Sudan University of Science and Technology

College of Graduate Studies

Control of Industrial Gas Turbine Speed

التحكم فى سرعة التوربينة الغازية الصناعية

A Thesis Submitted in Partial Fulfillment to the Requirements for the Degree of M.Sc. in Electrical Engineering (Microprocessor and Control)

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الآية

{ أَمَّنْ هو قانتٌ آناءَ اللَّيلِ ساجداً وقائماً يَحذَرُ الآخرةَ ويَرجو رحمةَ ربِّهِ قلْ هل يستوي الَّذين يعلمونَ والَّذين لا يعلمونَ إنَّما يَتَذكَّرُ أولوا الألباب}

صدق الله العظيم

سورة الزمر الآية (39)

DEDICATIONS

This thesis is dedicated to:

The sake of **Allah**, my Creator and my Master,

My great teacher and messenger, Mohammed (May Allah bless and grant him), who taught us the purpose of life,

My great parents, who never stop giving of themselves in countless ways, my beloved family and those people who have guided and inspired me throughout my journey of education.

ACKNOWLEDGEMENT

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I would like to acknowledge my direct supervisor Dr. Awadalla Taifour Ali for his enthusiasm, inspiration and huge efforts to explain things clearly and simply. I would like to thank the Sudan University of Science and Technology for accepting me in its graduate program and motivated me to do this work.

I can’t end without thanking my friends engineering for knowledge regarding the Sudanese Thermal Power company, and my family. I would like to thank all the people that supported me through my academic way.

ABSTRACT

In this study, speed control system has been designed for the heavy-duty gas turbine. The speed control includes three control loops: acceleration control - speed control -temperature control. Acceleration control determines the speed during the initial start-up period. Then, the speed/load controller is selected by a minimum selector to control the speed of the gas turbines. When the load increases, the torque increases and the speed decreases, the fuel should be increase to maintain the speed of the turbine at requires system.

In this study, the gas turbine speed control system was modeled using MATLAB/SIMULINK and a Proportional-Integral-Derivative (PID) controller was designed to improve system performance.

مستخلص

في هذه الدراسة ، صمم نظام تحكم في سرعة التوربينة الغازية الثقيلة . التحكم في السرعة يشمل ثلاث حلقات تحكم: التحكم فى التسارع - التحكم في السرعه - التحكم فى درجة الحرارة. ويحدد التحكم في التسارع السرعة أثناء فترة البدء الأولية . يتم اختيار وحدة تحكم السرعة / الحمل من قبل الحد الأدنى لمحدد السيطرة على سرعة التوربينات الغازية . بازدياد الحمل يزداد العزم وتقل السرعة ويجب زيادة الوقود ليتضمن سرعه التوربية متطلبات النظام.

في هذه الدراسة ، تم نمذجه نظام التحكم فى سرعه التوربينة الغازية باستخدام برنامج MATLAB/SIMULIN وتم تصميم متحكم Proportional-Integral-Derivative (PID) لتحسين اداء النظام .

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F	Electrical frequency
N	speed of rotor
P	number of poles
e(t)	Error signal
K_p	Proportional gain
K_i	Integral gain
K_d	Derivative gain
K_4	Gain of radiation shield (instantaneous)
K_5	Gain of radiation shield
T_4	Time constant of thermocouple
T_5	Time constant of temperature control
T_t	Overheat control integration rate
F_d	Fuel demand signal
w_f	Fuel demand
V_c	Output of the minimum value gate
E_1	Outputs of the valve position
K_v	Gain valve positioner
T_V	Valve positioner time constant
K_f	Gain fuel system
T_f	Fuel system actuator time constant
K_3	Ratio of fuel adjustment
K_6	Essentially the minimum amount of fuel at no-load
T_{CD}	Compressor discharge volume time constant
T_R	Reference temperature
T_{TD}	Transport delay
c	Constant the valve position
Z	Constant the governor mode
T_x	Exhaust temperature
τ	Torque

LIST OF ABBREVIATIONS

AC	Alternator Current
AGC	Automatic Generation Control
AVR	Automatic Voltage Regulator
DC	Direct Current
EMF	Electrical Magnetic Field
HRSG	Heat Recovery Steam Generator
LFC	Load Frequency Control
PID	Proportional-Integral-Derivative
PMSM	Permanent Magnet Synchronous Machine
PSS	Power System Stabilizer

CHAPTER ONE

INTRODUCTION

1.1 Overview

Gas turbine engine is currently the most sought machine for the purpose of power generation and propulsion application. Its economic viability to fit as one technology solution for multiple energy sources is its key inherent advantage. The gas turbines had its inception in 1791 by John Barber who patented the technology. Then onwards it has undergone various stages of development in various applications. The first gas turbine generator was set up in 1939 and it operated for 63 years [1]. The gas turbine engine is a complex assembly of different components such as compressors, turbines, combustion chambers, etc. The gas turbine usually consists of an axial compressor and combustion chamber and operating turbine. The typical model of industrial gas turbines in stability studies consists of three control loops: speed control, temperature control, acceleration control. The speed control is active during normal operating conditions. The temperature control loop takes control of the gas turbine when the exhaust temperature exceeds a fixed maximum value. The acceleration control loop is designed to take control of the fuel system when the generator experiences an acceleration which exceeds the set limit.

1.2 Problem Statement

Gas turbines have, during the last decades, become more common as a power generating engine due to their flexibility and low specific investment costs. Development of gas turbines for power generation has gone hand in hand with the development of new gas turbines for use in aircraft engines. This increase in the proportion of gas turbine and combined-cycle units in power generation grids will affect the grid characteristics because of the gas turbine performance. Gas turbines will behave differently than other prime movers, e.g., hydroelectric units, when a frequency drop occurs in the system. The difference occurs because the dynamic behavior of the gas turbine depends on its rotational speed, which is proportional to the grid frequency. A drop in the grid frequency lowers the rotational speed of the gas turbine which affects the performance of the gas turbine and this can lead to unit instability during large frequency dips. This issue is more crucial when the gas turbine is used in an isolated grid or in grids with large renewable energy capacity and smart grids. To have a good frequency regulation in a power grid, there should be a balance between production and demand.

1.3 Objectives

The main objectives of this study are to:

- Maintain a constant speed control of the industrial gas turbine.
- Get transfer function for machine.
- Improve system performance using PID controller.
- The speed control simulation will be implemented using MATLAB/SIMULINK software.

1.4 Methodology

The methods to be followed to successfully complete the thesis are:

- Study the previous work.
- Study and clarify all the basic concepts of gas turbine speed control.
- Study PID controller.
- Evaluate performance of system based on simulation MATLAB/SIMULINK results.

1.5 Layout

This thesis consists of five chapters including this chapter. Chapter two gives a theoretical background, power plant, and then type of power generation, synchronous generators and PID controller. Chapter three deals with the system modeling, design and simulation of the gas turbine speed control using MATLAB/SIMULINK. Chapter four handles the simulation results and discussions. Finally chapter five presents conclusions and recommendations.

CHAPTER TWO

THEORETIAL BACKGROUND

2.1 Power Plant

Power plant or a power generating station is basically an industrial location that is utilized for the generation and distribution of electric power in mass scale, usually in the order of several 1000 Watts. These are generally located at the sub-urban regions or several kilometers away from the cities or the load centers, because of its requisites like large land and water demand, along with several operating constraints like the waste disposal etc. For this reason, a power generating station has to not only take care of efficient generation but also the fact that the power is transmitted efficiently over the entire distance. And that's why; transformer switch yard to regulate transmission voltage also becomes an integral part of the power plant. At the center of it, however, nearly all power generating stations has an Alternator Current (AC) generator, which is basically a rotating machine that is equipped to convert energy from the mechanical domain (rotating turbine) into electrical domain by creating relative motion between a magnetic field and the conductor. The energy source harnessed to turn the generator shaft varies widely, and is chiefly dependent on the type of fuel used [2].

2.2 Types of Power Generation

As mention depending on the type of fuel used, the power generating stations as well as the types of power generation are classified. Therefore the three major classifications for power production in reasonably large scale are:

- Thermal power generation
- Nuclear power generation
- Hydro-electric power generation

A part from these major types of power generations could be resorted to small scale generation techniques as well, to serve the discrete demands. These are often referred to as the alternative methods or non-conventional energy of power generation and can be classified as:

- Solar power generation
- Geo-thermal power generation
- Tidal power generation

- Wind power generation

2.3 Thermal Power Generation

The thermal power generation can be classified as:

- Steam turbine engine
- Gas turbine engine

2.4 Steam Turbine Engine

Steam turbine engine is shown in Figure 2.1. uses several types of fuel to boil the water available to steam. This steam is then super-heated in the super heater to extreme high temperature. This super-heated steam is then allowed to enter into the turbine, as the turbine blades are rotated by the pressure of the steam. The turbine is mechanically coupled with alternator in a way that its rotor will rotate with the rotation of which results in the generation of electric power. The steam after entering into the turbine, after having imparted energy into the turbine rotors, the steam is made to pass out of the turbine blades into the steam condenser of turbine in the condenser, cold water at ambient temperature is circulated with the help of pump which leads to the condensation of the low pressure wet steam. Then this condensed water is further supplied to low pressure water heater. Where the low-pressure steam increases the temperature of this feed water, it is again heated in high pressure. This outlines the basic working methodology of a steam turbine power plant [3].

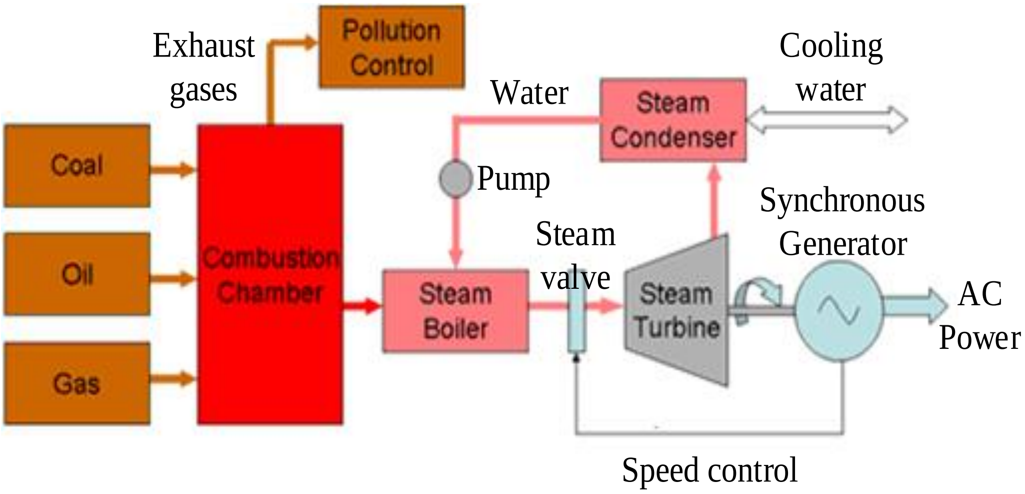

Figure 2.1: Steam turbine engine

2.5 Gas Turbine

The gas turbine is an internal combustion engine that uses air as the working fluid. The engine extracts chemical energy from fuel and converts it to mechanical energy using the gaseous energy of the working fluid (air) to drive the engine.

