CHALMERS

Comparing and Evaluating Frequency Response characteristics of Conventional Power Plant with Wind Power Plant

Thesis for the Degree of Master of Science in Engineering (MSc Eng.)

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Dedication

I dedicate this report to
All Mighty Allah (The Most Merciful, The Most Gracious) and
Muhammed (Sallallahu alaihi wa Sallam).
My family- Parents, Brothers & Sister and my Wife who gave me life, love & care and my Teachers who gave me education and to my relatives & friends for their support.

Mohammad Bhuiyan

I dedicate my work to
My God, who created and blessed me with all happiness,
My Father, who turned himself a God just to bless me,
My Mother, who showers me with pure love and affection,
My Teachers, who gave me knowledge and confidence,
And to My friends and relatives who is always with me for all my endeavors'.

Dinakar Sundaram

ABSTRACT

This thesis investigates the suitability to use wind power installations, equipped with variable speed wind turbines with power electronic interfaces, for power system frequency control by studying the active power output response to a change in network frequency. The result is later compared to the frequency response of conventional generators (hydro, gas turbine and thermal power plant) that are mainly used for primary and secondary frequency control. In this thesis a market available multi-MW variable speed wind turbine is investigated. It is found that wind energy can be used as an excellent source for compensating frequency deviation.

Characteristic curves (Turbine Valve/Gate, Mechanical Power & Speed deviation,) of Hydro, Steam, and Thermal power model are varied considerably with specified load. The relation between Gate/valve (water/steam input) and Mechanical power (output) of the dynamic model is very significant because it adjusts the operation of Governor Action. Here in Hydro, Steam, and Thermal power model, we focus on to find out the response between input (gate/valve) and out put (Speed deviation & Mechanical power) with varying step load (5 to 10 percent). We compared the wind power characteristics (Electrical power) with characteristics of Conventional power (Hydro, Thermal & Steam) plant by increasing the load of the power system which will in return increase the demand of the system and create corresponding variation in the system frequency; According to primary frequency control (Local automatic control which delivers reserve power in opposition to any frequency change), the conventional power plant takes time (the Rise time and Settling time in case of Mechanical power is 04-25 sec and 20-68 sec respectively to stabilize the system against 5% load disturbance) to meet the increased power demand thereby balancing the system frequency.

In this thesis, we suggest to use the wind energy to meet the raised power and to stabilize the system frequency, during this transition time; Here wind energy is run in de-rated power (5-10% lower from its rated power). When the demand is increased, conventional power plant takes time to meet the demand and consequently frequency of the system fluctuate causing imbalance; at that time we increase the Electrical power output of wind Energy from derated to its rated value to meet the demand and to stabilize the frequency of the system. For which we found the Rise time and settling time of the wind turbine to be 03 sec – 09 sec and 08 sec –38 sec respectively.

So, Wind energy can be used as a limited ancillary resource to meet the load demand as well as active power control in power systems.

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Table of Contents

List of Symbols & Abbreviations:

Hydro Power Unit

Symbols

U	Velocity of water
H_g	Hydraulic head at Gate/Valve
G	Gate position
K_u	Proportionality constant for flow equation
P_m	Turbine mechanical output power
η	Turbine efficiency
ρ	Water density
g_a	Acceleration due to gravity
H	Hydraulic head at Gate/Valve
Q	Actual turbine flow
K_p	Proportionality constant for mechanical power
L	Length of conduit
A	Pipe area
a_g	Acceleration due to gravity
ρLA	Mass of water in the conduit
$\rho\ a_g \Delta H$	Incremental change in pressure at turbine gate
t	Time in second
T_w	Water starting time in second
T_M	Mechanical starting time in second
D	Damping Constant
M	Inertia Coefficient
T_G	Main Servo time constant
R_T	Temporary Droop
T_R	Reset time
R_P	Permanent Droop

Abbreviations:

TDC	Transient Droop Compensator

Wind Energy

Symbols:

P_w	Wind power density
q_d	Dynamic pressure of the wind
x	moving wind in a given point (m)
ρ	Air-density
λ	tip-speed ratio
β	Pitch angle of the Blade
α	Angle of attack
C_p	Aerodynamic Co-efficient of performance
w_{turb}	Rotor speed
R	Rotor Radius
V_{WIND}	Wind speed

Abbreviations:

WTG	Wind Turbine Generator
DFIG	Double fed Induction Generator
WRIG	Wound Rotor Induction Generator
WRSG	Wound Rotor Synchronous Generator
PMSG	Permanent Magnet Synchronous Generator
MW	Mega Watt
PM	Permanent Magnet

Steam Power Plant

Symbols:

W	Weight of steam inside the vessel
V	Volume of vessel
ρ	Density of steam
Q	Steam mass flow rate
P_m	Turbine mechanical output power
η	Turbine efficiency
P	Pressure of steam inside the vessel
P_0	Rated pressure
Q_0	Rated flow out of vessel
ΔTm	Turbine Torque
ΔVcv	Control valve position
T_{RH}	Reheat time constant

T_{CH}	Charging time constant
T_{CO}	Crossover piping time constant
F_{HP}, $F_{LP,}$ F_{IP}	Fraction of turbine powers
t	Time in second
D	Damping Constant
M	Inertia Coefficient
T_G	Main Servo time constant

Thermal Power Unit

Symbols:

W	Weight of steam inside the vessel
V	Volume of vessel
ρ	Density of steam
Q	Steam mass flow rate
P_m	Turbine mechanical output power
η	Turbine efficiency
P	Pressure of steam inside the vessel
P_0	Rated pressure
Q_0	Rated flow out of vessel
T_R	Reheat time constant
T_1	Charging time constant
T_{CO}	Crossover piping time constant
K_R	Fraction of turbine powers
t	Time in second
D	Damping Constant
M	Inertia Coefficient
T_G	Main Servo time constant

