of three phase fault.

5.5.4 Simulation Results of 6 bus System

The six bus system (presented in Chapter II) has been modeled with an additional induction machine. Fault is applied near the synchronous machine (at bus 5), near the induction machine (at bus 6), and at bus 4 which is equal distance from both the machines. This section explains the results in detail.

5.5.4.1 No fault

When there is no fault in the system, the base measurements are givens in table 5.7. The speed of the asynchronous machine is quite a bit higher than 1 pu as it is operating in generator mode.

Table 5.7 Terminal voltage & speed of synchronous and induction machines for 6 bus system

Indicators	Synchronous machine	Induction machine
Terminal voltage (pu)	1.053	0.985
Speed (pu)	1.0	1.01

A three phase fault has been applied at buses 5 and 6 (near the induction machine and synchronous machine respectively).

5.5.4.2 Fault at Synchronous generator

Results when 3 phase fault applied near the synchronous generator are presented in Table 5.8.

Table 5.8 Indicators of both machines during 3 phase fault at synchronous generator

	Synchronous machine	Induction machine
Terminal voltage reduction (pu)	0	0.496
Terminal voltage peak (pu)	1.15	1.02
Maximum speed (pu)	1.011	1.019
Settling time (sec)	8	7

When a fault is applied at the synchronous machine, the reduction of the synchronous generator voltage due to the fault is high compared to the voltage of the induction generator. The speed of the synchronous machine has been changed from 1 to 1.011(difference=0.011) and of induction generator from 1.01 to 1.019 (difference=0.009). Hence the increment in the speed of the synchronous generator is high. The settling time of the synchronous machine is high compared to the induction machine which means the asynchronous generator is taking less time to recover from the fault when compared to the synchronous generator.

5.5.4.3 Fault at Asynchronous generator

Results when 3 phase fault applied near the synchronous generator are presented in Table 5.9.

Table 5.9 Indicators of both machines during 3 phase fault at asynchronous generator

	Synchronous machine	Induction machine
Terminal voltage reduction (pu)	0.728	0
Terminal voltage peak (pu)	1.15	1.02
Maximum speed (pu)	1.005	1.019
Settling time (sec)	8	7

When a fault is applied at induction machine, the effect of the terminal voltage magnitude of induction generator has much more impacted compared to that of synchronous generator. The speed of the synchronous generator is increasing from 1.0 to 1.005 (difference=0.005) and that of induction generator is from 1.01 to 1.019 (difference=0.009). Hence the speed change of induction generator is high compared to the synchronous generator.

5.5.4.4 Fault at bus 4

Table 5.10 Indicators of both machines during fault at bus 4 for 6 bus system

	Synchronous machine	Induction machine
Terminal voltage reduction (pu)	0.33	0.05
Terminal voltage peak (pu)	1.15	1.02
Maximum speed (pu)	1.007	1.022
Settling time (sec)	8	7

When a 3-phase fault applied at equal distance from synchronous and induction generators, the change in the speed and the terminal voltages of the synchronous generator are more affected compared to the induction generator except the pu maximum speed.

From the analysis and the results, it is concluded that the change in the induction machine parameters are less compared to the effect on the synchronous generator. The fault contribution of an induction generator is less, usually it dies out within a few cycles [5] and thus the settling time of an induction generator is less compared to the synchronous generator.

5.6 Summary

This chapter presented the details and the classification of the stability. The stability analysis used in this research is explained and all the results including gas turbine integrated with four bus, and six bus systems are given. The transient stability has been assessed using the stability indicators. A three phase and a phase-to-ground fault have been applied near the generator for stability studies. A six bus system studies are performed by applying fault at different locations.

5.7 References

[1] P. Kundur, *Power System Stability and Control*. New York: McGraw Hill, 1994.

[2] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. Van Cutsem, and V. Vittal, "Definition and classification of power system stability", IEEE Transactions on Power Systems, Vol. 19, No. 2, August 2004, pp:1387 – 1401.

[3] J.G. Slootweg and W.L. Kling, "Impacts of distributed generation on power system transient stability", *Proceedings of the IEEE Power engineering society summer meeting*, Jul 2002, Vol 2, pp 862 – 867.

[4] W. I. Rowen, "Simplified mathematical representations of single shaft gas turbines in mechanical drive service," presented at the Int. Gas Turbine and Aeroengine Congr. and Expo., Cologne, Germany, 1992.

[5] C.L Souza, L.M Neto, G.C Guimaraes, A.J Moraes, "Power System Transient Stability Analysis Including Synchronous and Induction Generators", *IEEE porto Power Tech Conference*, Sept 2001.

CHAPTER 6

ECONOMIC AND ENVIRONMENTAL ANALYSIS

6.1 Introduction

This chapter deals with the modeling of the power system for investigating the economic and the environmental impacts using Hybrid Optimization Model for Electric Renewables (HOMER). HOMER is a design model that determines the optimal architecture and control strategy of the hybrid system. Based on the given ratings, HOMER builds all the possible combinations and calculates an optimal solution. It ranks the systems according to the Net Present Cost (NPC). Different biomass energy types: agricultural residues, energy crops, forest residues, and animal waste; are taken as the inputs to the modeled power system and cost optimization analysis was developed. The Net Present Cost (NPC) is taken as the measure to analyze the economic aspects as well as to compare the biomass economics with the diesel source. The main advantage of the biomass is its environment friendly nature. This chapter also explains the detailed analysis on the effect of the different biomass resources on the environment. Research efforts include only studying the effect of carbon dioxide emissions in the environment not the other environmental factors such as sulfur and nitrogen.

HOMER is a powerful software to design micro power systems and to analyze the cost of the power system. Extensive research efforts have been done in HOMER related to the modeling of the hybrid power system and analyzing its economical and environmental impact. The developed hybrid systems include different combinations of diesel, renewable energy sources, photovoltaic cells, or batteries. These hybrid systems are especially applicable for remote villages. The authors in [2] discuss the economic analysis and environmental impacts of integrating the photovoltaic array into diesel-electric power systems for remote villages. The methodology to design the hybrid power system which consists of photovoltaic panel and fuel cells has been presented in [3]. This paper emphasizes on the hydrogen hybrid power system to obtain a reliable autonomous system with the optimization of the components size and the improvement of the capital cost. Authors in [4] present the modeling of the hybrid system consisting of diesel generator to which micro hydro power plant is added. It explains the cost effectiveness and the reduction of the gas pollutants by using hybrid systems and compares it with the conventional diesel source of the same capacity of the load. Modeling of a hybrid system composed of a wind turbine, photovoltaic panels, and fuel cells is discussed in [5]. The authors proposed a new fuzzy logic power flow controller to provide continuous power based on the economic power generation. They concluded from the analysis that the renewable energy sources would be a feasible solution for distribution generation of electric power for standalone application at remote locations.

This chapter explains the modeling of the power system in HOMER in detail by explaining all the components and its cost analysis. The results with different types of the biomass fuels as well as the comparison with the diesel generator will be discussed in detail. The effect of the biomass generation on the environment is emphasized by considering the CO_2 emissions. The results and conclusions from these economic and environmental analyses are presented at the end of this chapter.