2.5.1 Type of gas turbine

Gas turbine can be classified as:

A- Open cycle gas turbine

i. Single shaft gas turbine: Single shaft gas turbine is shown in Figure 2.2 is the simplest form of land base gas turbines where compressor and turbine are connected via the same shaft yet they have the same speed of rotation [4].

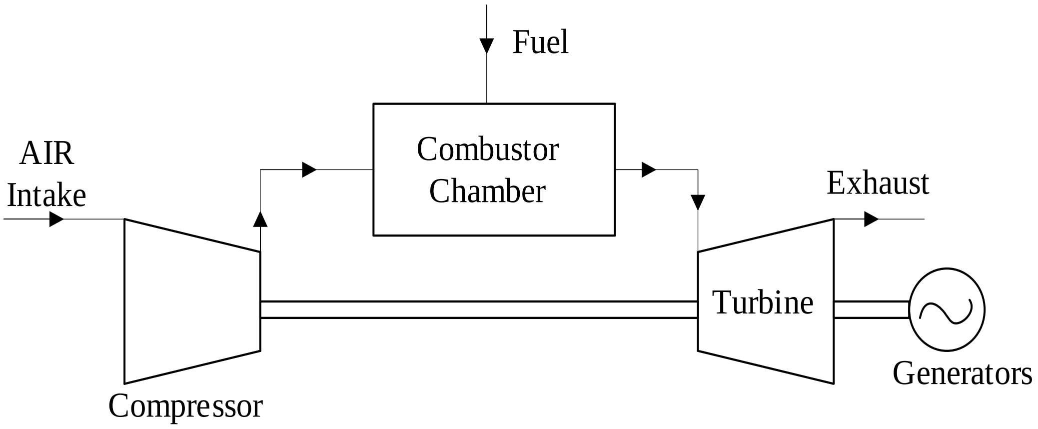

Figure 2.2: Single shaft gas turbine

ii. Two shaft gas turbines: The design of two - shaft gas turbine is shown in Figure 2.3 has the air compressor and gas producer on one shaft and the power turbine on a second independent shaft. This design provides the speed flexibility needed to cover a wider performance map of the driven equipment more efficiently. This allows the gas producer to operate at the speed necessary to develop the horsepower required by the driven equipment such as centrifugal compressors or pumps. Major components include the compressor, combustion system, gas producer turbine, and power turbine. This design includes a two-stage gas producer turbine and a two-stage power turbine [4].

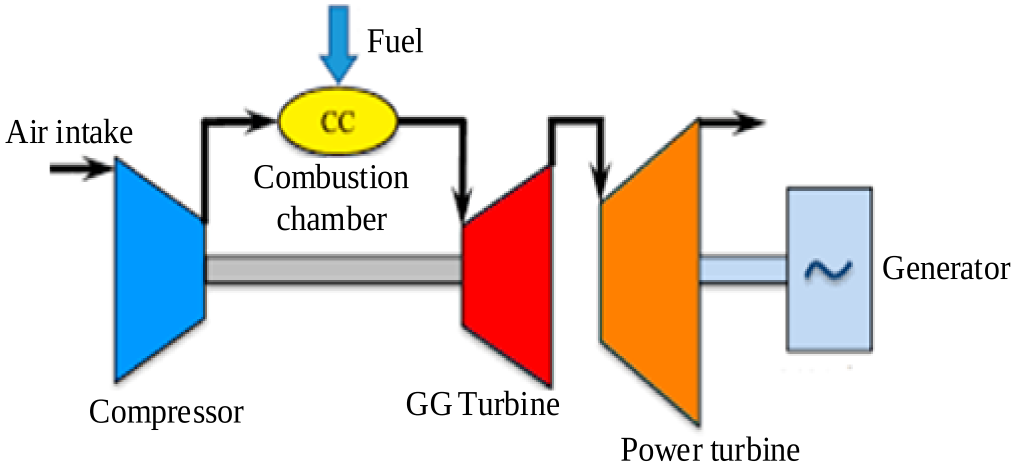

Figure 2.3: Two shaft gas turbine

B- Combined cycle gas turbine

A combined cycle power plant is shown in Figure 2.4 produces electricity in two stages. The first stage is a simple cycle combustion turbine plant. Natural gas or a high-grade fuel such as aviation or diesel fuel is injected and burnt inside the combustor of a gas turbine. The combustion gases drive the rotation of the turbine and the coupled generator to produce electricity. The second stage: the hot gases leaving the gas turbine passes into a boiler to produce steam. This process is called a Heat Recovery Steam Generator (HRSG). The steam then rotates the steam turbine and coupled generator to produce electricity. Combined cycle power plants can reach 60% efficiency [4].

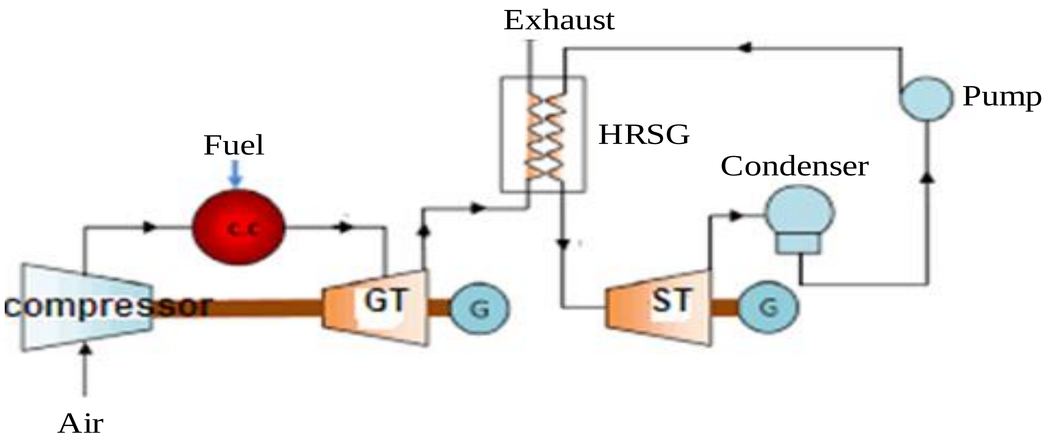

Figure 2.4: Combined cycle gas turbine

C- Closed cycle gas turbine

Closed cycle gas turbines are shown in Figure 2.5 are not so common like open cycles, on these engines the working fluid that is exit from turbine is goes through heat rejection process and recycled a gain as input for compressor, examples of working fluid used in this cycle are hydrogen, helium [4].

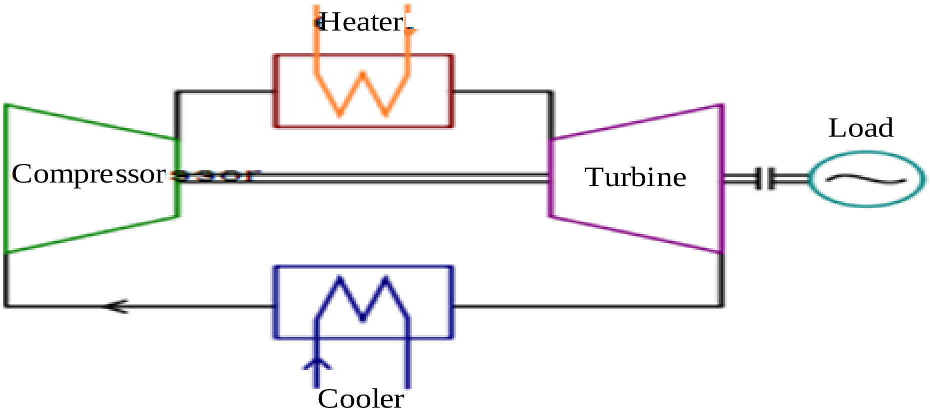

Figure 2.5: Closed cycle gas turbine

2.5.2 Major component of gas turbine

The gas turbine contains the following major component:

A- Air inlet system

Gas turbine consumes large mass of air. The main parts of air intake filter house is normally designed to have large shape so to make sure that the pressure drop across it will minimize, it contains air filter and air intake silencer.

i. Air filter element: Air entering compressor must be filtered from any dust or residues that may enter and cause fouling to the which reduce compressor blades efficiency, the use of series of filter instead of one big filter is more practical because design and erection complexity are reduced, also if pressure drop in air intake increases, a set of small filters can easily be removed instead of removing the hall big filter [4].

ii. Air intake silencer: Due to high speed of air intake filter house, a large noise level will produce and silencer must be used to reduce noise level.

B- Compressor

The compressor is located at the front behind the air intake, it consist of spinning fan with a number of fixed blades arranged in several rows. Air is drawn into the engine from its surroundings by using compressor fans. These fans are driven from the turbine by a shaft. This air is heated by being compressed and is led into one of several combustion chambers. Compressor can reach typical pressure up to forty times higher than atmospheric pressure. The objective of compressor is to compress the air to:

- Combustion chamber
- Turbine cooling system
- Bearing and sealing

C- Combustion chamber

Adds heat energy to the airflow, the output power of the gas turbine is directly proportional to the combustor firing temperature; i.e., the combustor is designed to increase the air temperature up to the material limits of the gas turbine while maintaining a reasonable pressure drop. Type of combustion chamber:

- can type
- annular type
- silo type

D- Turbine

The turbine converts the gaseous energy of the air/burned fuel mixture out of the combustor into mechanical energy to drive the compressor, driven accessories, and, through a reduction gear, the propeller. The turbine converts gaseous energy into mechanical energy by expanding the hot, high-pressure gases to a lower temperature and pressure. Each stage of the turbine consists of a row of stationary vanes followed by a row of rotating blades. This is the reverse of the order in the compressor. In the compressor energy is added to the gas by the rotor blades, and then converted to static pressure by the stator vanes. In the turbine, the stator vanes increase gas velocity, and then the rotor blades extract energy. The vanes and blades are airfoils that provide for a smooth flow of the gases. As the airstream enters the turbine section from the combustion section, it is accelerated through the first stage stator vanes. The stator vanes also called nozzles form convergent ducts that convert the gaseous heat and pressure energy into higher velocity gas flow. In addition to accelerating the gas, the vanes turn the flow to direct it into the rotor blades at the optimum angle. As the mass of the high velocity gas flows across the turbine blades, the gaseous energy is converted to mechanical energy. Velocity, temperature and pressure of the gas are sacrificed in order to rotate the turbine to generate shaft power. The efficiency of the turbine is determined by how well it extracts mechanical energy from the hot, high-velocity gasses. Since air flows from a high-pressure zone to a low- pressure zone, this task is accomplished fairly easily. The use of properly positioned airfoils allows a smooth flow and expansion of gases through the blades and vanes of the turbine [4].