Chapter-1

INTRODUCTION

Contents Overview

1.1 Introduction

A world without electricity is un-imaginable. Electricity has become one of the most common needs to mankind. But to engineers producing safe power and to meet the growing demand is a mammoth task, which cannot be easily achieved without trying different ways of power production. Recently, renewable energy resources have attracted considerable interest for power production due to extensive depletion of non – renewable sources like coal and oil which are used in almost all conventional power plants for power production through out the world. In next 50 years, production of energy using non-renewable resources will be limited in most countries and cost for power generation will be increased drastically. It is obvious that present civilization depends on energy. After the Second World War, now world's population is 6 billion and still growing, which will be doubled in next 5 decades. The following figure-1.1 represents the total Electricity production in the world from 1980 to 2005. [10]

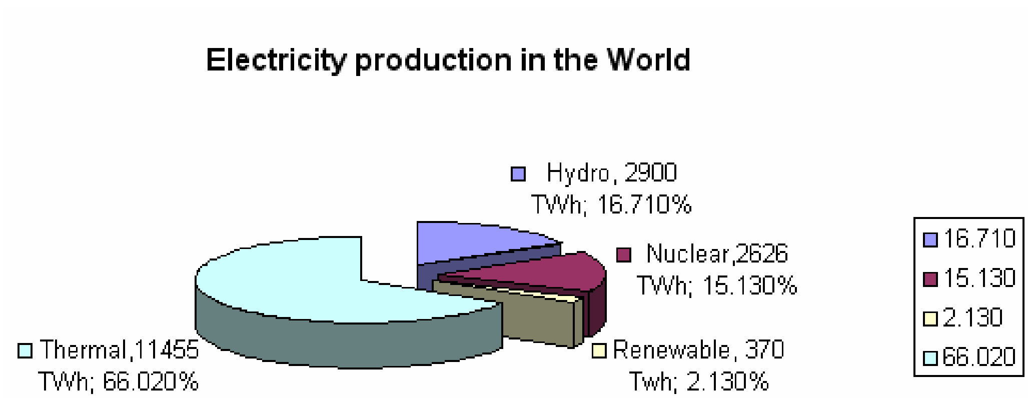
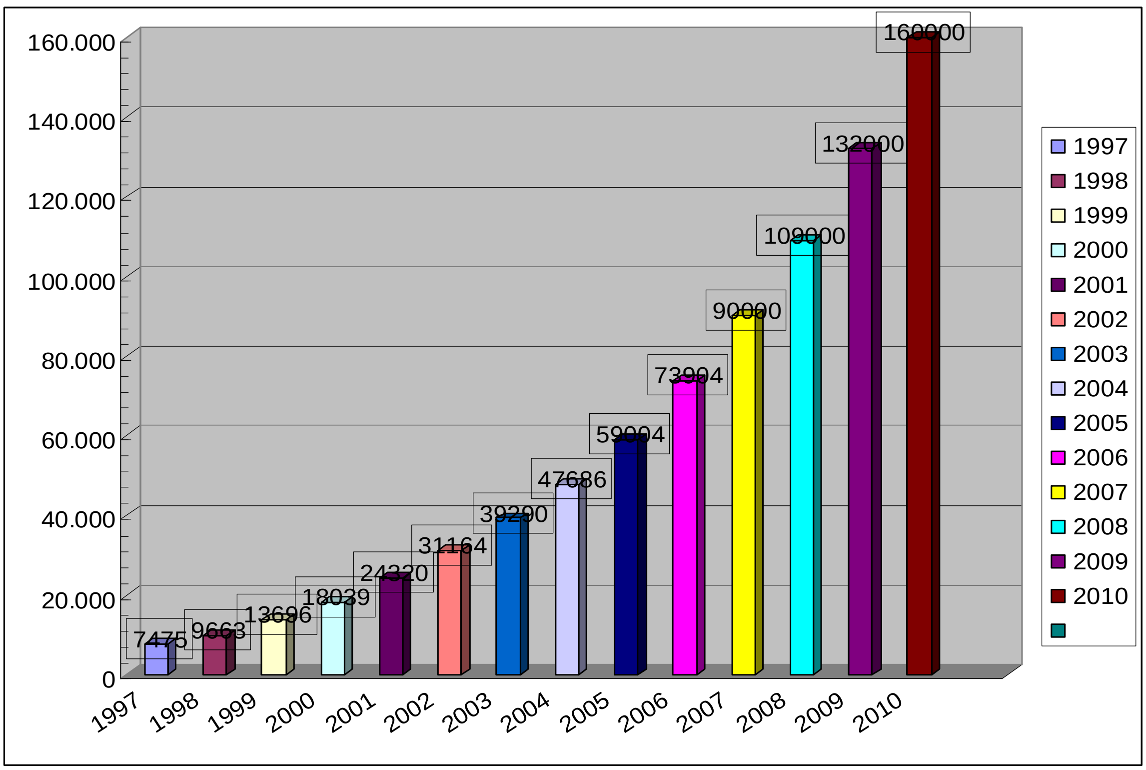


Fig.-1.1 shows worldwide Electricity production (1980-2005). Source-EIA.

Energy to support the entire World's need will rise to great heights, which cannot be met by producing power with non-renewable energy resources alone. Now it is very essential to move on to renewable energy resources for power generation. One drawback of the renewable energy resources is that it can not provide constant energy supply & cannot also be stored directly. Renewable energy includes wave energy, solar energy, wind energy, geothermal energy and biomass. Out of which, extensive research and practical power production is carried out from water, solar, and wind energy. The reason for opting renewable sources is not only because we are running out of fuels like coal, oil for power production, but also it is eco–friendly and safe.