6.2. Components in the Model

A simple small power system has been developed in HOMER which consists of a biomass generator, loads, and a grid. The details of these components and the input-output parameters of every component are explained in the following section.

6.2.1 Biomass Generator

HOMER assumes the biomass feedstock is fed into a gasifier to create biogas. One or more generators then consume the biogas to produce electricity. When a generator block is opened, the window appears as shown in Figure 6.1.

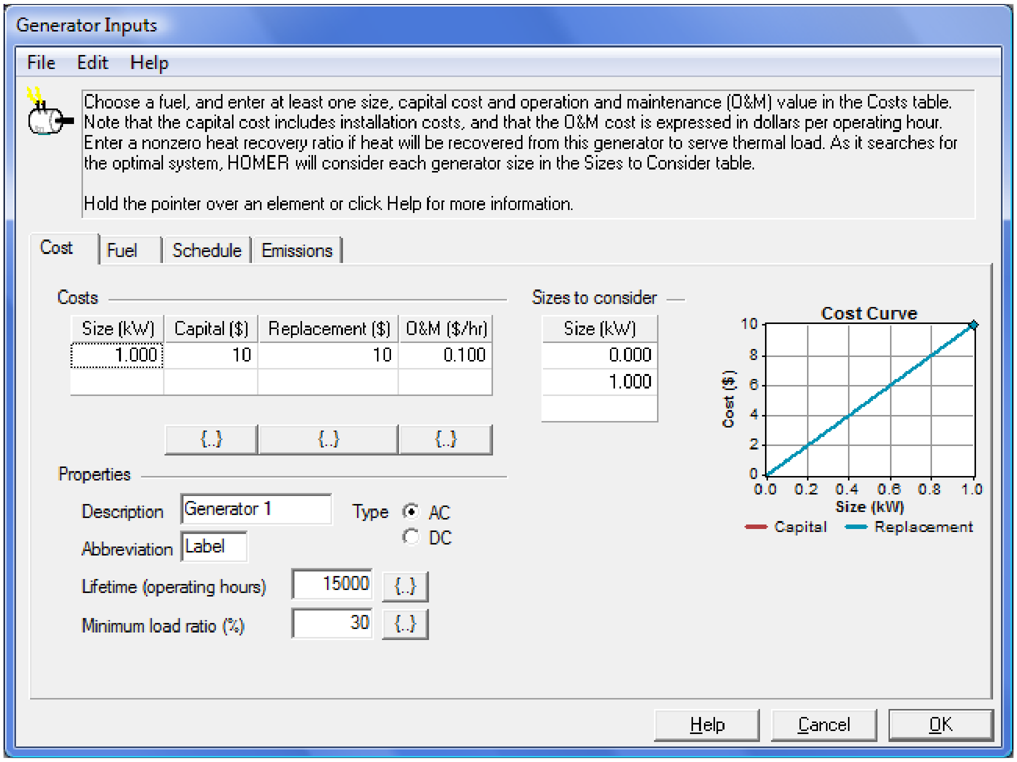


Figure 6.1 Generator dialog window in HOMER

In the cost window, one can give the size of the generator, its capital, replacement, and operational and maintenance cost as the inputs to the generator. Based on the user's data for the size and the cost, it will automatically update the cost curve. In fuel window, the type of fuel can be specified whether it is a biomass, diesel, gasoline, or natural gas. In the schedule tab, the user can indicate whether he or she wants the generator to be ON/OFF at a particular time. The emissions window helps the user to include the amount of carbon monoxide, unburned hydrocarbons, particulate matter, fuel sulfur, or nitrogen oxides released by generating using the particular type of source.

HOMER also can perform sensitivity of the outputs to the changes in the inputs. Different sizes of the generator are considered to study the sensitivity analysis as well as the economic architecture of the power system. The considered generator sizes are: 500 kW, 1100kW, 1209kW, and 1300kW. These sizes of the generators are chosen such that it produces power equal to the peak load, above peak load, and below peak load. Different costs of the generator are given in the table 6.1 [6].

Table 6.1 Costs involved with the biomass generator

Type of cost	$/kW
Capital cost	1000
Replacement cost	800
Operational and maintenance cost	0.01

6.2.2 Load

The load dialog window is as shown in Figure 6.2. Here the user can either upload any load profile file for the whole year or can enter the load profile for the 24 hour period. HOMER automatically calculates the whole year load profile from the 24 hour loads based on the day-to-day random variability and step values.

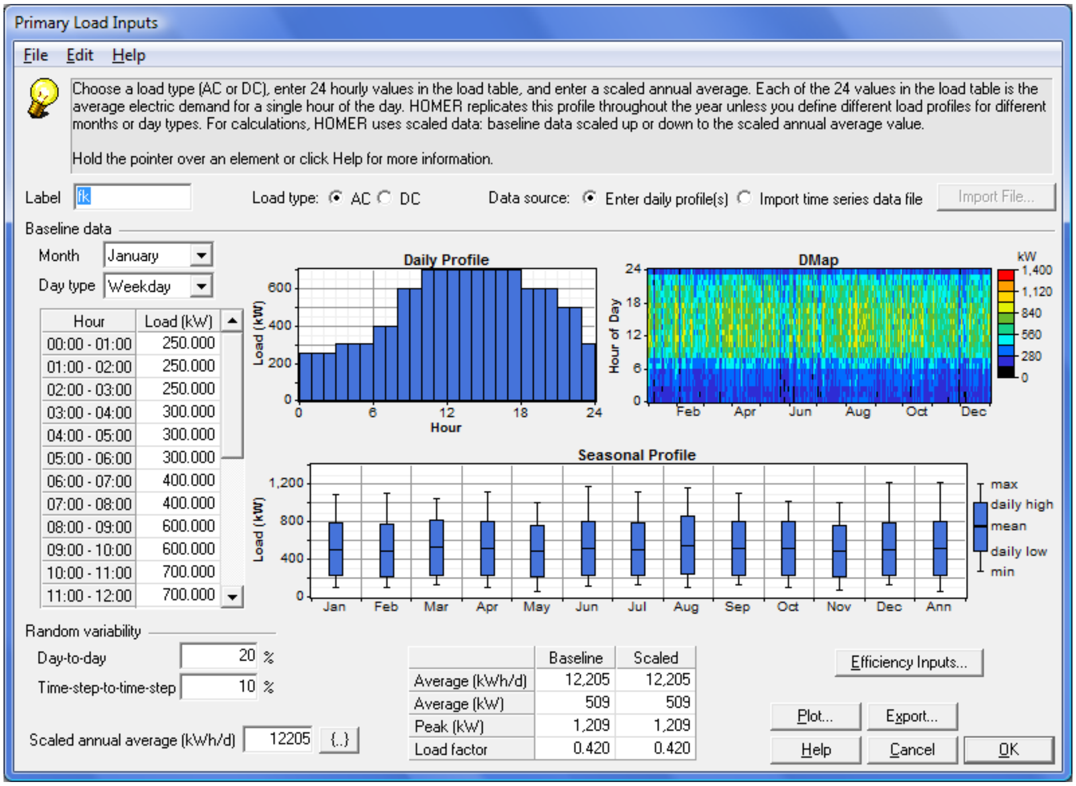


Figure 6.2 Dialog window of load component in HOMER

The daily load profile is as shown in Figure 6.3 [6]. The yearly load profile with 20% day-to-day random variability and time-step-to-step 10% is as shown in Figure 6.4. The peak load considered is 1209 kW and average daily load is 12 MWh/day.