E- Exhaust

After the gas has passed through the turbine, it is discharged through the exhaust, though most of the gaseous energy is converted to mechanical energy by the turbine, a significant amount of power remains in the exhaust gas. This gas energy is accelerated through the convergent duct shape of the exhaust to make it more useful as jet thrust - the principle of equal and opposite reaction means that the force of the exhausted air drives the airplane forward [4].

2.6 Synchronous Generators

Three phase synchronous generators are the primary source of all the electrical energy we consume. These machines are the largest energy converters in the world. They convert mechanical energy into electrical energy, in power ranging up to 1500MW. Synchronous machines are principally used as AC generators. They supply the electric power used by all sectors of modern societies: industrial, commercial, agricultural and domestic. Synchronous generators usually operate together or in parallel, forming a large power system supplying electrical energy to the loads or consumers. Synchronous generators are built in large units. The source of mechanical power, the prime mover, may be a diesel engine, a steam turbine, a water turbine, gas turbine or any similar device [5].

2.6.1 Generator construction

The important parts of the generator synchronous are:

A- Stator

The stationary part of the generator is called stator. It includes various as following:

i. Stator frame: It is the outer body of the generator made of cast iron.

ii. Stator core: The stator core is made of silicon steel material. It is made from a number of stamps which are insulated from each other. Its function is to provide an easy path for the magnetic lines of force and accommodate the stator winding.

iii. Stator winding: Slots are cut on the inner periphery of the stator core in which three phases or one phase winding is placed. Enameled copper is used as winding material. The winding is star connected. The winding of each phase is distributed over several slots. When the current flows in a distributed winding it produces an essentially sinusoidal space distribution of EMF.

B- Rotor

The rotating part of the generator is called rotor. There are two types of rotor construction, namely the salient pole type and the cylindrical rotor type.

i. Rotor core: The rotor core is made of silicon steel stampings. It is placed on the shaft. At the outer periphery, slots are cut in which exciting coils are placed.

ii. Rotor winding or exciting winding: It is placed on the rotor slots, and current is passed through the winding in such a way that the poles are formed according to the requirement.

iii. Slip rings: Slip rings provide Direct Current (DC) supply to the rotor windings.

C- Miscellaneous parts

The miscellaneous parts are:

i. Brushes: Brushes are made of carbon, and they slip over the slip rings. A DC supply is given to the brushes. Current flows from the brushes to the slip rings and then to the exciting windings.

ii. Bearings: Bearings are provided between the shaft and the outer stationary body to reduce the friction. They are made of high carbon steel.

iii. Shaft: The shaft is made of mild steel. Mechanical power is taken or given to the machine through the shaft.

2.6.2 Control of generator

There are several ways to control generators:

A. Excitation system

The performance requirements of the excitation system are determined by considerations of the synchronous generator. The basic requirement is that the excitation system supply and automatically adjusts the field current of the synchronous generator to maintain the terminal voltage as the output varies within the continuous capability of the generator. The excitation system should contribute to effective control of voltage and enhancement of system stability. It should be capable of responding rapidly to a disturbance so as to enhance transient stability and of modulating to generator field so as to enhance small-signal stability. The typical excitation control system for a large synchronous generator is shown in Figure 2.6 [6].

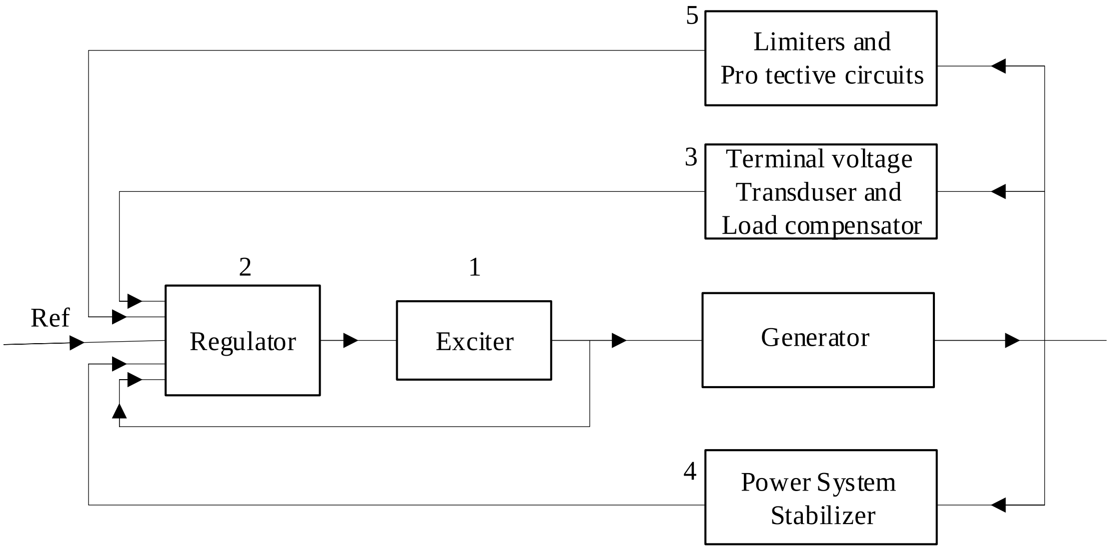

Figure 2.6: Functional block diagram of the typical excitation control

1. Exciter: Provides DC power to the synchronous machine field winding, constituting the power stage of the excitation system.
2. Regulator: Processes and amplifies input control signals to a level and form appropriate for control of the exciter. This includes both regulating and excitation system stabilizing functions rate feedback or lead-lag compensation.
3. Terminal voltage transducer and load compensator: senses generator terminal voltage rectifies and filters it to DC quantity, and compares it with a reference which represents the desired terminal voltage.
4. Power system stabilizer: provides an additional input signal to the regulator to damp power system oscillations. Some commonly used input signals are rotor speed deviation, accelerating power, and frequency deviation.
5. Limiters and protective circuits: These include a wide array of control and protective functions which ensure that the capability limits of the exciter and

synchronous generator are not exceeded. Some of the commonly used functions are the field-current limiter, maximum excitation limiter, terminal voltage limiter, volts-per-Hertz regulator and protection and under excitation limit.

The Types of excitation systems are:

i. DC excitation system: The DC excitation system is shown in Figure 2.7 is utilizes dc generators as source of excitation power and provides current to the rotor of the synchronous generator through slip rings. The exciter may be driven by a motor or the shaft of the generator. It may be either self -excited or separated excited. When separately excited, the excited field is supplied by a pilot exciter comprising a permanent magnet generator [6].

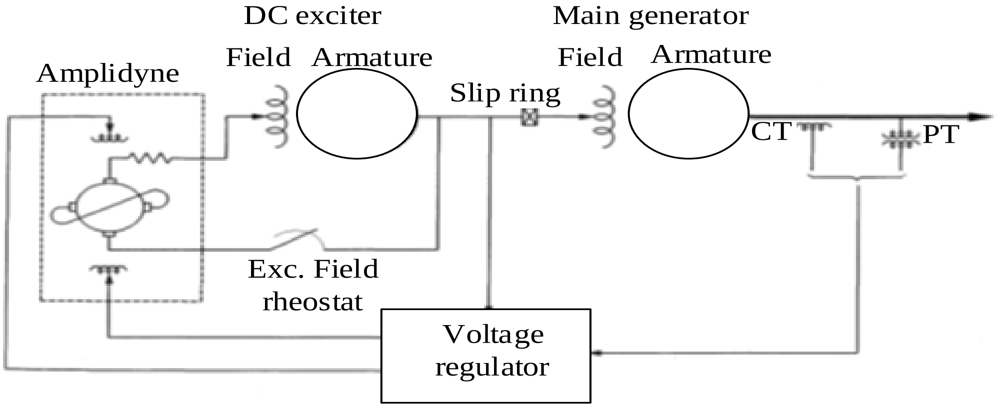

Figure: 2.7: DC excitation system

ii. AC excitation system: The system utilizes alternators ac generator as source of the main generator excitation power. The exciter is on the same shaft as the turbine generator. The ac output of the exciter is rectified by controlled or non- controlled rectifiers to produce the direct current needed for the generator field. The rectifiers may be stationary or rotating .AC excitation systems can thus take many forms depending on the rectifier arrangement in use:

- Stationary rectifier systems
- Rotating rectifier systems

iii. Static excitation system: All components in these systems are static or stationary. Static rectifiers, controlled or uncontrolled, supply the excitation current directly to the field of the main synchronous generator through slip rings. The supply of power to the rectifiers is from the main generator through a transformer to step down the voltage to an appropriate level, or in some cases from auxiliary windings in the generator. The following of three forms of static excitation system:

- Potential – source controlled – rectifier system
- Compound – source rectifier system
- Compound – controlled rectifier excitation systems

B. Automatic Voltage Regulator

Automatic Voltage Regulator (AVR) is shown in Figure 2.8 is regulate the generator's terminal voltage by controlling the amount of exciter's current fed to the generator's field winding. Basically the AVR function for generator is to ensure voltage generated from power generator running smooth to maintain the stable voltage in specified limit. It can stabilize the voltage value when suddenly change of load for power supply demand, If the generator running in parallel condition, the AVR can controlled the voltage that it produce to ensure of equal value for reactive load sharing. For the big system of interconnected power distribution with parallel design, it must have a full controlled and transient stability particular must added for requirement to the AVR for generator [6].

AVR sub system also includes a number of limiters whose function is to protect the AVR, exciter and generator from excessive voltage and currents. They do this by maintaining the AVR signals between preset limits. Thus, the amplifier is protected against excessively high input signals, the exciter and the generator against too high a field current, the generator against too high and armature current and too high a power angle.

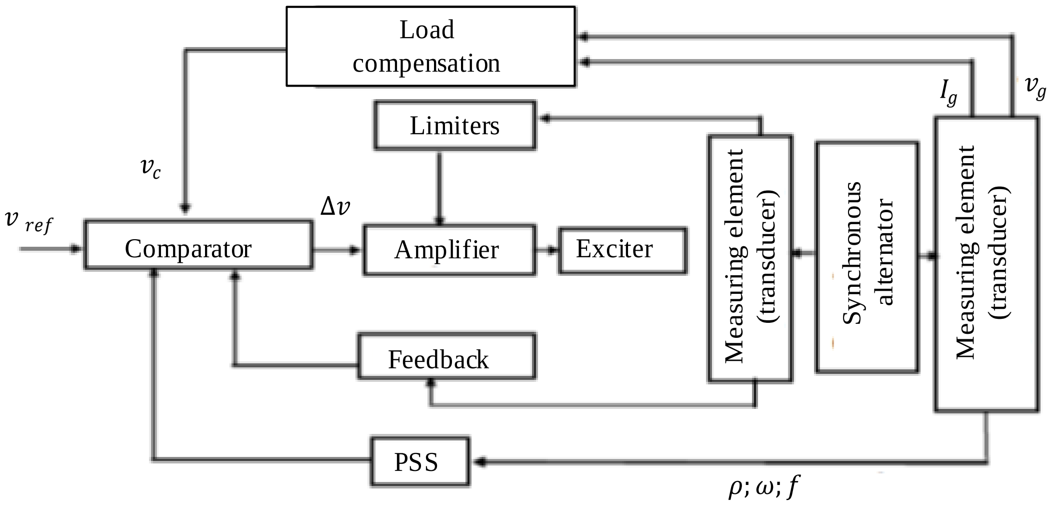

Figure 2.8: AVR for generator

The last three limiters have in-built time delays to reflect the thermal time constant associated with the temperature rise in the winding. A Power System Stabilizer (PSS) is sometimes added to the AVR sub system to help damp power swings in the system. PSS is typically a differentiating element with phase shifting corrective elements. Its input signals maybe proportional to rotor speed, generator output frequency or the electrical or the electrical real power output of the generator.