Among the renewable sources, power production from wind turbines is mostly concentrated as a result of relatively high efficiency. In recent years one can notice growing wind energy market and installation of tall towers carrying wind turbines, through out the country, on sea – shores and wherever possible. The following figure-1.2 represents the Worldwide installed



capacity in 2006

Fig.-1.2 shows worldwide wind Energy- Total Installed capacity (MW) and prediction 1997-2010. Source: [WWEA]

and prediction 1997-2010. This indicates the rising need to produce power from wind for the future. But wind energy systems are not that efficient to meet the demand of a grid standing all alone. So it is made to operate with conventional power plants to maintain stable system frequency and to meet the rise in demands. This way power obtained from wind turbine is used efficiently.

1.2 AIM of our work

Our strategy was to improve the stability of power in the power system by the collective operation of power plants (conventional with wind) of different magnitude in order to maintain stable frequency.

1.3 Problem background

We all know that during peak hour's power demand rises, which in return creates instability (power of the entire system) and might result in further complications (out of synchronization, black out, etc) To avoid this instability and also to meet the demand we use stored or reserved energy or power coming from less efficient system (renewable energy).

Taking wind power into consideration, it supplies the grid with sufficient power during these unstable conditions and makes the system stable within few seconds. The reason using wind power for this transition time is that the conventional power plants takes more time to meet the rise in demand and to stabilize the system frequency. But wind power acts quickly and meets the rise in demand until the conventional power plants resumes to continue its supply. And also to make this operation efficient different grid connection configuration, changes in modeling of wind turbine are studied and used in practice. In this thesis, we suggest a new way to meet the increased power demand and to stabilize the system frequency.

1.4 Frequency control requirements

Stability of power system means the ability of power in a system to maintain synchronism and maintain voltage when any transient disturbances occur like faults, line trips and large variation of load.

Generally, the power systems operate within standard operating limits i.e. 50 ±0.2 Hz. Under any fault conditions or abnormal or exceptional situation, the frequency is permitted to move outside of the mentioned limits. In large power generation case (1000 MW to 1320 MW)or in feed losses, the maximum frequency range is contained to the assigned limits i.e. not exceeding 1 % above and below 50 Hz (50±0.5 Hz.); range of 49.5 to 50.5 Hz. The following figure-1.3 represents the frequency deviation of the system at contingency period. [11] [12]

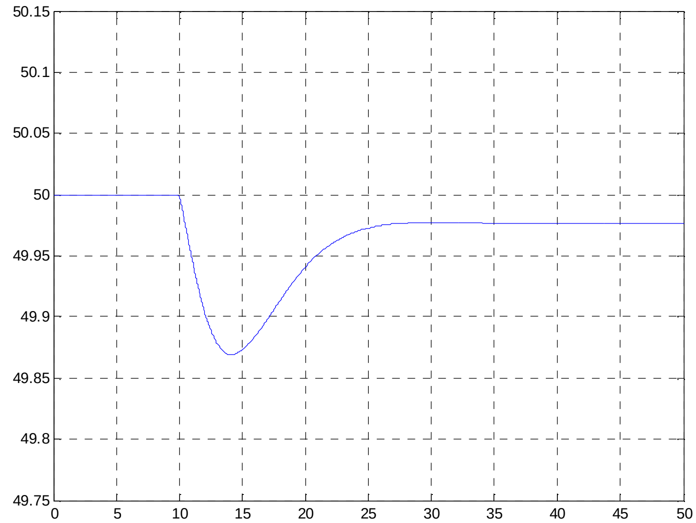


Fig.-1.3 showed the frequency deviation at contingency period.

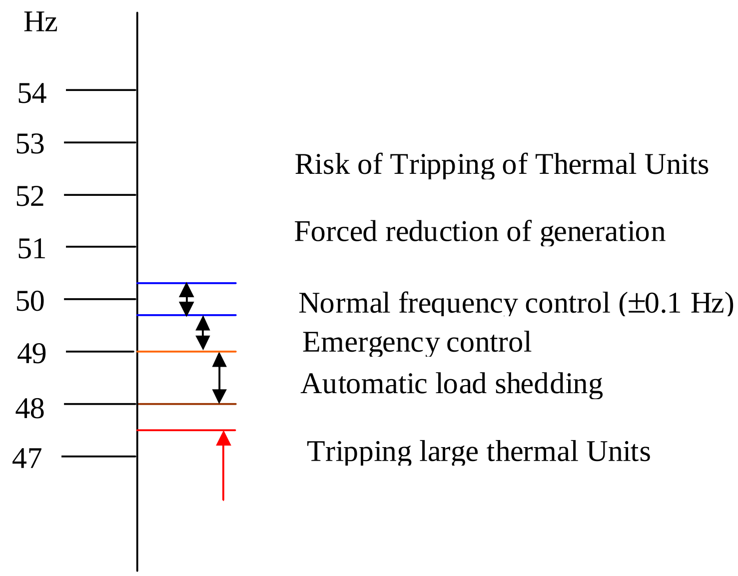


Fig.-1.4 showed the frequency range of System at normal operation and tripping condition.

1.5 Frequency requirement under normal conditions

1.5.1 Power plant Impacts:

Frequency regulated turbine generators must be used to avoid mechanical resonance. When the turbine operates near resonant modes then damage might occur. Hence a turbine which has resonant frequencies away from the operating frequency is used.[14]

1.5.2 Load Impacts:

Power quality is prone to go worse as a result of poor system frequency control. In order to maintain good quality a variable frequency drives (VFD) is used. These VFD's are very much insensitive to frequency changes.

1.5.3 Frequency requirement under contingency conditions:

The above said requirements are followed very strictly during normal conditions, while those requirements are relaxed during contingencies. The power system itself is designed to recover quickly when sudden contingency occurs.

1.6 Importance of Wind Energy

Wind energy is considered to be one of the most establishing energy through out the world. Its non-polluting character and plenty of availability has made wind energy as a major research area for power engineers. Several researches to trap energy from wind and to improve its energy efficiency are carried out through out world. Denmark, Netherlands, Sweden, Australia, United States of America, United Kingdom, etc… are involved in these researches. Wind energy conferences are held to share and discuss the improvements and recent researches carried on wind energy related issues.