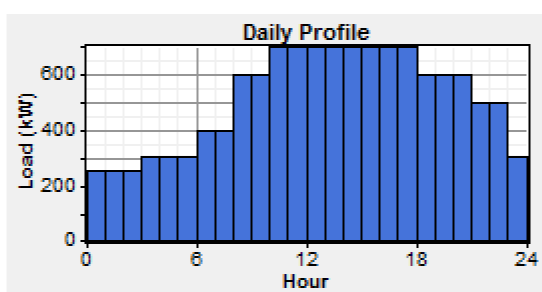


Figure 6.3 Daily load profile example

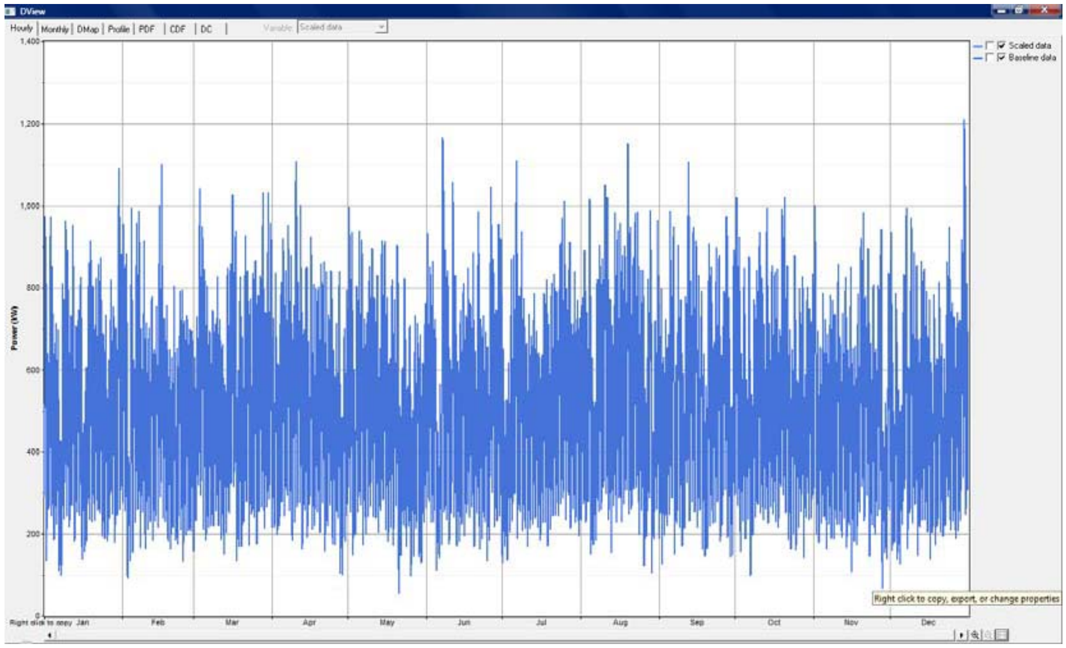


Figure 6.4 Annual load profile example

6.2.3 Grid

The user has three choices on modeling the grid. A user option "Do not model grid" allows the user to model off-grid system. A system connected to the grid can be modeled when "System is connected to grid" button is checked. If the user wants to model an off-grid system but compare its economics with that of grid extension, "Compare stand-alone system to grid extension" option can be selected.

When the system is connected to the grid, the price for buying the power from the grid needs to be specified. If the user does not want to sellback the power, he or she can mention the sellback rate as 0 $/kWh. The grid dialog window is as shown in Figure 6.5. The price for buying the power from the grid is assumed as 0.1$/kWh and for sell back is

0.05 $/kWh [1]. Two different capacities of the grid: 0 and 700 kW are considered for the analysis. While optimizing the power system, HOMER takes both the grid capacities into account and ranks them according to their NPC.

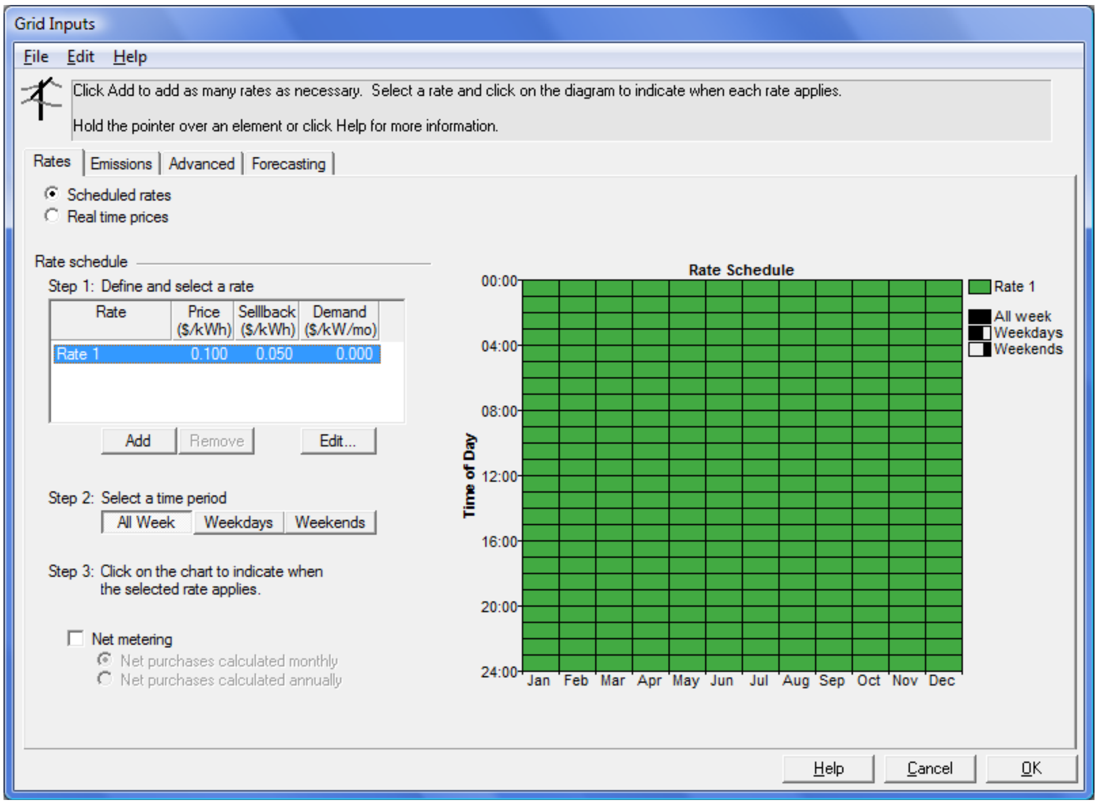


Figure 6.5 Grid dialog window in HOMER

6.3 Biomass Resources

For the analysis, four major biomass resources that are used widely: agricultural residues, forest residues, energy crops, and animal waste are considered. The costs and the availability of these resources are taken as inputs for the simulation.