C. Automatic Generation Control

The control of generation and frequency is commonly known as Load Frequency Control (LFC) or Automatic Generation Control (AGC). With primary speed control action, a change in system load will result in a steady state frequency deviation, depending on the governor droop characteristic and frequency sensitivity of the load. All generating unit on speed governing will contribute to the overall change in generation, irrespective of the location of the load change. Restoration of system frequency to nominal value requires supplementary control action which adjusts the load reference set point (through the speed-changer motor). therefore, the basic means of controlling prime-mover power to match variations in system load in a desired manner is through control of the load reference set points of selected generated units .as system load is continually changing, it is necessary to change output of generators automatically. The primary objectives of AGC are to regulate frequency to the specified nominal value and to maintain the interchange power between control areas at the scheduled values by adjusting the output of selected generators [6].

2.6.3 Speed of rotation of synchronous generator

Synchronous generators are synchronous, during their operation. Means: electrical frequency is synchronized with mechanical speed of rotor. Relation between electrical frequency of stator and mechanical speed of rotor as shown before:

$$F = \frac{NP}{120} \tag{2.1}$$

Where:

F: Electrical frequency in Hz

N: Speed of rotor in rpm

P: Number of poles

Electric power generated at 50Hz or 60Hz, so rotor must turn at fixed speed depending on number of poles on machine, to generate 60Hz in two pole machines, rotor must turn at 3600rpm, and to generate 50Hz in two pole machines, rotor must turn at 3000rpm. There are five conditions that must be met before the synchronization: voltage - frequency - phase sequence - phase angle - waveform to that of the system to which it is being synchronized.

2.7 Proportional - Integral – Derivative Controller

The PID controller is shown in Figure 2.9 is the most common control algorithm used in industry and has been universally accepted in industrial control. The popularity of PID controllers can be attributed partly to their robust performance in a wide range of operating conditions and partly to their functional simplicity, which allows engineers to operate them in a simple, straightforward manner. The standard form of the controller is expressed by the governing function:

$$u(t) = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \qquad (2.2)$$

Where u(t) is the summation of three dynamic functions of the error e(t) from a specified reference output. The proportional control is used for increasing the loop gain to make the system less sensitive to load disturbance. The integral control is used to eliminate steady state errors. The derivative control is used to improve closed loop system stability. The parameters of PID controller have to be chosen properly, in order to achieve the desired performance [7].

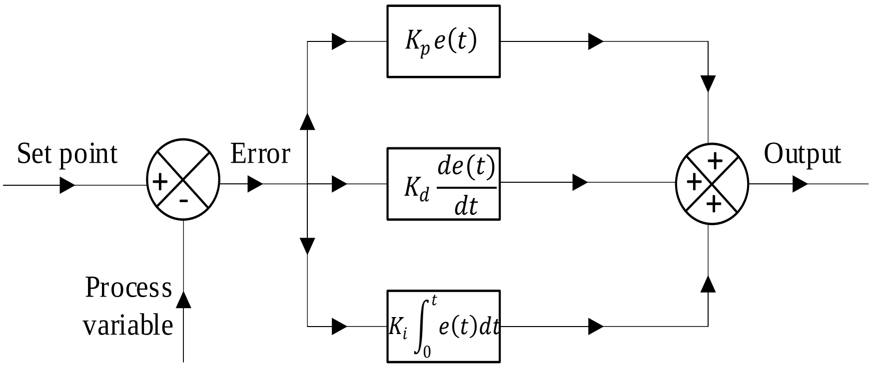

Figure 2.9: Basic PID control algorithm

The characteristic of PID controller is show in Table 2.1. A proportional controller K_p will have the effect of reducing the rise time and will reduce, but never eliminate, the steady-state error. An integral control K_i will have the effect of eliminating the steady-state error, but it may make the transient response worse. A derivative control K_d will have the effect of increasing the stability of the system, reducing the overshoot, and improving the transient response. Effects of each of controllers K_p , K_d, K_i on a closed -loop system are summarized.

Table 2.1: Characteristics of PID controller

Response	Rise Time	Over Shoot	Settling Time	Steady State Error
K_p	Decrease	Increase	Small Change	Decrease
K_i	Decrease	Increase	Increase	Eliminate
K_d	Small Change	Decrease	Decrease	Small Change

CHAPTER THREE

DESIGN OF GAS TURBINE SPEED CONTROL SYSTEM

3.1 Introduction

Rowen [7] has developed the transfer function block diagram is shown in Figure 3.1 of heavy and time constant by test and actual field experience accumulated from numerous installations in many different applications. In dynamic analysis of combined cycle plants, twin shaft gas turbine model, combustion turbine model and biomass - based gas turbine plant and even in turbine power generation this transfer function model has been used. Basically, Rowen’s model has speed, temperature and acceleration controllers.

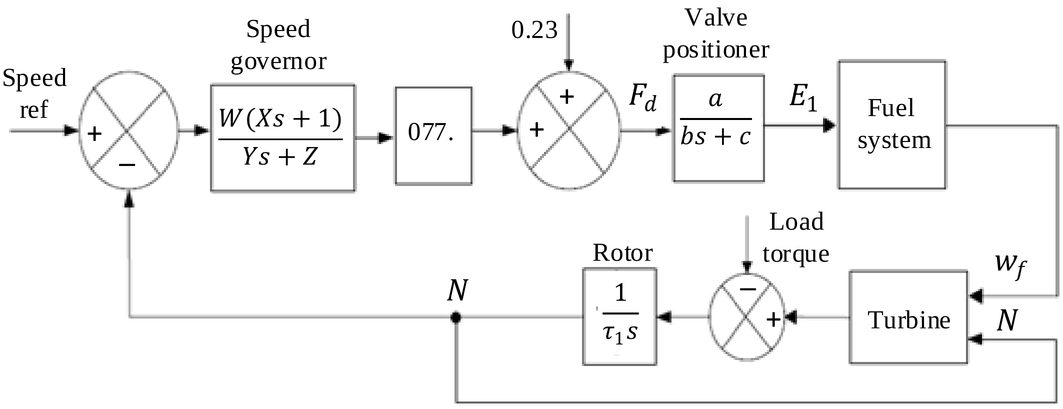

Figure 3.1: Transfer function model of gas turbine plant

3.2 Mathematical Model for Gas Turbine Speed Control

The model of gas turbine speed control is shown in Figure 3.2 consists of three control loops: speed control -temperature control -acceleration control. The speed control is the main control loop during normal operating conditions. The temperature and acceleration control are active in the case of abnormal operating conditions. The output of the three control loops are the input to a minimum value gate so that the loop which takes control is the one which output is the lowest of the three. The output of minimum value gate commands the fuel system and therefore the mechanical power delivered by the gas turbine [8].

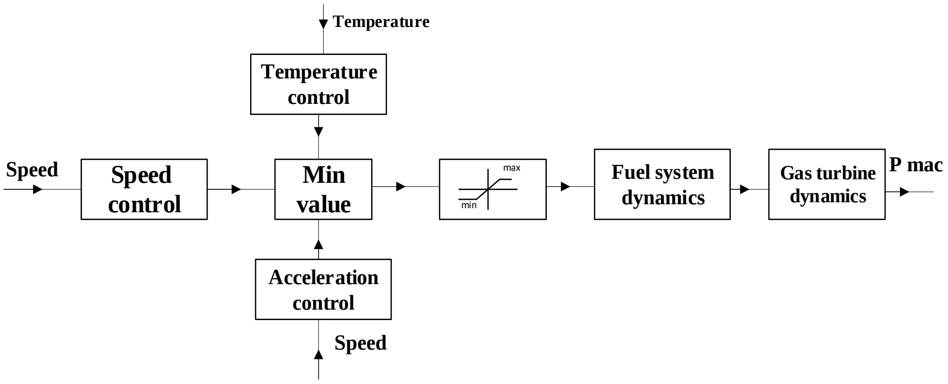

Figure 3.2: Modal of gas turbine speed control

Gas turbine speed control simulation is shown in Figure 3.3. A generic mathematical representation of the single shaft gas turbine.