Researches are usually carried out in developing concepts and developing components for the wind turbines. When we speak about developing concepts it can be related to controlling of wind turbines in different possible ways, design of wind turbine generators, construction and environment, etc… and researches related to developing components includes developing advanced power electronics, fabrication of new wind blade designs, etc.[24]

1.7 Researches related to Frequency Control of wind turbines

Several researches related to frequency control of the wind turbines are carried out in different ideas and ways. Like using the DFIG (Doubly Fed Induction Generator), which gives an internal response and makes the frequency decrease faster when more air is injected. This kind of research is carried out in Ireland and it suggests the use of DFIG because frequency excursion of a system increases when there is a loss of generation; this can be solved in a way by using DFIG. And in another research carried out to determine how to control the wind frequency thereby controlling the grid frequency, shows the usage of fuel cells.. This way tripping of conventional power plants from the grid will be reduced and the grid frequency can be maintained and several other researches are being carried out in different parts of the globe to improve the efficiency of wind power.[25][26]

1.8 Suggestions from our thesis

We suggest to run the wind turbine de-rated during normal operation of the grid when the conventional power plants supply the demand needs. When the demand rises in the grid, the reserved power of the conventional power plants is used to meet the increased demand but it takes time (about 180 seconds) for the conventional power plant to make the system stable. At this point we tried running the wind turbine at its full efficiency and meet the risen demand until the conventional power plant takes control of the demand again. This way system stability could be maintained by sharing of the load demand between wind turbine power plant and the other operating conventional power plant.

Chapter 2

STEAM TURBINES

Contents Overview

2.1Steam turbines

A steam turbine derives its source from the boiler of a nuclear reactor or fossil fuels furnaces and it converts the high pressured steam into rotating energy at high temperatures which in turn is converted into ELECTRICAL ENERGY.

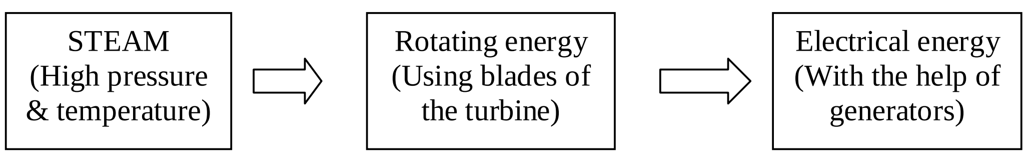


Fig. 2.1 representation of principle of steam turbines

Building of steam turbines always rests upon the 1) unit size and 2) steam conditions. All turbines have a set of moving blades called rotors or buckets and stationary blades called vanes or nozzle sections. Through these nozzles, steam is accelerated with high velocity and this steam is converted to shaft torque by the buckets. Usually turbines are with multiple sections. They may be either TANDEM-COMPOUND or CROSS-COMPOUND.[7]

2.1.1Tandem-compound:

One shaft would hold all the sections and with a single generator. Mostly used now-a-days as it is not that expensive compared to cross-compound. Tandem compound configuration for a fossil fuelled unit run at 3600 r/min for 60 Hz system and at 50 Hz. It is 3000 r/min. figures 2.1.1 a, b, c and d shows various configurations of steam turbines.

2.1.2Cross-compound:

It has two shafts connected to two separate generators and it is being run by one or more turbine sections. Still it is considered to be as one unit and controlled with one of controls. It is obvious that's cross-compound improves efficiency and increased capacity but it is expensive. In Cross compound configuration for a fossil fuelled, both shafts may run at 3600 r/min or one at 3600 r/min and other at 1800 r/min for a 60Hz system. For a 50 Hz system it is 3000 r/min and 1500 r/min. figures 2.1.2 a and b shows different configurations of cross compound steam turbines.