Agricultural Residues

The agricultural residues can be obtained from field or seed crops, fruit or nut crops, vegetable crops, and nursery crops. Straw or stubble from barley, beans, oats, rice, rye, and wheat, stalks; stovers from corn, cotton, sorghum, soybeans; orchard pruning, brushes, and vegetable crop residues consist mostly of vines and leaves that remain on the ground after harvesting can be used to generate electricity [7]. The availability of the corn in Mississippi is 1,141,000 tons/year and the cost of generating electricity from corn is nearly $ 40/ton [8 and 9]. This cost includes the cleaning, transportation, and storing.

Energy Crops

Energy crops are the fast-growing crops that are grown for the specific purpose of producing energy (electricity or liquid fuels) from all or part of the resulting plant. The most popular energy crops include switchgrass, willow, and poplar. The cost of using energy crops is high compared to the agricultural residues because the agricultural residues are the remaining waste products after harvesting where as the energy crops are grown with the sole aim of producing energy. The cost of the energy crops varies on the type of harvesting field, environment, and the number of acres used for harvesting. The availability of the switchgrass in Mississippi is 4.9 million tons and the cost of the energy crops is approximately $65/ton [10]. This cost includes the harvesting, cleaning, drying, transportation, and storing.

Forest Residues

Forest residues refer to treetops, branches, small-diameter wood, stumps, dead wood and even misshapen whole trees – as well as undergrowth and low-value species [11]. Mississippi logging residues availability is 3.6 million tons/year [12] and the cost of logging residues is nearly $ 30/ton whereas the cost of the pellets is $ 36/ton as it includes cleaning, drying, and pellet making.

Animal Waste

Animal waste can be used to generate electricity by using anaerobic digestion or fermentation technique. Poultry litter, animal dung, and human waste can be used in this process. The availability of cow dung is 9,08,120 tons/year and the cost is approximately $50/ton [13]. This cost includes the cost of the digester, any other equipment for storing, and the transportation.

6.4 Modeling the System in HOMER

The developed model is shown in Figure 6.6. Based on the inputs given for the generator, load, and the grid, the simulations have been done. HOMER ranks the systems by total Net Present Cost (NPC) not by the cost of energy (COE).

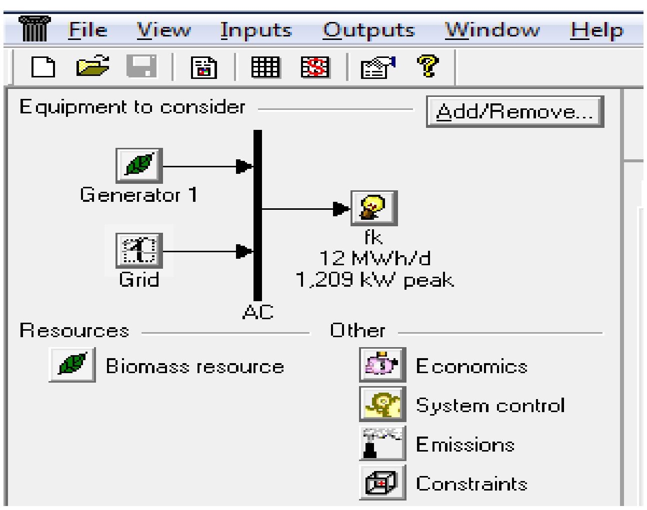


Figure 6.6 Power system test case in HOMER

Net Present Cost (NPC)

Net present cost is the discounted value of all the cash flows needed to operate and purchase the hybrid system over its lifetime. NPC is calculated by using the below formula [1].

$$C_{NPC} = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \tag{6.1}$$

Where

$C_{ann,tot}$-total annualized cost ($/yr), defined as the sum of the annualized costs of each system component, plus the other annualized cost including capital, replacement, and operational and maintenance costs.

CRF (i, N) -capital recovery factor and is the function of the real interest rate and the project lifetime. This factor is used to discount the cash flows to time zero. It is given by the following equation.

$$CRF(i,\ N) = \frac{i(1+i)^N}{(1+i)^{N-1}} \tag{6.2}$$

Where i- interest rate

N- number of years

$CRF(i,\ R_{proj})$- project life time (years)

Cost of Energy

It is the average cost per kWh of useful electrical energy produced by the system. To calculate the COE, HOMER divides the annualized cost of producing electricity with the loads and grid sales. The equation for solving the COE is given below [1].

$$COE = \frac{C_{ann,tot}}{E_{prim}+E_{def}+E_{grid,sales}} \quad (6.3)$$

Where

E_{prim}- primary load served (kWh/yr)

E_{def} – deferrable load served (kWh/yr)

$E_{grid,sales}$ - total grid sales(kWh/yr)

Renewable Fraction

It is the portion of the system's total energy production originating from renewable power sources. The equation for calculating renewable fraction is given in equation [1].

$$f_{ren} = \frac{E_{ren}+H_{ren}}{E_{tot}+H_{tot}} \quad (6.4)$$

E_{ren}- renewable electrical production (kwh)

H_{ren} - renewable thermal production (kwh)

E_{tot} - total electrical production (kwh)

H_{tot} - total thermal production (kwh)

6.5 Simulation Results

The developed power system is tested with four different types of biomass sources and the total net present cost is compared with the conventional energy source. A range of costs is taken rather than a single value as the costs of these sources may vary time to time. Hence a range of net present costs exist. The results with agricultural residues, energy crops, forest products, animal waste, and diesel are presented in Figures 6.7 to 6.11 based on screenshot from HOMER. In the results, the label and grid columns show the available biomass generators and grid of different capacities. Columns 5 and 6 give the initial and operating costs of different configurations. As mentioned, total NPC is a measure to find the optimal solution. The renewable fraction of the energy from the biomass, tons of biomass used to generate power, and the hours of operation are given in the results.

Sensitivity Results | Optimization Results

Sensitivity variables

Biomass Price ($/t) 30

Double click on a system below for simulation results.

		Label (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Biomass (t)	Label (hrs)
		500	700	$ 500,000	527,570	$ 7,244,118	0.127	0.30	4,886	2,631
		1100	700	$ 1,100,000	638,777	$ 9,265,714	0.163	0.45	8,210	2,631
		1209	700	$ 1,209,000	660,760	$ 9,655,735	0.170	0.45	8,457	2,631
		1300	700	$ 1,300,000	679,121	$ 9,981,440	0.175	0.45	8,662	2,631
		1100	0	$ 1,100,000	1,228,122	$ 16,799,514	0.295	1.00	21,479	8,760
		1209	0	$ 1,209,000	1,317,811	$ 18,055,052	0.317	1.00	22,541	8,760
		1300	0	$ 1,300,000	1,393,471	$ 19,113,240	0.336	1.00	23,453	8,760

Sensitivity Results | Optimization Results

Sensitivity variables

Biomass Price ($/t) 40

Double click on a system below for simulation results.