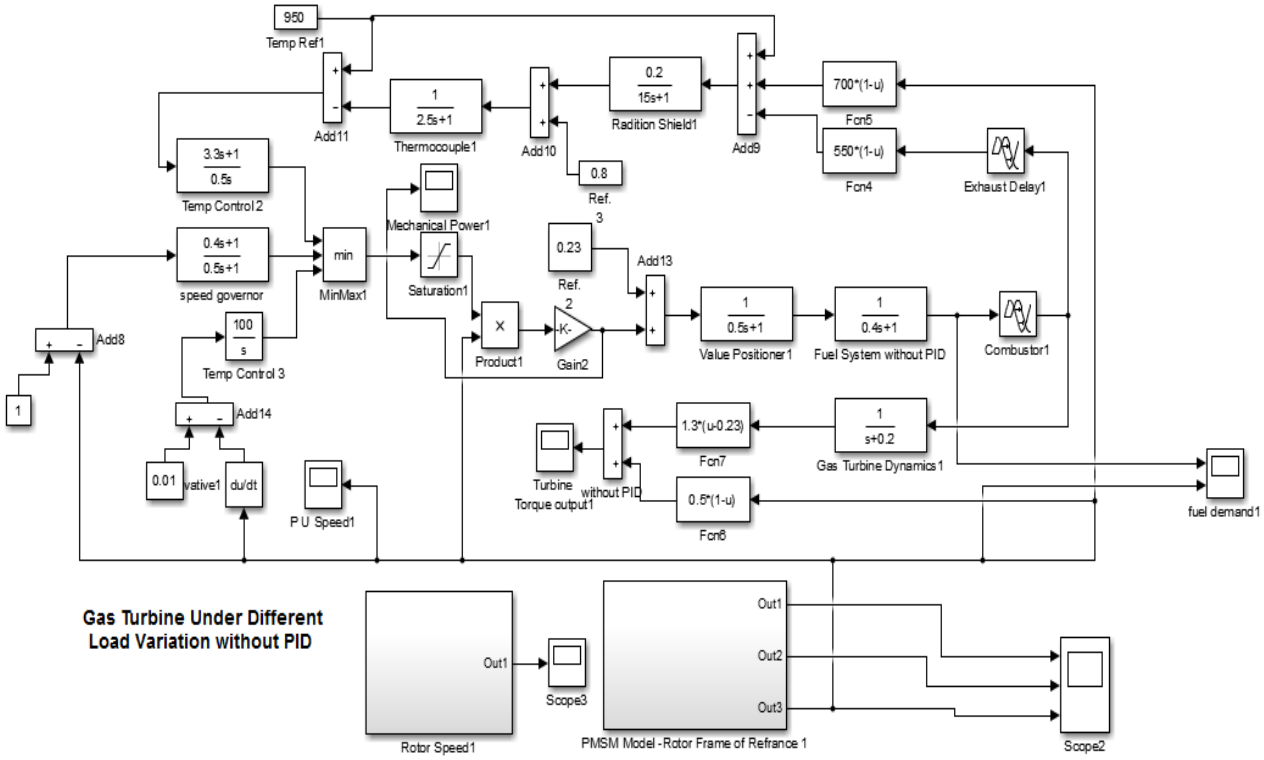

Figure 3.3: Gas turbine speed control simulation

3.2.1 Speed control

The speed control as shown in Figure 3.4 is active during normal operating conditions. The input to this control is the speed deviation. The speed control operates on the speed error formed between a reference (one per-unit) speed and the turbine rotor speed. It is the primary means of control for the turbine under part load conditions. Speed control is usually modeled by using a (lead-lag) transfer function. In this work a lead lag transfer function has been used to represent the speed controller, as shown in the block diagram of the speed control the k is the controller gain, T_1 (T_2) is the governor lead (lag) time constant, and Z is a constant representing the governor mode (droop or isochronous). A droop governor is a straight proportional speed controller in which the output is proportional to the speed error. An isochronous speed controller is a proportional-plus-reset speed controller in which the rate of change of the output is proportional to the speed error [8].

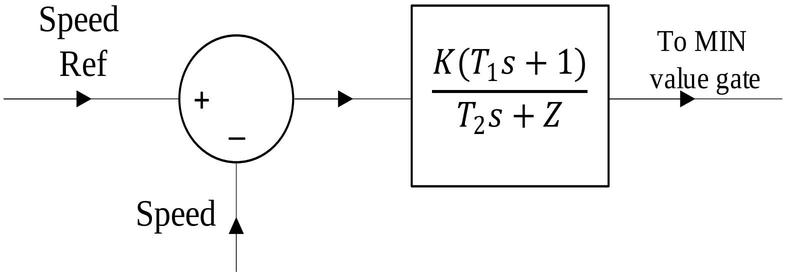

Figure 3.4: Speed controller

The coefficients values of the governor transfer function used here are given blew:

$k = 1$

$T_1 = 0.4$

$T_2 = 0.5$

$Z = 1$

3.2.2 Temperature control

The temperature control loop is shown in Figure 3.5 takes control of the gas turbine when the exhaust temperature exceeds a fixed maximum value. If the load demanded to the turbine increases when the generator is running under normal operating conditions, the output power of the gas turbine will increase due to the action of the speed control. This increase makes the exhaust temperature to rise. If this temperature is higher than the maximum rated exhaust temperature, the temperature control output will be lower than that of the load - frequency control, thus taking control of the response of the turbine. The temperature limit depends on the ambient temperature.

The fuel burned in the combustor results in turbine torque and in exhaust gas temperature. The exhaust temperature is measured using a series of thermocouples incorporating radiation shields, T_t is the temperature controller integration rate and T_3, T_4 are time constants associated with the radiation shield and thermocouple, respectively. K_4 And K_5 are constants associated with radiation shield and T_5 is the time constant associated with temperature controller. The output from the thermocouple is compared with a reference temperature, which is normally higher than the thermocouple output. This forces the output of the temperature control to stay on the maximum limit permitting the dominance of speed control through the minimum value gate when the thermocouple output exceeds the reference temperature, the difference becomes negative, and the temperature control output starts decreasing. When this signal becomes lower than the speed controller output, the former value will pass through the minimum value gate to limit the turbine's output, and the turbine operates on temperature control. The input to the temperature controller is the exhaust temperature T_x and the output is the temperature control signal to the minimum value gate [8]. The T_x can be calculated as follows:

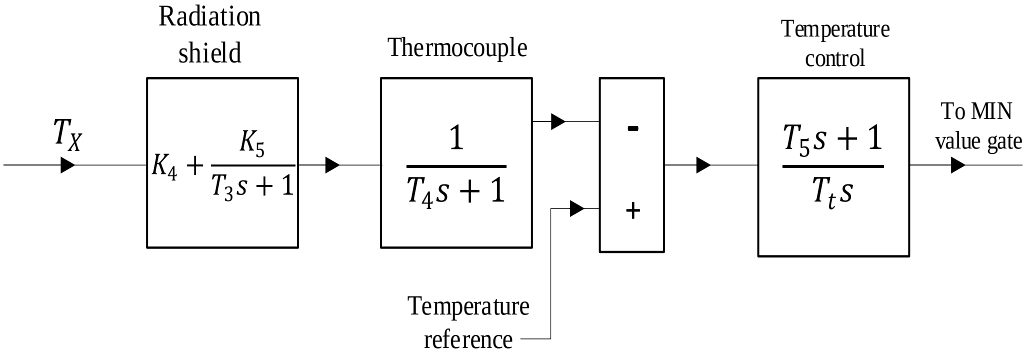

Figure 3.5: Temperature controller

$$\mathrm{Tx} = T_R - 700(1 - w_f) + 550\,(1 - N) \tag{3.1}$$

Where:

K_4 = Gain of radiation shield (instantaneous) = 0

K_5 = Gain of radiation shield = 0.2

T_3 = Time constant of radiation shield (s) = 15

T_4 = Time constant of thermocouple (s) = 25

T_5 = Time constant of temperature control (overheat) (s) = 3.3

T_t = overheat control integration rate (s) = 0.5

$N = 1$ p.u

3.2.3 Acceleration control

The acceleration control is shown in Figure 3.6 is designed to take control of the fuel system when the generator experiences an acceleration which exceeds a limit. This condition can occur during startup and load rejection processes. The acceleration control would prevent an over-speed of the gas turbine that could damage the shaft. The input signal to the acceleration control is the gas turbine speed. It goes through a differential block to obtain the acceleration of the turbine. Then, the acceleration is compared to an acceleration limit, and an error signal is obtained. The error signal is the input to a control block whose output goes to the minimum value gate.

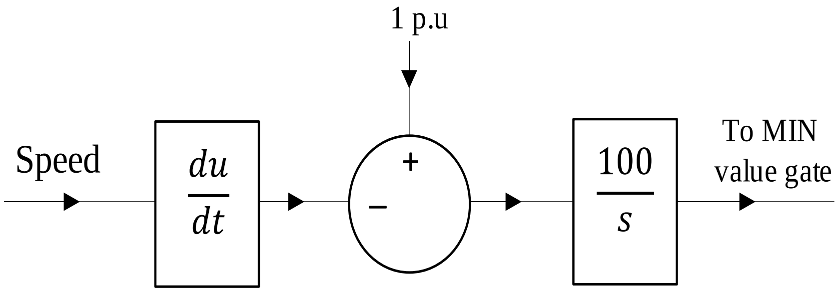

Figure 3.6: Acceleration controller

When the speed of the gas turbine starts to increase at a rate higher than the acceleration limit, the output of the integrator will start to decrease from its initial value which is the maximum output power. Since the gas turbine is delivering less power, it will take time to the acceleration control output to reach a value lower than the output of the speed control. Moreover, it has to be noted that if the acceleration is high and a high over-speed is being experienced by the gas turbine, the speed control output will tend also to reduce its output. The result would be that the command signal would tend to reduce the consumption of fuel, but by means of the speed control instead of the acceleration control. That is why the integrator limit should have a value slightly higher than the actual power delivered by the gas turbine [8].

3.2.4 Fuel system

The fuel system is shown in Figure 3.7 consists of the fuel valve and actuator. The fuel flow out from the fuel system results from the inertia of the fuel system actuator and of the valve position whose equations are: The valve position transfer function is:

$$E_1 = \frac{K_v}{T_V s + c} F_d \tag{3.2}$$

The fuel system actuator transfer function is:

$$w_f = \frac{K_f}{T_f s + 1} E_1 \tag{3.3}$$

Where:

F_d = Fuel demand signal

w_f = Fuel flow

K_v = Gain value positioner = 1

T_V = Value positioner time constant (s) = 0.5

C = Constant = 1

K_f = Gain fuel system = 1

T_f = Fuel system actuator time constant (s) = 0.4

In Equation (3.2) and Equation (3.3), K_v is the valve position gain, K_f is the fuel system actuator gain, T_V is the valve position time constants, T_f is the fuel system actuator time constants, c is a constant, F_d is the input and $E_1$is the outputs of the valve position and W_f is the fuel demand signal in $p \cdot u$ .The output of the minimum value gate V_c represents the least amount of fuel needed for that particular operating pointand is an input to the saturation and is an input to the product. Another input to the product is the per-unit turbine speed N (limited by the acceleration control). The value of output from product B is scaled by the gain K_3 and is an input to the fuel system; another input to the fuel system K_6 is essentially the minimum amount of fuel flow at no-load, rated speed [8].

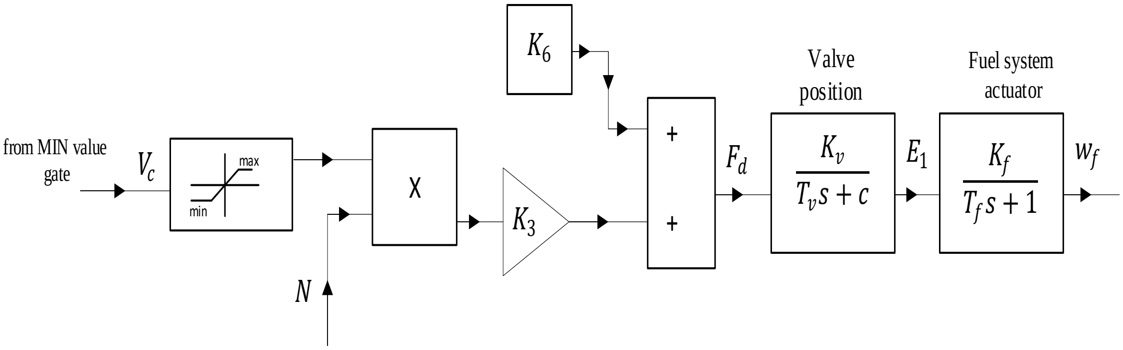

Figure 3.7: Fuel system

Where:

K_3 = Ratio of fuel adjustment = 0.77

K_6 = Essentially the minimum amount of fuel flow at no – load = 0.23

3.2.5 Compressor-turbine system

The compressor-turbine is the heart of the system and is essentially a linear, non-dynamic device (with the exception of the rotor time constant). There is a small transport delay T_{CR} , associated with the combustion reaction time, a time lag T_{CD} , associated with the compressor discharge volume and a transport delay T_{TD} , for transport of gas from the combustion system through the turbine. As shown in Figure 3.8 compressor-turbine package in this figure both the torque and the exhaust temperature characteristics of the single-shaft gas turbine are essentially linear with respect to fuel flow and turbine speed and are given by the following equations:

$$Torque = K_{HHV}\left(W_{f2} - 0 \cdot 23\right) + 0 \cdot 5(1 - N) \tag{3.4}$$

$$Exhaust\ Temp = T_x = T_R - 700\left(1 - W_{f1}\right) + 550(1 - N) \tag{3.5}$$

Where K_{HHV} is a coefficient which depends on the enthalpy or higher heating value of the gas stream in the combustion chamber and T_R is the reference temperature, the K_{HHV} and the constant 0.23 in the torque expression cater for the typical power/fuel rate characteristic, which rises linearly from zero power at 23% fuel rate to the rated output at 100% fuel rate. The input to this subsystem is the $p \cdot u$. Fuel demand signal W_f and outputs are the $p \cdot u$. Turbine torque and exhaust temperature [8].