Diagrams:
Tandem compound

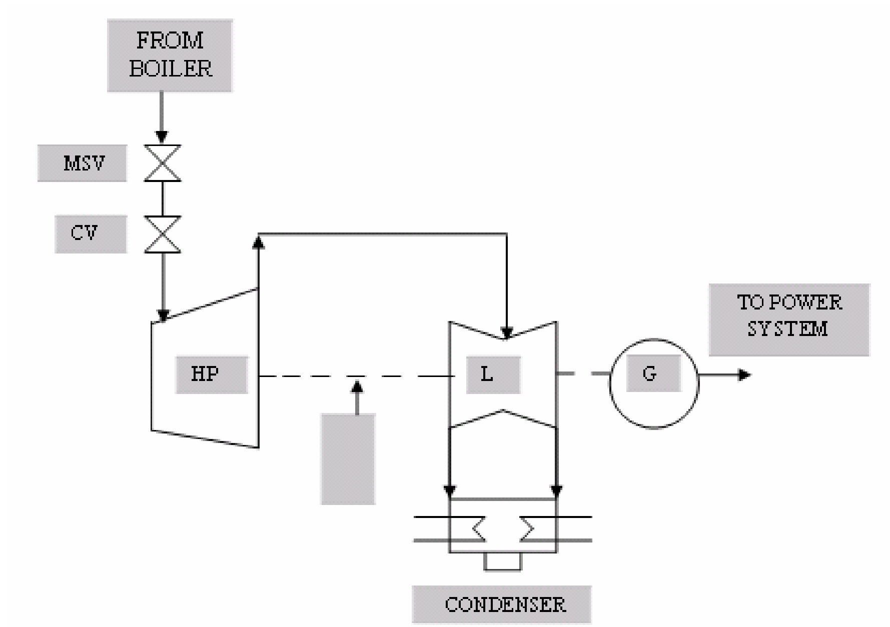


Fig.- 2.1.1a Non-reheat steam turbine- Tandem compound

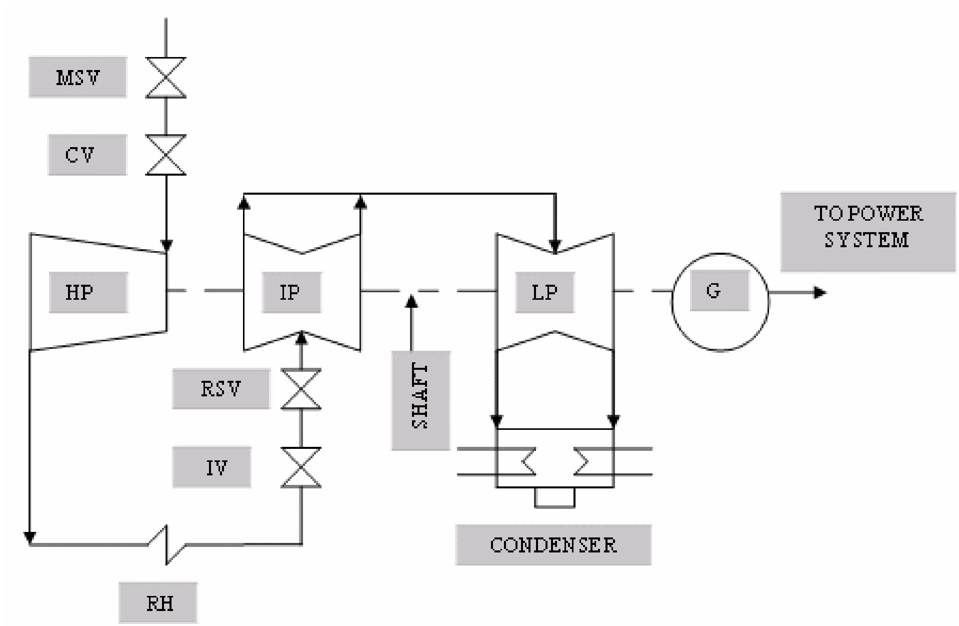


Fig.- 2.1.1b Single-reheat type 1- Tandem compound