		Label (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Biomass (t)	Label (hrs)
		500	700	$ 500,000	563,776	$ 7,706,952	0.135	0.10	2,355	2,631
		1100	700	$ 1,100,000	704,666	$ 10,107,999	0.177	0.20	4,968	2,631
		1209	700	$ 1,209,000	730,326	$ 10,545,023	0.185	0.21	5,457	2,631
		1300	700	$ 1,300,000	751,761	$ 10,910,032	0.192	0.23	5,866	2,631
		1100	0	$ 1,100,000	1,442,915	$ 19,545,302	0.343	1.00	21,479	8,760
		1209	0	$ 1,209,000	1,543,221	$ 20,936,540	0.368	1.00	22,541	8,760
		1300	0	$ 1,300,000	1,628,004	$ 22,111,350	0.388	1.00	23,453	8,760

Sensitivity Results | Optimization Results

Sensitivity variables

Biomass Price ($/t) 45

Double click on a system below for simulation results.

		Label (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Biomass (t)	Label (hrs)
		500	700	$ 500,000	575,552	$ 7,857,481	0.138	0.10	2,355	2,631
		1100	700	$ 1,100,000	729,507	$ 10,425,552	0.183	0.20	4,968	2,631
		1209	700	$ 1,209,000	757,611	$ 10,893,810	0.191	0.21	5,457	2,631
		1300	700	$ 1,300,000	781,090	$ 11,284,948	0.198	0.23	5,866	2,631
		1100	0	$ 1,100,000	1,550,312	$ 20,918,194	0.367	1.00	21,479	8,760
		1209	0	$ 1,209,000	1,655,925	$ 22,377,284	0.393	1.00	22,541	8,760
		1300	0	$ 1,300,000	1,745,270	$ 23,610,404	0.415	1.00	23,453	8,760

Figure 6.7 Results with Agricultural Residues for the price of 30-45 $/ton

Sensitivity Results | Optimization Results

Sensitivity variables

Biomass Price ($/t) 60

Double click on a system below for simulation results.

Label (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Biomass (t)	Label (hrs)
500	700	$ 500,000	610,878	$ 8,309,066	0.146	0.10	2,355	2,631
1100	700	$ 1,100,000	804,031	$ 11,378,210	0.200	0.20	4,968	2,631
1209	700	$ 1,209,000	839,464	$ 11,940,173	0.210	0.21	5,457	2,631
1300	700	$ 1,300,000	869,075	$ 12,409,697	0.218	0.23	5,866	2,631
1100	0	$ 1,100,000	1,872,503	$ 25,036,876	0.440	1.00	21,479	8,760
1209	0	$ 1,209,000	1,994,039	$ 26,699,516	0.469	1.00	22,541	8,760
1300	0	$ 1,300,000	2,097,068	$ 28,107,572	0.494	1.00	23,453	8,760

Sensitivity Results | Optimization Results

Sensitivity variables

Biomass Price ($/t) 65

Double click on a system below for simulation results.

Label (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Biomass (t)	Label (hrs)
500	700	$ 500,000	622,653	$ 8,459,595	0.149	0.10	2,355	2,631
1100	700	$ 1,100,000	828,872	$ 11,695,763	0.205	0.20	4,968	2,631
1209	700	$ 1,209,000	866,749	$ 12,288,961	0.216	0.21	5,457	2,631
1300	700	$ 1,300,000	898,404	$ 12,784,613	0.224	0.23	5,866	2,631
1100	0	$ 1,100,000	1,979,900	$ 26,409,768	0.464	1.00	21,479	8,760
1209	0	$ 1,209,000	2,106,744	$ 28,140,258	0.494	1.00	22,541	8,760
1300	0	$ 1,300,000	2,214,334	$ 29,606,624	0.520	1.00	23,453	8,760

Sensitivity Results | Optimization Results

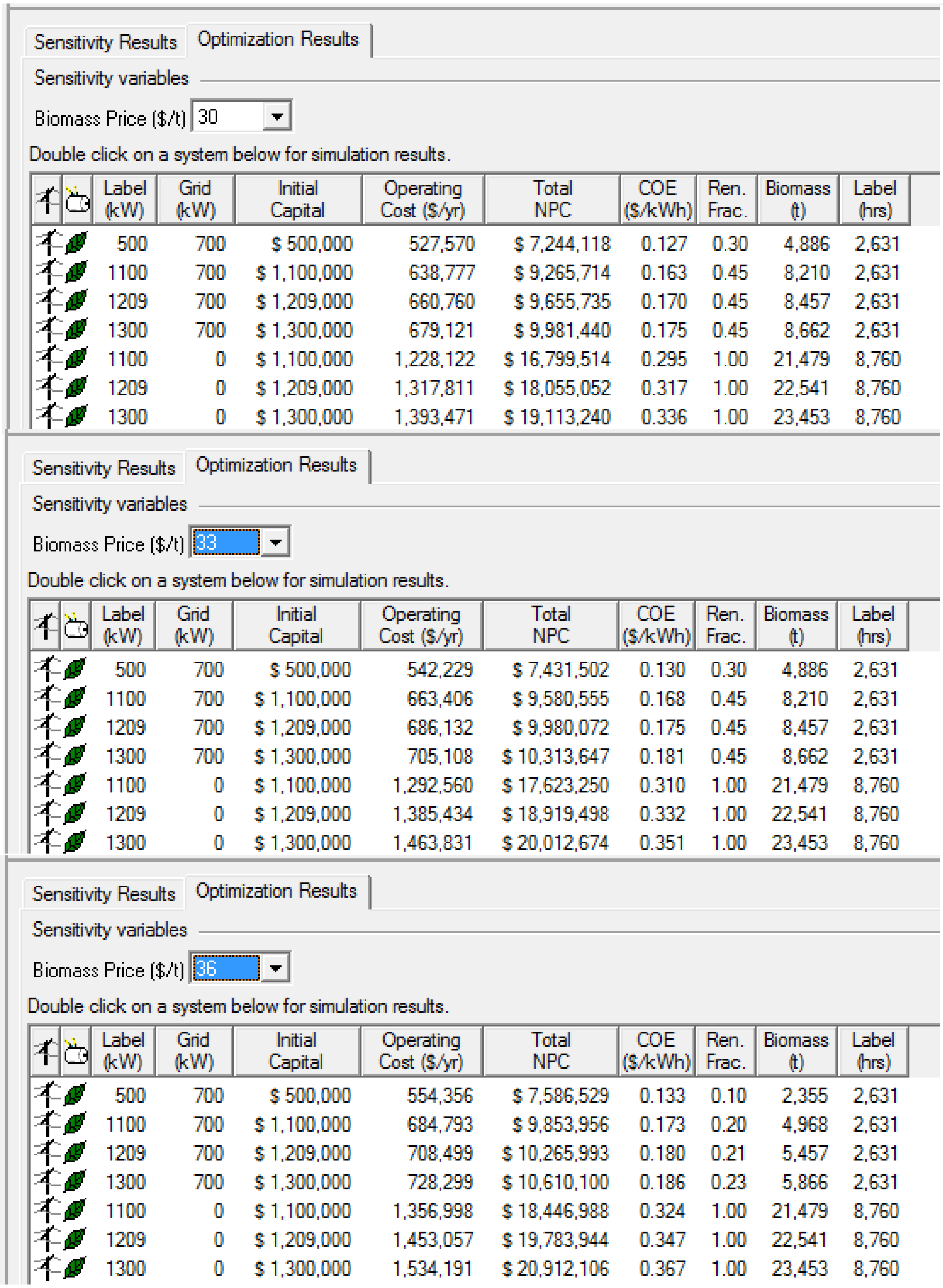
Sensitivity variables

Biomass Price ($/t) 70

Double click on a system below for simulation results.