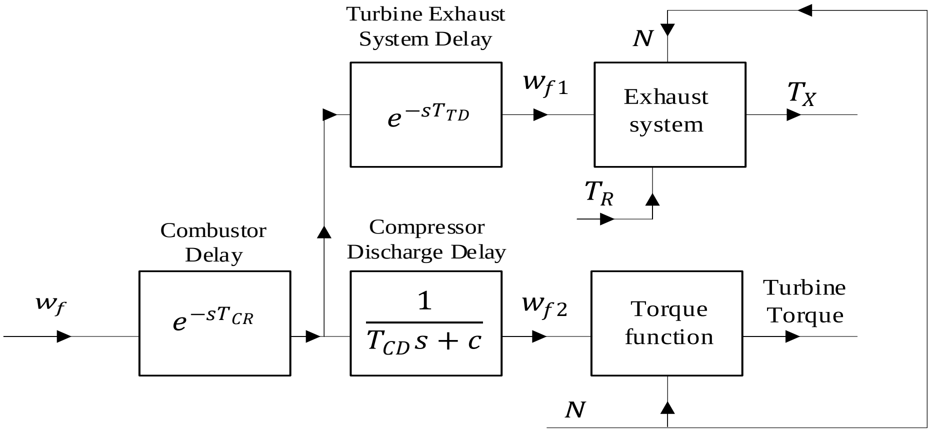

Figure 3.8: Compressor-turbine package

Where:

T_{CD} = Compressor discharge volume time constant (s) = 1

C = Constant = 0.2

3.2.6 Permanent magnet synchronous machine

In a Permanent Magnet Synchronous Machine (PMSM), the DC field winding of the rotor is replaced by a permanent magnet. The advantages are elimination of filed copper loss, higher power density, lower rotor inertia, and more robust construction of the rotor. The drawbacks are loss of flexibility of field flux control and possible demagnetization. The machine has higher efficiency than an induction machine, but generally its cost is higher. The property of a permanent magnet and the selection of the proper materials are very important in the design of PMSM. A good permanent magnet should produce a high magnetic field with a low mass, and should be stable against the influences which would demagnetize it [8].

3.3 System Design Using PID Controller

PID controller is predominantly used for industrial control due to its ease of operation. The actual speed is compared with a reference and the error signal is applied to PID controller, PID controller settles the speed exactly at rated value with less oscillation and at a faster rate. The governor PID setting is shown in Table 3.1.

Table 3.1: The governor PID settings

P	I	D
3.6	1.08	1.8

Gas turbine speed control simulation using PID controller is shown in Figure 3.9.

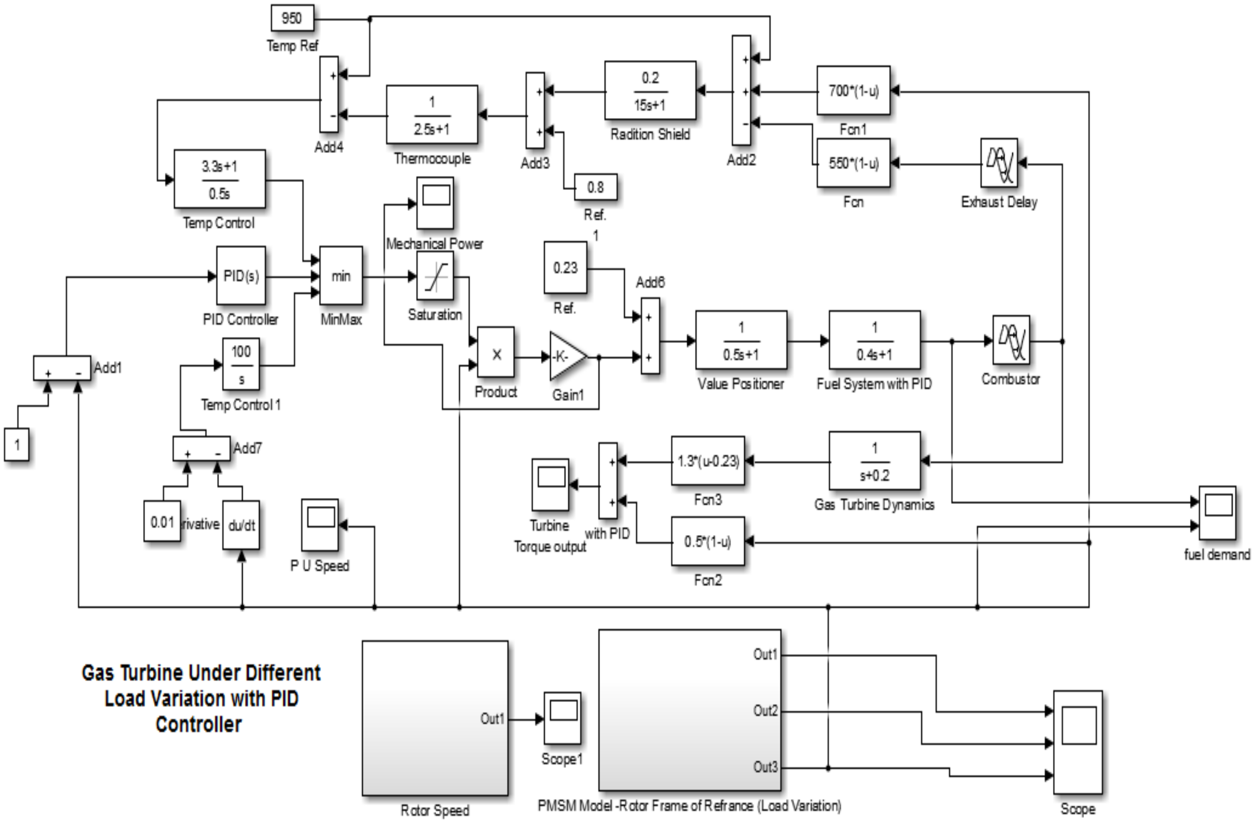

Figure 3.9: Gas turbine speed control simulation using PID controller

CHAPTER FOUR

SYSTEM SIMULATION RESULTS AND DISCUSSIONS

4.1 Introduction

A mathematical model of the gas turbine as explained in chapter three is modeled with MATLAB/SIMULINK. Speed reference was kept constant at 1 $p.u.$ for all simulations.

4.2 System Simulation Results without PID Controller

The response of the developed gas turbine is given in the following simulation results:

4.2.1 Mechanical power

Initially the gas turbine is operated at no-load. After that the gas turbine is loaded with variable load. The mechanical power of gas turbine response is shown in Figure 4.1.

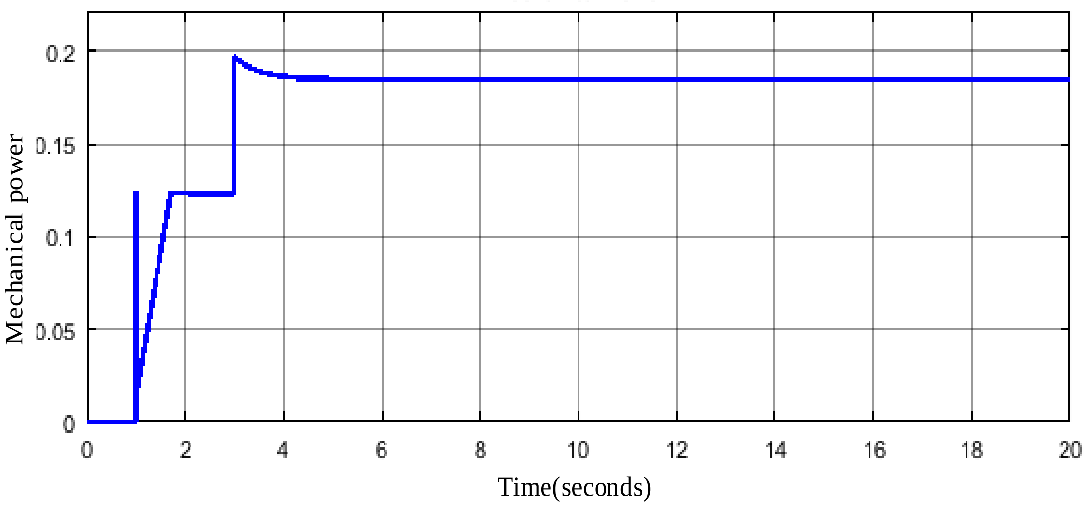

Figure 4.1: Mechanical power

4.2.2 Fuel demand

The fuel demand at no load it is 23% $(0.23\,\mathrm{p.u.})$. The load is applied to the gas turbine, which rises linearly from zero power at 23% fuel rate to the rated output at 100% fuel rate, increasing the amount of fuel required to keep the combustion process alive. The fuel demand of gas turbine response is shown in Figure 4.2.

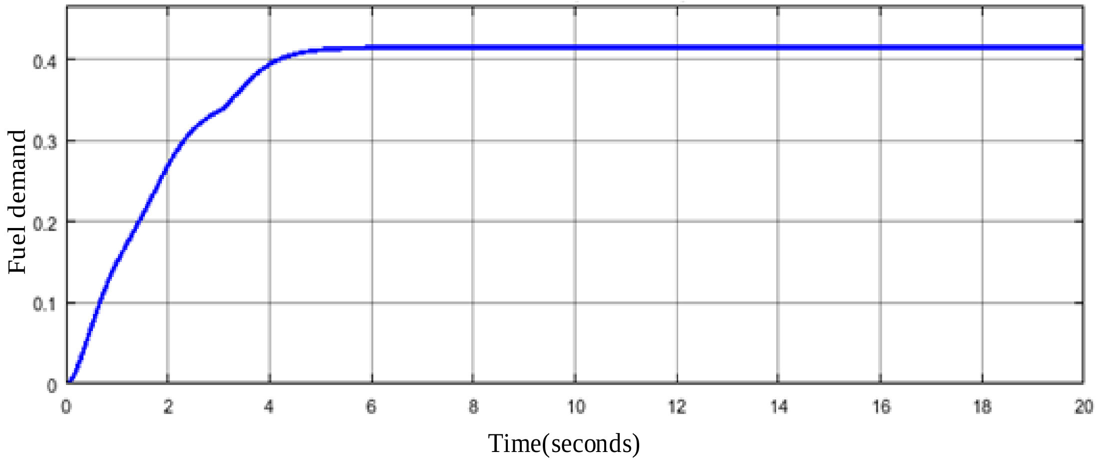

Figure 4.2: Fuel demand

4.2.3 Per unit speed - load

Speed/load controller is double variable controller, before connect to load, speed/load controller only speed after connect to load it will shaft to load control. Initial rate of speed change is maintained after removal of rated load torque. The speed is compared with the reference speed and the error is given to the speed governor. The per unit speed (load variation) of gas turbine response is shown in Figure 4.3.