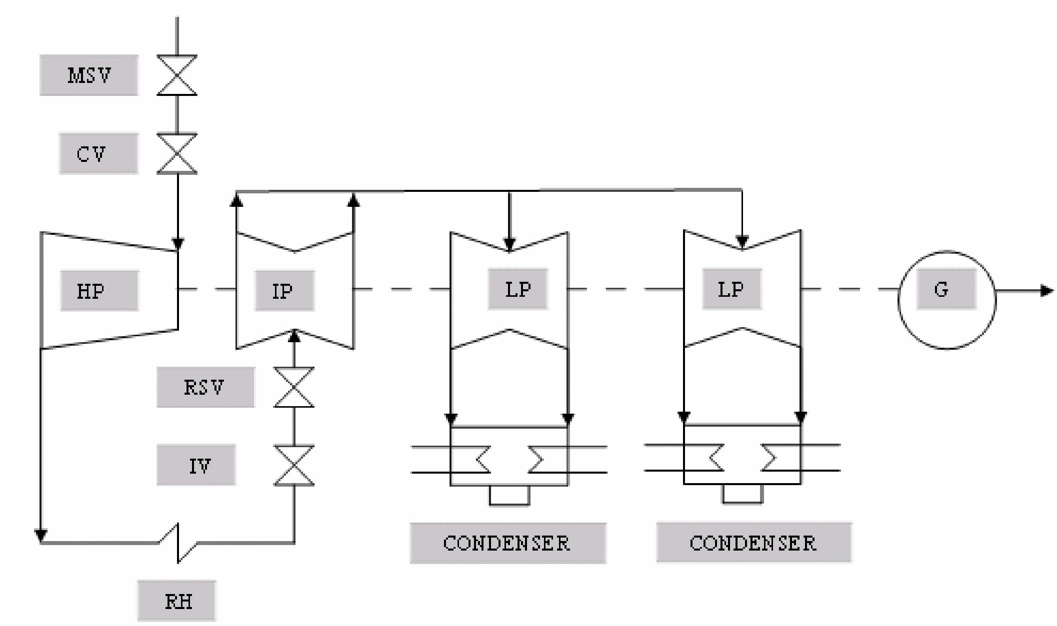


Fig.- 2.1.1c Single-reheat type 2- Tandem compound

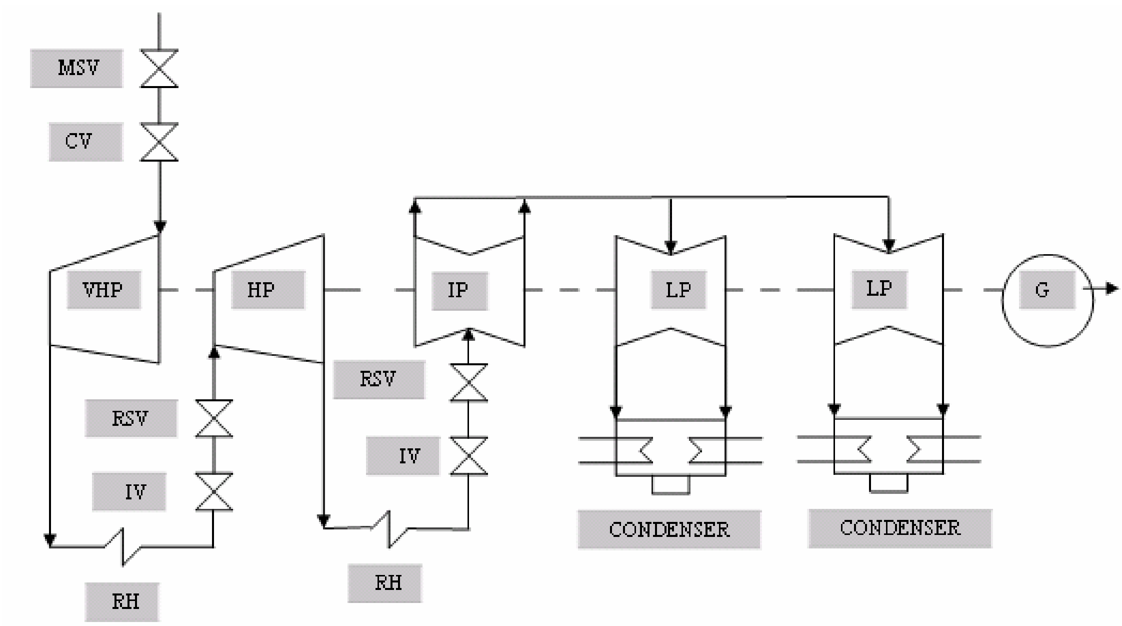
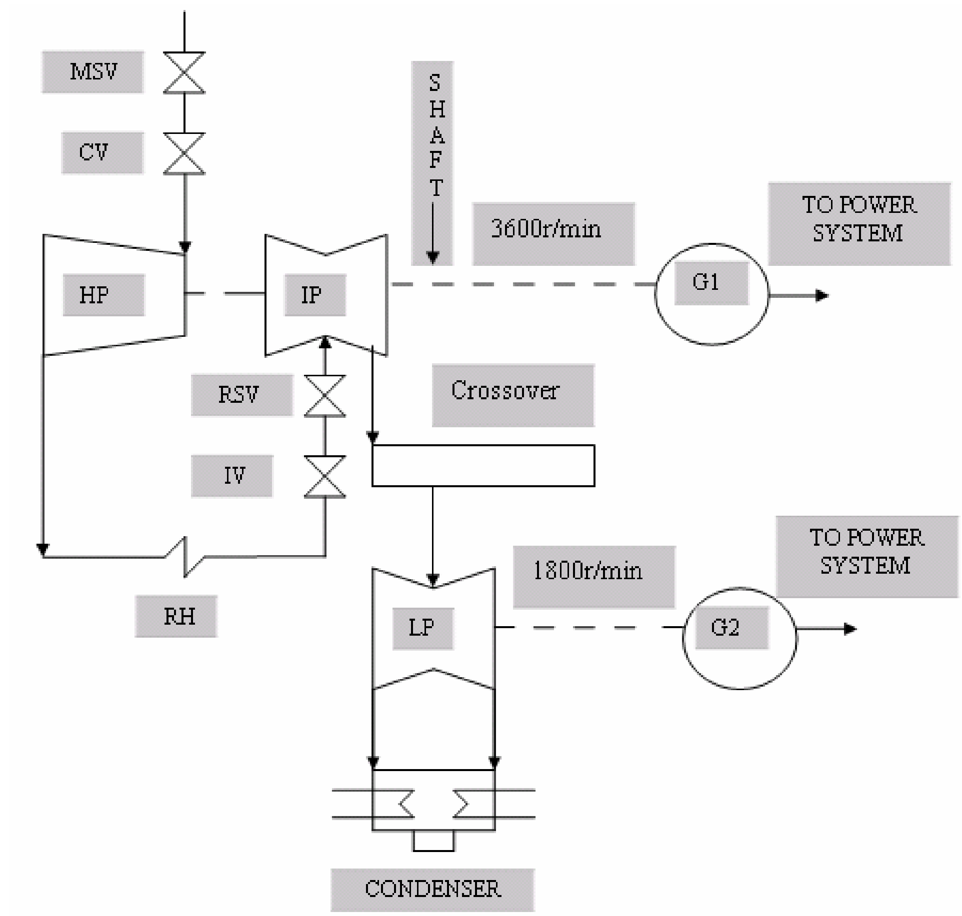
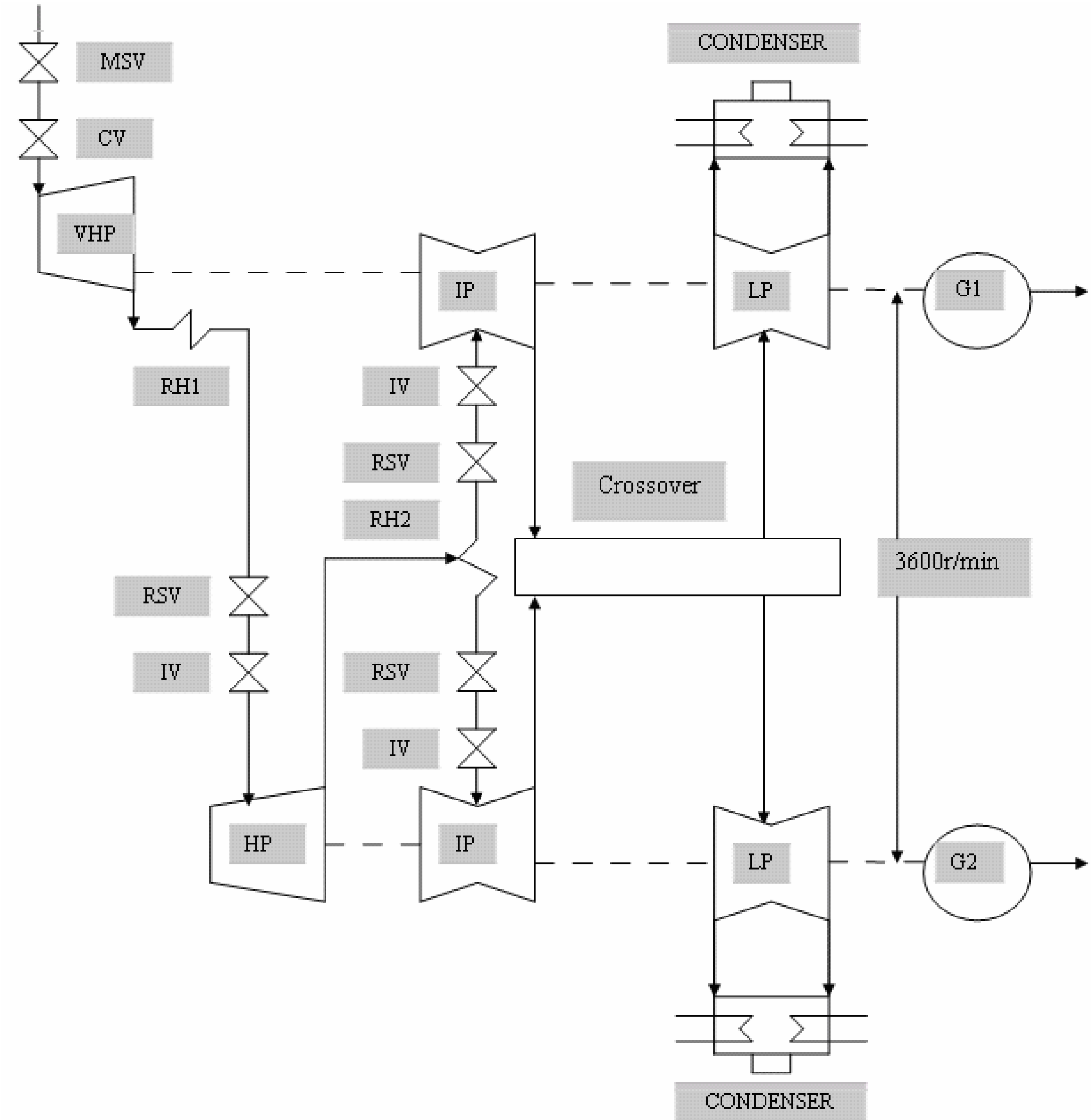