Label (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Biomass (t)	Label (hrs)
500	700	$ 500,000	634,428	$ 8,610,123	0.151	0.10	2,355	2,631
1100	700	$ 1,100,000	853,713	$ 12,013,316	0.211	0.20	4,968	2,631
1209	700	$ 1,209,000	894,033	$ 12,637,749	0.222	0.21	5,457	2,631
1300	700	$ 1,300,000	927,732	$ 13,159,529	0.231	0.23	5,866	2,631
1100	0	$ 1,100,000	2,087,297	$ 27,782,664	0.488	1.00	21,479	8,760
1209	0	$ 1,209,000	2,219,449	$ 29,581,004	0.519	1.00	22,541	8,760
1300	0	$ 1,300,000	2,331,601	$ 31,105,680	0.546	1.00	23,453	8,760

Figure 6.8 Results with Energy Crops for the price of 60-70 $/ton



Sensitivity Results | Optimization Results

Sensitivity variables

Biomass Price ($/t) 30

Double click on a system below for simulation results.

Label (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Biomass (t)	Label (hrs)
500	700	$ 500,000	527,570	$ 7,244,118	0.127	0.30	4,886	2,631
1100	700	$ 1,100,000	638,777	$ 9,265,714	0.163	0.45	8,210	2,631
1209	700	$ 1,209,000	660,760	$ 9,655,735	0.170	0.45	8,457	2,631
1300	700	$ 1,300,000	679,121	$ 9,981,440	0.175	0.45	8,662	2,631
1100	0	$ 1,100,000	1,228,122	$ 16,799,514	0.295	1.00	21,479	8,760
1209	0	$ 1,209,000	1,317,811	$ 18,055,052	0.317	1.00	22,541	8,760
1300	0	$ 1,300,000	1,393,471	$ 19,113,240	0.336	1.00	23,453	8,760

Sensitivity Results | Optimization Results

Sensitivity variables

Biomass Price ($/t) 33

Double click on a system below for simulation results.

Label (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Biomass (t)	Label (hrs)
500	700	$ 500,000	542,229	$ 7,431,502	0.130	0.30	4,886	2,631
1100	700	$ 1,100,000	663,406	$ 9,580,555	0.168	0.45	8,210	2,631
1209	700	$ 1,209,000	686,132	$ 9,980,072	0.175	0.45	8,457	2,631
1300	700	$ 1,300,000	705,108	$ 10,313,647	0.181	0.45	8,662	2,631
1100	0	$ 1,100,000	1,292,560	$ 17,623,250	0.310	1.00	21,479	8,760
1209	0	$ 1,209,000	1,385,434	$ 18,919,498	0.332	1.00	22,541	8,760
1300	0	$ 1,300,000	1,463,831	$ 20,012,674	0.351	1.00	23,453	8,760

Sensitivity Results | Optimization Results

Sensitivity variables

Biomass Price ($/t) 36

Double click on a system below for simulation results.

Label (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Biomass (t)	Label (hrs)
500	700	$ 500,000	554,356	$ 7,586,529	0.133	0.10	2,355	2,631
1100	700	$ 1,100,000	684,793	$ 9,853,956	0.173	0.20	4,968	2,631
1209	700	$ 1,209,000	708,499	$ 10,265,993	0.180	0.21	5,457	2,631
1300	700	$ 1,300,000	728,299	$ 10,610,100	0.186	0.23	5,866	2,631
1100	0	$ 1,100,000	1,356,998	$ 18,446,988	0.324	1.00	21,479	8,760
1209	0	$ 1,209,000	1,453,057	$ 19,783,944	0.347	1.00	22,541	8,760
1300	0	$ 1,300,000	1,534,191	$ 20,912,106	0.367	1.00	23,453	8,760

Figure 6.9 Results with Forest Products for the price of 30-36 $/ton

Sensitivity Results | Optimization Results

Sensitivity variables

Biomass Price ($/t) 46

Double click on a system below for simulation results.

	Label (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Biomass (t)	Label (hrs)
	500	700	$ 500,000	577,907	$ 7,887,586	0.139	0.10	2,355	2,631
	1100	700	$ 1,100,000	734,476	$ 10,489,062	0.184	0.20	4,968	2,631
	1209	700	$ 1,209,000	763,068	$ 10,963,568	0.193	0.21	5,457	2,631
	1300	700	$ 1,300,000	786,955	$ 11,359,931	0.199	0.23	5,866	2,631
	1100	0	$ 1,100,000	1,571,792	$ 21,192,774	0.372	1.00	21,479	8,760
	1209	0	$ 1,209,000	1,678,466	$ 22,665,432	0.398	1.00	22,541	8,760
	1300	0	$ 1,300,000	1,768,723	$ 23,910,216	0.420	1.00	23,453	8,760

Sensitivity Results | Optimization Results

Sensitivity variables

Biomass Price ($/t) 48

Double click on a system below for simulation results.

	Label (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Biomass (t)	Label (hrs)
	500	700	$ 500,000	582,617	$ 7,947,798	0.140	0.10	2,355	2,631
	1100	700	$ 1,100,000	744,412	$ 10,616,084	0.186	0.20	4,968	2,631
	1209	700	$ 1,209,000	773,982	$ 11,103,083	0.195	0.21	5,457	2,631
	1300	700	$ 1,300,000	798,687	$ 11,509,898	0.202	0.23	5,866	2,631
	1100	0	$ 1,100,000	1,614,751	$ 21,741,932	0.382	1.00	21,479	8,760
	1209	0	$ 1,209,000	1,723,548	$ 23,241,730	0.408	1.00	22,541	8,760
	1300	0	$ 1,300,000	1,815,629	$ 24,509,838	0.430	1.00	23,453	8,760

Sensitivity Results | Optimization Results

Sensitivity variables

Biomass Price ($/t) 50

Double click on a system below for simulation results.

	Label (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Biomass (t)	Label (hrs)
	500	700	$ 500,000	587,327	$ 8,008,009	0.141	0.10	2,355	2,631
	1100	700	$ 1,100,000	754,348	$ 10,743,105	0.189	0.20	4,968	2,631
	1209	700	$ 1,209,000	784,895	$ 11,242,598	0.197	0.21	5,457	2,631
	1300	700	$ 1,300,000	810,418	$ 11,659,864	0.205	0.23	5,866	2,631
	1100	0	$ 1,100,000	1,657,709	$ 22,291,088	0.391	1.00	21,479	8,760
	1209	0	$ 1,209,000	1,768,630	$ 23,818,026	0.418	1.00	22,541	8,760
	1300	0	$ 1,300,000	1,862,536	$ 25,109,458	0.441	1.00	23,453	8,760

Figure 6.10 Results with Animal waste for the price of 46-50 $/ton

Sensitivity Results | Optimization Results

Sensitivity variables

Diesel Price ($/L) 0.6

Double click on a system below for simulation results.