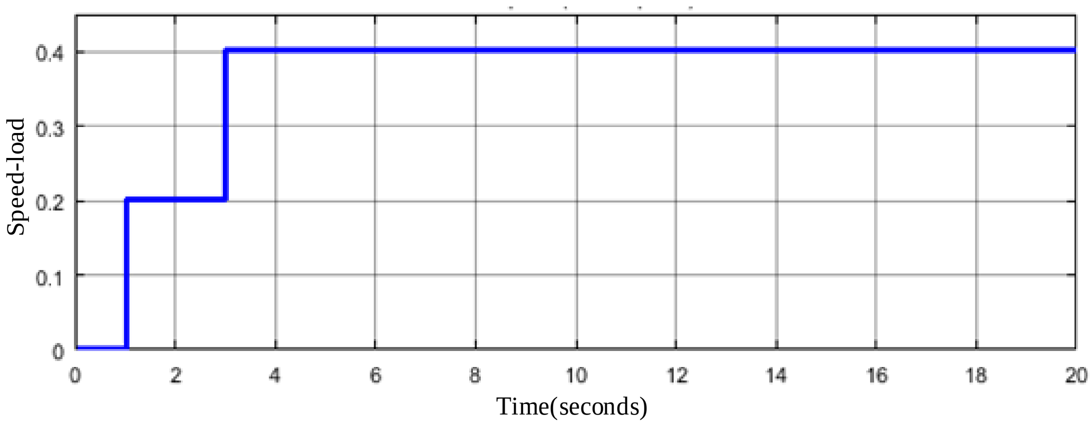

Figure 4.3: Per unit speed (load variation)

4.2.4 Turbine torque

The torque characteristics of gas turbine are essentially linear with respect to fuel flow and turbine speed, the generator torque is the same as the shaft torque which produced by turbine at steady- state. The turbine torque of gas turbine response is shown in Figure 4.4.

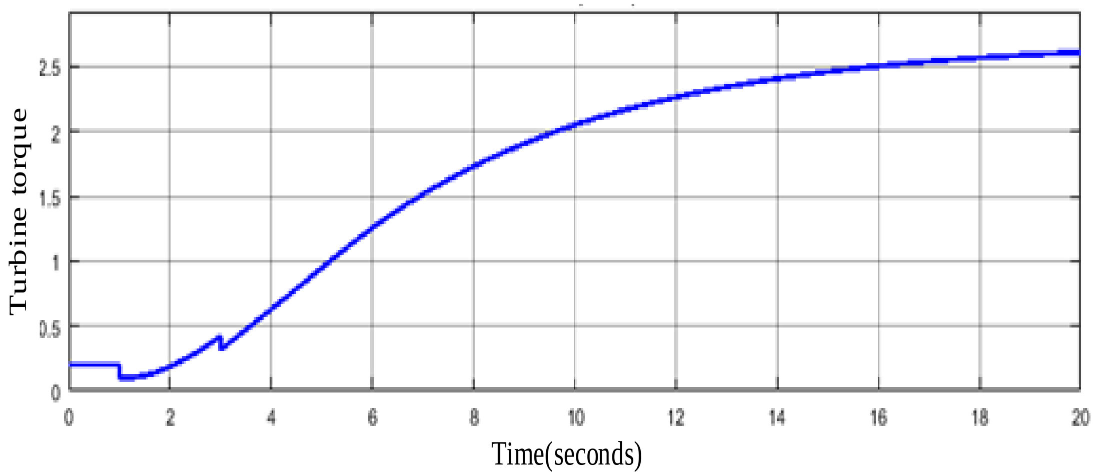

Figure 4.4: Turbine torque

4.2.5 Rotor speed

When the gas turbine is operated at no-load, the speed of the rotor is equal to 10 p. u. and the stator line voltage of the generator reaches no-load steady-state value of 10. p. u. When the generator is loaded the voltage decreases from no-load value to 5 p. u. The rotor speed of gas turbine response is show in Figure 4.5.

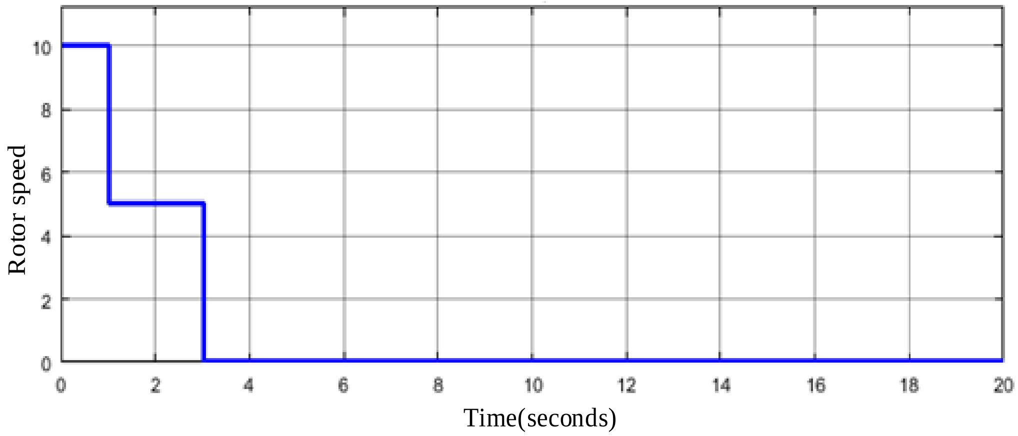

Figure 4.5: Rotor speed

4.2.6 Fuel demand and load

The fuel demand and load are compared is shown in Figure 4.6.

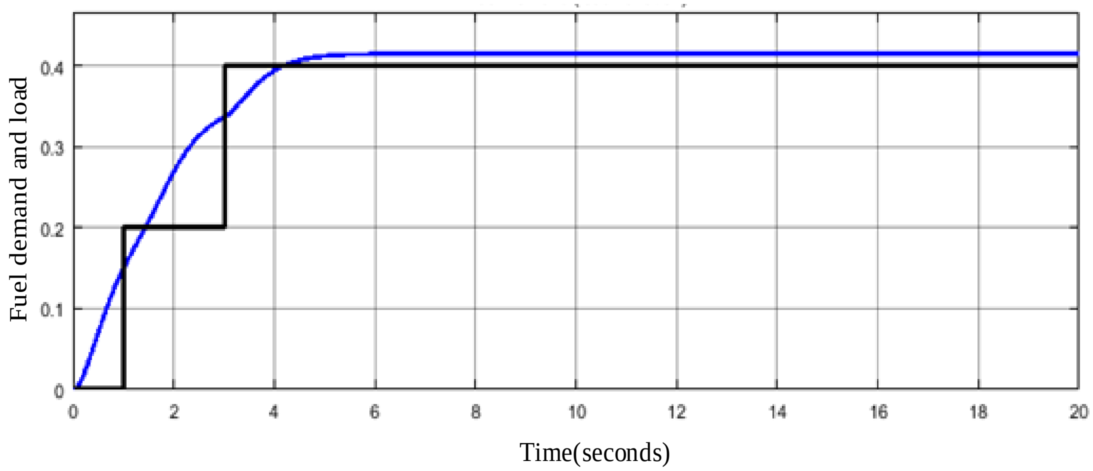

Figure 4.6: Fuel demand and rotor speed

4.3 System Simulation Results with PID Controller

The response of the improved gas turbine using PID controller is given in the following simulation results:

4.3.1 Mechanical power

The mechanical power of the gas turbine controlled with PID controller is shown in Figure 4.7.

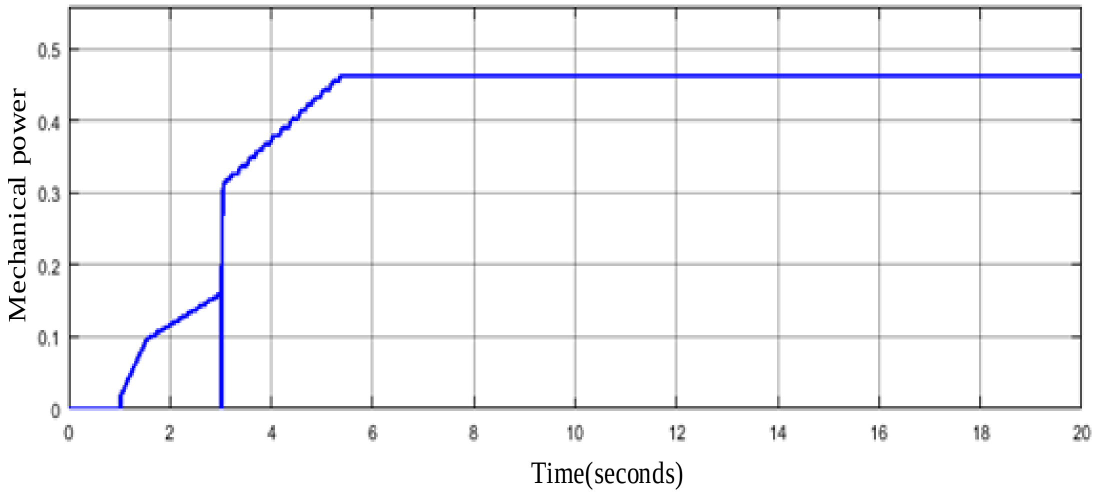

Figure 4.7: Mechanical power

4.3.2 Fuel demand

The fuel demand of the gas turbine controlled with PID controller is shown in Figure 4.8.

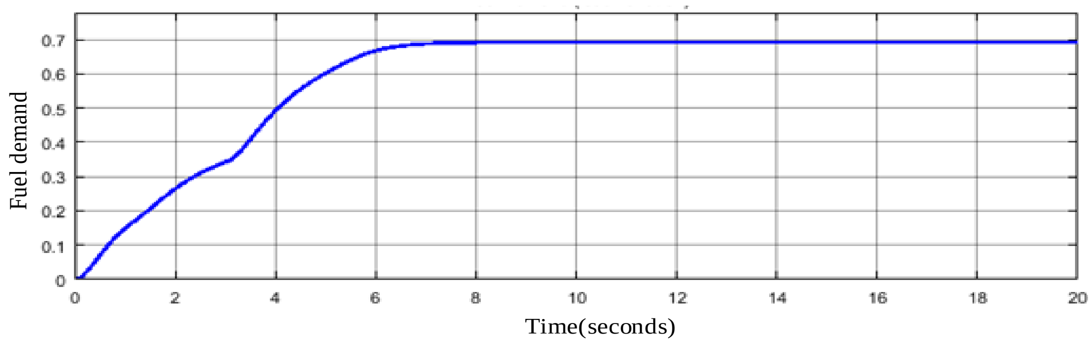

Figure 4.8: Fuel demand

4.3.3 Per-unit speed (load variation)

The per unit speed (load variation) of the gas turbine controlled with PID controller is shown in Figure 3.9.