Fig.- 2.1.1d Double-reheat type- Tandem compound

Cross compound



<u>Fig.- 2.1.2.a</u> Single-reheat type- Cross compound



<u>Fig.- 2.1.2b</u> Double reheat- Cross compound

2.2 Turbine sections:

1. High pressure (HP)
2. Intermediate pressure (IP)
3. Low pressure (LP)
4. Reheat (RH)

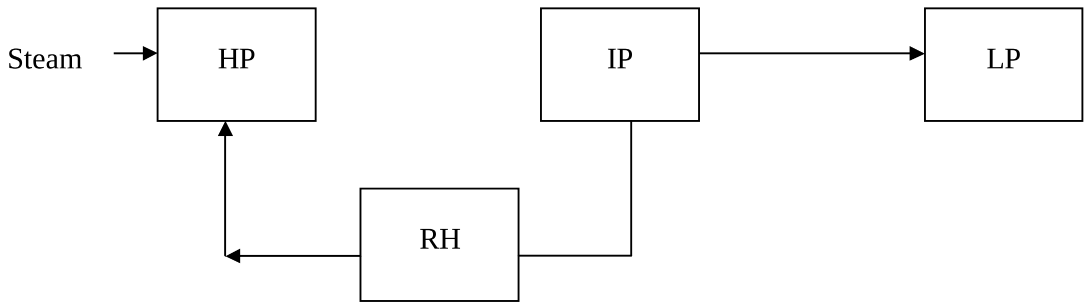


Fig.- 2.2 different sections of a steam turbine

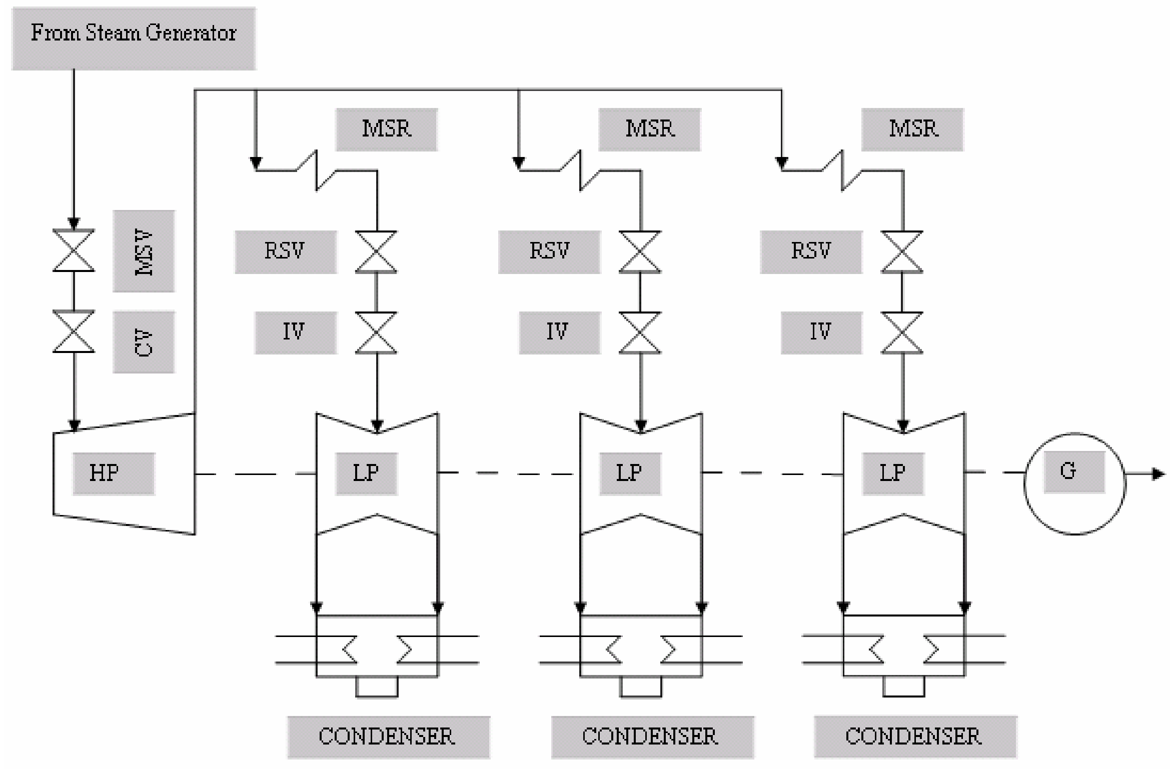
Above figure shows a reheat system, where the outlet steam of HP section passes thro RH before entering IP. Efficiency of a reheat system is always improved and higher than a non-reheat system. Presence of IP and LP sections depends on the entire systems.