		Label (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Label (hrs)
		500	700	$ 100,000	541,528	$ 7,022,551	0.123	0.00	212,646	2,631
		1100	700	$ 220,000	653,059	$ 8,568,290	0.150	0.00	449,190	2,631
		1209	700	$ 241,800	673,574	$ 8,852,337	0.155	0.00	493,406	2,631
		1300	700	$ 260,000	690,698	$ 9,089,443	0.160	0.00	530,350	2,631
		1100	0	$ 220,000	1,257,595	$ 16,296,290	0.286	0.00	1,927,626	8,760
		1209	0	$ 241,800	1,326,154	$ 17,194,498	0.302	0.00	2,025,207	8,760
		1300	0	$ 260,000	1,384,846	$ 17,962,978	0.315	0.00	2,109,098	8,760

Sensitivity Results | Optimization Results

Sensitivity variables

Diesel Price ($/L) 0.8

Double click on a system below for simulation results.

		Label (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Label (hrs)
		500	700	$ 100,000	584,058	$ 7,566,217	0.133	0.00	212,646	2,631
		1100	700	$ 220,000	742,897	$ 9,716,722	0.171	0.00	449,190	2,631
		1209	700	$ 241,800	772,255	$ 10,113,815	0.178	0.00	493,406	2,631
		1300	700	$ 260,000	796,768	$ 10,445,372	0.183	0.00	530,350	2,631
		1100	0	$ 220,000	1,643,121	$ 21,224,596	0.373	0.00	1,927,626	8,760
		1209	0	$ 241,800	1,731,195	$ 22,372,286	0.393	0.00	2,025,207	8,760
		1300	0	$ 260,000	1,806,665	$ 23,355,246	0.410	0.00	2,109,098	8,760

Figure 6.11 Results with Diesel for the price of 0.6-0.8 $/liter

6.5.1 Results Summary

The results presented in Table 6.1 are summarized in Table6.2.

Table 6.2 Net present costs for different fuels

Fuel type	**Fuel cost ($/ton or $/lt)**	**Net present cost (NPC)**
Agricultural residues	30 – 45	$ 7,244,118 – $ 7,857,481
Energy crops	60 – 70	$ 8,309,066 – $ 8,610,123
Forest products	30 – 36	$ 7,244,118 – $ 7,586,529
Animal waste	46 – 50	$ 7,887,586 – $ 8,008,009
Diesel	0.6 – 0.8	$ 7,022,551 – $ 7,566,217

The range of net present costs for the power system with different sources is presented in Table 6.2. Energy crops are costlier than other sources because of its additional harvesting cost. From the results, it is observed that the agricultural and forest residues are cheaper compared to other renewable sources. The cost of generating power from the diesel generator is cheaper than the other renewable energy sources, but the environmental effect from the biomass resources is less compared to the diesel. This study will be discussed in detail in next section. Though right now at this position, the biomass resources are costly compared to the diesel, in future, with the advanced technologies, renewable sources are expected to become cheaper.

6.6 Environmental Impact

Carbon dioxide is the main greenhouse gas that contributes to the global warming. Fossil fuels release CO_2 to the atmosphere during their burning to release the energy. The amount of the CO_2 from the fossil fuels is more when compared to the biomass. Biomass also releases the CO_2 into the atmosphere, but the amount of carbon dioxide emissions will be neutralized with the grown biomass which uses CO_2 in their photosynthesis process. If the biomass resource is being used sustainably, there are no net carbon emissions over the time frame of a cycle of biomass production. In addition minor amounts of greenhouse gases may be created in producing the technology to transform the renewable energy resource into useable energy. The amount of the carbon dioxide emissions from different biomass fuels and of the diesel are clearly studied and analyzed with the help of HOMER.

Figure 6.12 compares the levels of atmospheric greenhouse gases associated with one-million tons of biomass residues converted to energy in the year 2000, with the levels of atmospheric greenhouse gases that would have been caused by the same one-million tons of material in various alternative disposal pathways [14]. It also gives an idea of CO_2 that will be released from different sources for the future years.

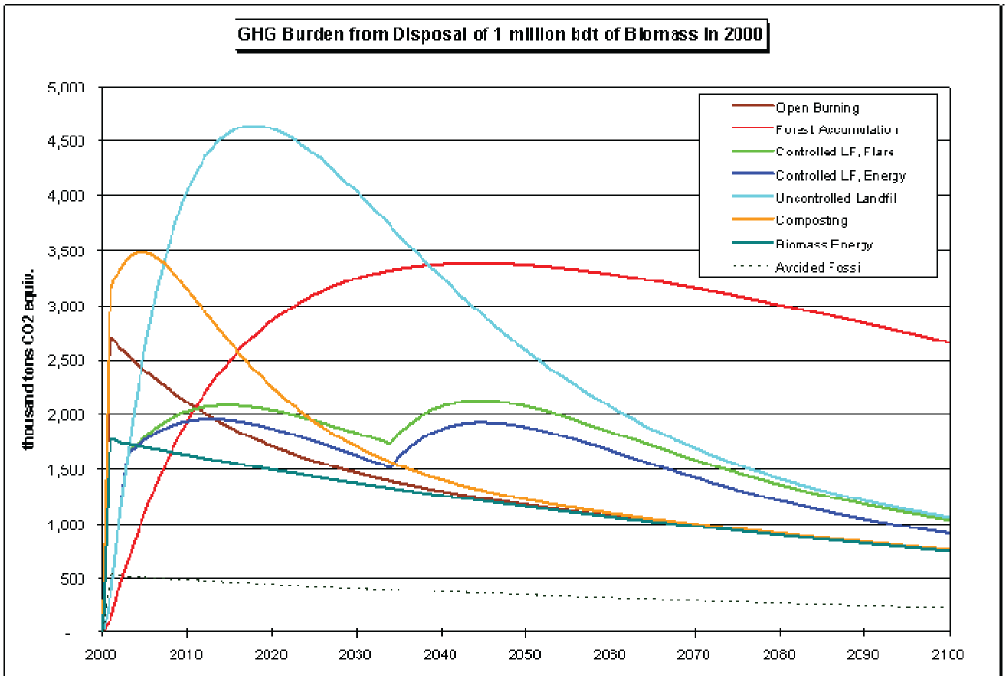


Figure 6.12 CO_2 emissions of different fuels

6.6.1 Simulation Details and Results

The carbon contents of different energy sources are presented in Table 6.3 based on [9, 14-18]

Table 6.3 Carbon content of different sources

No	Fuel type	Carbon content (%)
1	Agricultural resources	47.4
2	Energy crops	40
3	Forest residues	15
4	Animal waste	45
5	Diesel	88

The carbon contents presented in Table 6.3 are taken as the inputs for the power system of different biomass fuels and the simulation results are presented. The quantity of all the biomass fuels obtained is 2355 tons and the CO_2 emissions are given in Table 6.4.

Table 6.4 CO_2 emissions of different sources

No	Fuel type	Quantity	CO_2 emissions (kg/yr)
1	Agricultural resources	2355 tons	2547,986
2	Energy crops	2355 tons	2547,348
3	Forest residues	2355 tons	2545,190
4	Animal waste	2355 tons	2544,284
5	Diesel	212,646 lt/yr	3103,888

The carbon dioxide emissions from the different renewable sources as well as of diesel are shown in table. From the results, it is evident that the CO_2 emissions from the diesel are more compared to the biomass resources as the amount of carbon that is released during the conversion process is high compared to the biomass resources. Though CO_2 emissions of the animal waste is less compared to agricultural and forest residues, the nitrogen emissions are crucial in the process of anaerobic digestion.