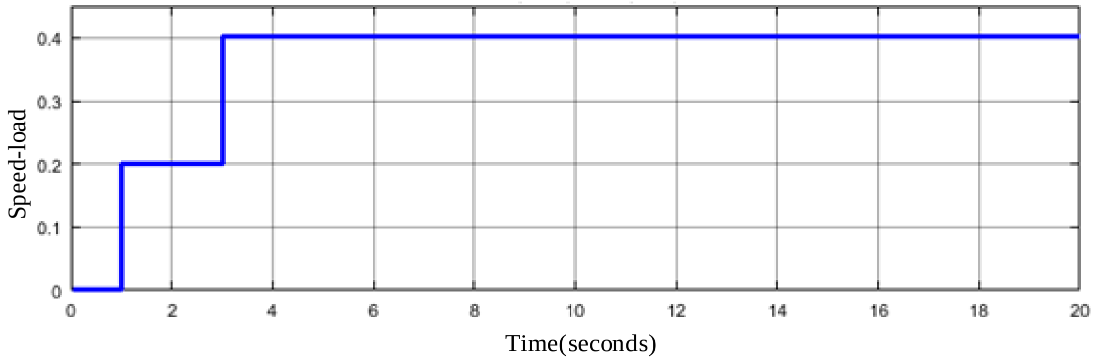

Figure 4.9: Per unit speed (load variation)

4.3.4 Turbine torque

The turbine torque of the gas turbine controlled with PID controller is shown in Figure 4.10.

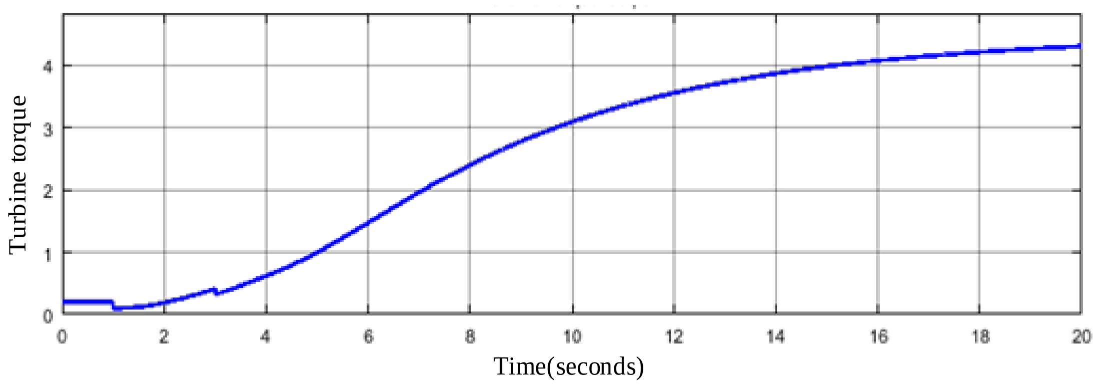

Figure 4.10: Turbine torque

4.3.5 Rotor speed

The rotor speed of the gas turbine controlled with PID controller is shown in Figure 4.11.

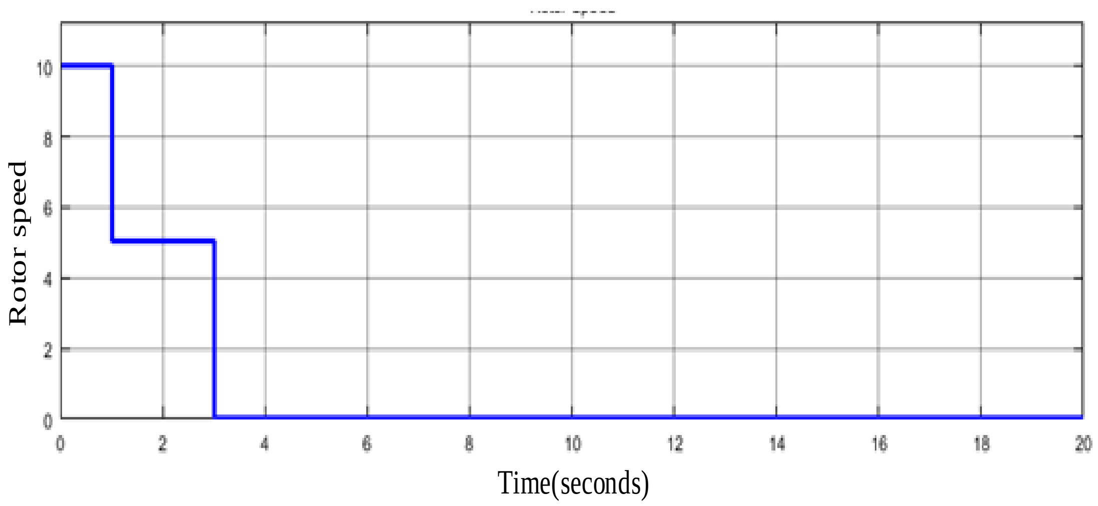

Figure 4.11: Rotor speed

4.3.6 Fuel demand and load

The fuel demand and load after of the gas turbine controlled with controller is shown in Figure 4.12.

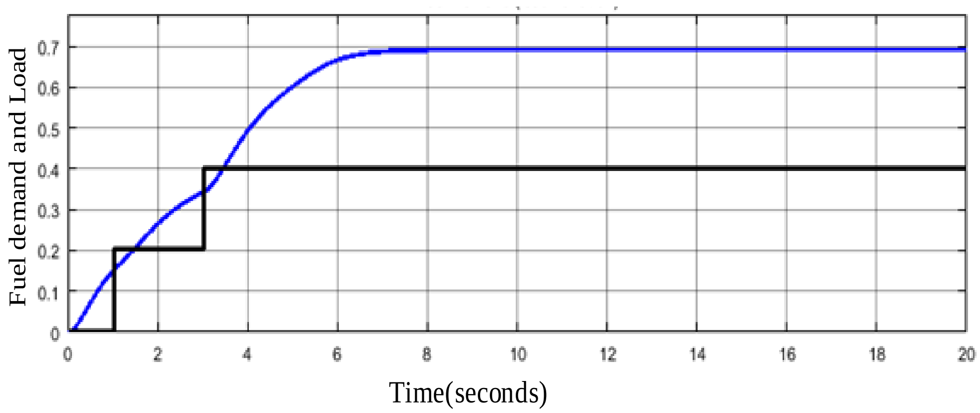

Figure 4.12: Fuel demand and load

4.3.7 Compare fuel and load variation

The compare between fuel without PID controller and fuel of the gas turbine controlled with PID controller and load variation is shown in Figure 4.13.

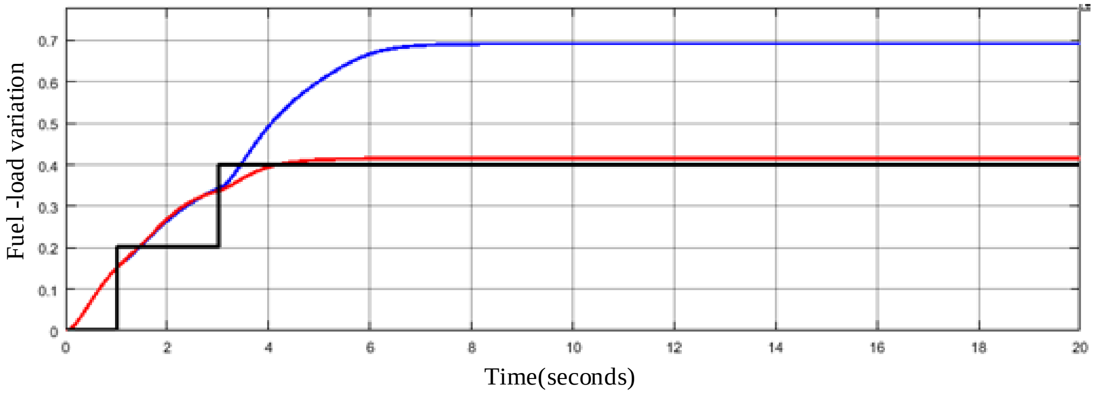

Figure 4.13: Compare fuel and load variation

4.4 Discussions

The model of a single - shaft gas turbine system is suitable for power management, and the speed control loop is necessary for the system stability. Low value selection plays a major role in the response of the model. The turbine torque increased with load and the rotor speed decreased, the variation of load results in changing the speed which should by controlled be increasing or decreasing the amount of inlet fuel. The system with PID controller improves the fuel valve time response.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In this study the gas turbine speed control system has been designed, the model is good for power generation. Detailed mathematical modeling of the control systems of the gas turbine is given and simulation of the developed gas turbine system model is carried out. The simulation results show that the developed model of the gas turbine system has the ability to meet the power requirements of the load.

5.2 Recommendations

At the end of this study, it recommended that:-

- Apply of intelligent control technique to control gas turbine.
- Improving the transient response of the gas turbine by steam injection in combustor chamber during load variation.
- Improving the transient response of the gas turbine by flow divider.

REFERENCES

[1] Kim J H, Song T W, Kim T S and Ro S T, “Model Development and Transient Behavior of Heavy Duty Gas Turbines”, Journal of Engineering for Gas Turbines and Power, ASME, Vol. 123, pp. 589-594, July 2001.

[2] Philip. J. Potter, “Power Plant Theory and Design”, pp. 22-30, Mar. 2000.

[3] B. Singh, “Power Plant Engineering”, pp. 22-29, Jan. /Feb. 2003.

[4] H. Cohen, “Gas Turbine Theory 4th Edition”, pp. 152-158, Feb. 2005.

[5] T. Wildi, “Electrical Machines, Drives and Power Systems “, Prentice Hall, Vol. 62, pp. 1-11, 2002.

[6] P. kundru, “Power System Stability and Control”, pp. 761-766, Jul. 2001.

[7] W. I. Rowen, “Simplified Mathematical Representations of Single Shaft Gas Turbines in Mechanical Drive Service”, International Gas Turbine and Aero Engine Congress and Exposition, Cologne, Germany, 1992.

[8] Larry Goldstein, Bruce Hedman, Dave Knowles, Steven I. Freedman, Richard Woods and Tom Schweizer, “Gas-Fired Distributed Energy Resource Technology Characterizations”, National Renewable Energy Laboratory, NREL/TP-620-34783, Nov. 2003.