6.7 Summary

This chapter explained the economics of the different biomass resources and diesel fuel. HOMER software is used to model the system and to analyze the optimal power output as well as the overall cost of the system. The Net Present Cost (NPC) is taken as the measure to rank the different system combinations. Environmental effect of generating power from the diesel and biomass is presented and the amount of the carbon dioxide emissions that are released during energy release has been discussed based on the simulations.

6.8 References

[1] HOMER software, https://analysis.nrel.gov/homer/

[2] R. W. Wies, Johnson, R.A, Agrawal A.N, and Chubb, T.J, "Simulink model for economic analysis and environmental impacts of a PV with diesel-battery system for remote villages", *IEEE trans. On Power Systems*, Vol.20, Issue.2, pp. 692-700, May 2005.

[3] N N. Barsoum, P Vacent, "Balancing Cost, Operation and Performance in Integrated Hydrogen Hybrid Energy System", *First Asia International Conference on Modeling & Simulation*, pp.14-18.

[4] K Kusakana, J L. Munda, A A. Jimoh, "Economic and environmental analysis of micro hydropower system for rural power supply", *IEEE 2nd International Power ans Energy Conference, 2008*, pp. 441-444.

[5] M S. Alam, D W. Gao, " Modeling and Analysis of a Wind/PV/Fuel Cell Hybrid Power System in HOMER", *Industrial Electronics and Applications*, 2007, pp. 1594-1599.

[6] J H. Christopher, B John, "An Economic Evaluation of Small-scale Distributed Electricity Generation Technologies".accessed: 02-10-2009, available at: http://129.3.20.41/eps/othr/papers/0401/0401001.pdf

[7] P Paswater, "Agricultural and Forest Waste Feasibility Study" accessed: 02-10-2009, available at: http://www.ciwmb.ca.gov/Organics/Conversion/AgForestRpt/Agriculture/

[8] W Samuel, "Mississippi Biomass and Bioenergy Overview". accessed: 02-10-2009, available at: www.25x25.org/storage/25x25/.../Mississippi/mississippi_sungrant.pdf

[9] C Wayne, F Chris, M K. John, and B Warren, "The Feasibility of Generating Electricity from Biomass fuel sources in Georgia". accessed: 02-10-2009, available at: http://www.caed.uga.edu/publications/2003/pdf/FR-03-06.pdf

[10] M E. Walsh and D. Becker, "Biocost: A Software Program to Estimate the Cost of Producing Bioenergy Crops", *Proc., BIOENERGY '96, Biomass Technologies*, September 15-20, 1996.

[11] Wisconsin Biorefineries, "Biobased Feedstock", accessed: 02-10-2009, available at: http://www.wisbiorefine.org/feed/forestresidues.pdf

[12] Jianbang, G, Matthew L, Alan W. H, "Economics of Forest Biomass and Bioenergy" accessed: 02-10-2009, available at: http://essmextension.tamu.edu/publications/files/forestry/ForestBioenergy/6-2.pdf

[13] Renewable energy work group, 21st century energy plant, "Biomass Inventory: Animal Waste to Energy" accessed: 02-10-2009, available at: http://www.dleg.state.mi.us/mpsc/electric/capacity/energyplan/renewables/biomass%20resources.pdf

[14] USA biomass, "Net Greenhouse Gas Emissions from Biomass and Other Renewable Generators". accessed: 02-10-2009, available at: http://www.usabiomass.org/docs/library/Net%20Greenhouse%20Gas%20Emissions%20from%20Biomass%20and%20Other%20Renewable%20Generators.pdf

[15] US environmental protection agency (EPA), "Emission Facts: Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel" accessed: 02-10-2009, available at:. http://www.epa.gov/otaq/climate/420f05001.htm

[16] D C. Amanda and E W. Michael, "Cow power: the energy and emissions benefits of converting manure to biogas", accessed: 02-10-2009, available at: http://iopscience.iop.org/1748-9326/3/3/034002/fulltext?ejredirect=.iopscience

[17] "Animal waste to Power", accessed: 02-10-2009, available at: http://www.gastechnology.org/webroot/app/xn/xd.aspx?it=enweb&xd=4reportspubs\4_8focus\animal_waste_to_powerfocus.xml

[18] Biomass gas and electric, "Biomass Gas & Electric Energy Crop Review", accessed: 02-10-2009, available at: http://www.floridafarmtofuel.com/ppt/2008/farris.ppt

[19] Andy Whittington, "Availability of Poultry Litter as an Alternative Energy, Feedstock: The case of Mississippi", accessed: 02-10-2009, available at: http://ageconsearch.umn.edu/handle/34840

[20] T. Lambert, P. Gilman and P. Lilienthal, "Micropower system modeling with HOMER", accessed: 02-10-2009, available at: www.mistaya.ca/homer/MicropowerSystemModelingWithHOMER.pdf

CHAPTER 7

CONCLUSION AND FUTURE WORK

7.1 Introduction

This chapter gives the summary of the research work done related to modeling of the biomass generation system, and technical as well as the economic impacts of the biomass generation. This chapter concludes the findings, contributions, and the future work.

7.2 Summary

A comprehensive model for the biomass generation including a gas turbine has been developed. Developing a framework for analyzing the transient stability, economic feasibility, and environmental impact are the additional contributions of the research.

The research goals were achieved successfully by developing a gas turbine based on the thermodynamic principles, integrating the gas turbine with the power system, studying the transient stability using the stability indicators and investigating the sensitivity of the stability with respect to the gas turbine parameters. The 4 bus and 6 bus power distribution systems were used as the test case systems for the analysis using MATLAB/Simulink. The economical and environmental analysis is carried out using

HOMER software developed by NREL. A simple power system has been modeled and the net present cost of the different biomass fuels over their life time has been calculated using the built in optimization techniques. A range of the costs were obtained for the biomass and diesel fuels and comparative analysis has been done. The carbon dioxide emissions released by different fuels has been investigated. It is concluded from the work that the overall cost of biomass resources is high compared to the diesel fuel, but the carbon emission from the biomass is less compared to the diesel.

7.3 Research Contributions and Findings

This research work contributes following:

1. Development of comprehensive model for biomass generation.
2. Development of framework for stability analysis for biomass generation integrated to distribution system.
3. Development of framework for economic and environmental analysis for biomass generation integrated to distributed system.
4. Technical, economical, and environmental impacts of biomass.

Major findings of this research work include: from the economical analysis prove that agricultural residues are the most economic biomass resource among the considered biomass fuels. From the environmental analysis, it is concluded that the carbon dioxide emissions from the animal waste are less compared to other biomass resources. These results may vary depending on the plant location and the availability of the resources.

7.4 Future Work

This work can be extended by detailed modeling of a gasifier and to study the system behavior with the gasifier control strategies. More realistic data from the utility plants can be used to do analysis. This research concentrated only on the transient stability analysis, which can be extended to study the system behavior in isolated mode, contingency analysis, and small signal stability in the future. The test case systems included in the study are four and six bus systems. The research can be extended by developing a bigger system consists of different biomass generations as distributed generators.