2.3 Nuclear turbine units:

Usually nuclear units have tandem-compound configuration and run at 1800 r/min. typical nuclear turbine configuration is shown. It has 1 HP section and 3 LP sections and has no IP section. Some of the other important parts of this turbine configuration are

(a) Moisture separator re-heater (MSR), (b) Main inlet stop valves (MSV) (c) Control valves (CV) (d) Re-heater stop valves (RSV) (e) Intercepts valves (IV).

Every unit has 4 important valves, which are MSV, CV, IV, and RSV. These 4 are important valves and at least 2 of them will operate parallel or in series. Stop valve is used for tripping in case of emergency and is not used for speed and load control. Governor which is also known as “main inlet valve” controls the steam flow through the turbine during normal operation. Control and intercept valves are responsible for controlling of over speed incase of sudden loss of electrical load. Control valves used are usually of “plug diffuser types” and the intercept valves can be either 2plug type” or “butterfly type”, which is suitable for nuclear units. [7]



<u>Fig.- 2.3</u> Nuclear unit turbine system

As seen, steam from generator enters HP section after passing thro MSV and its being controlled by CV. Exhaust steam from HV section enters LP after passing thro MSR, where moisture content of the steam is reduced to avoid moisture losses and corrosion. A high pressure reheat system can be used and in that case an IP will be used.

2.4 Modeling of steam turbines:

Here, we discuss the characteristics, modeling of steam turbines and governing systems. And also protection of steam turbines and controls are explained. [7]

2.4.1 Transfer function

Here we derive the transfer function of a steam vessel and to develop the expression for a turbine stage.

Time constant of a steam vessel:-

Following figure is a representation of a steam vessel. And its continuity equation is given by

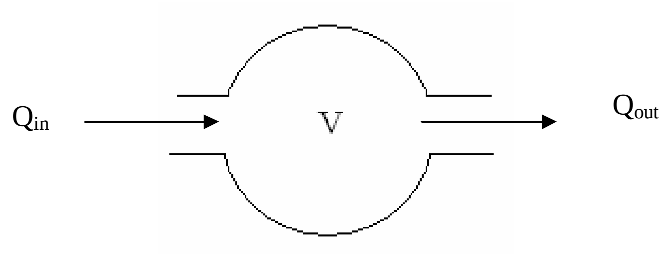


Fig.- 2.4 steam vessel

$$\frac{dW}{dt} = V\frac{d\rho}{dt} = Q_{in} - Q_{out} \qquad (1)$$

Where,
W= weight of steam inside the vessel in kg = Vρ
V= volume of vessel in m^3
ρ = density of steam kg/ m^3
Q= steam mass flow rate kg/s
t = time (s)

Assuming flow out of the vessel directly proportional to pressure inside the vessel, we get

$$Q_{out} = (Q_0 / P_0)\, P \qquad (2)$$

Where,
P = pressure of steam inside the vessel
P_0 = rated pressure
Q_0 = rated flow out of vessel

With constant temperature inside the vessel,

$$\frac{d\rho}{dt} = \frac{dP}{dt}\frac{\partial\rho}{\partial P} \qquad (3)$$

The change in density of steam with respect to pressure $\frac{\partial\rho}{\partial P}$ at a given temperature may be determined from steam tables. From equations (1), (2), and (3), we have

$$Q_{in} - Q_{out} = V\,\frac{dP}{dt}\frac{\partial\rho}{\partial P}$$

$$= V\,\frac{\partial\rho}{\partial P}\,\frac{P_0}{Q_0}\frac{dQ_{out}}{dt} \qquad (4)$$

Substituting $\frac{P_0}{Q_0}\, V\, \frac{\partial\rho}{\partial P}$ by time constant T_V

$$Q_{in} - Q_{out} = T_V\,\frac{dQ_{out}}{dt}$$

Using Laplace, equation (4) can be written as

$$Q_{in} - Q_{out} = T_V \, s \, Q_{out}$$

$$\frac{Qout}{Qin} = \frac{1}{1+TvS} \qquad (5)$$

2.5 Governor-Turbine Model

Following block diagram gives a representation of primary control in a steam unit. It includes a governor and turbine model. The governor in turn includes a speed changer, speed governor, speed relay, control valves and turbine system.

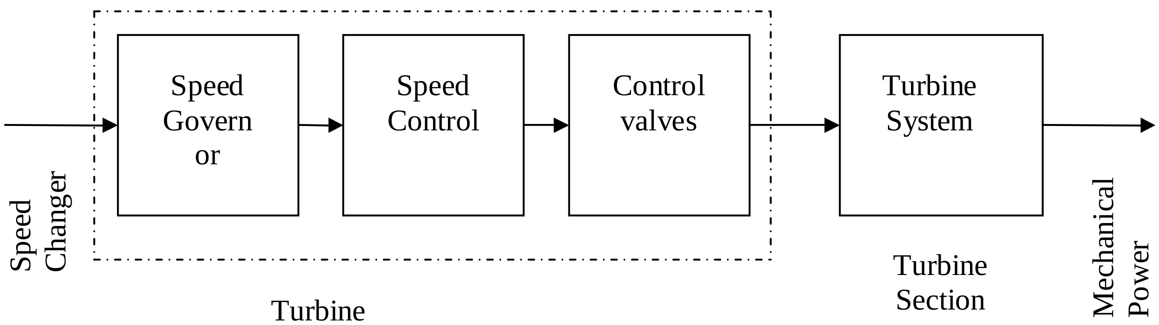


Fig.-2.5 Control system of Steam turbine

2.5.1 Governor Model

The isochronous or constant speed governor, which adjusts the turbine gate to bring back the frequency to the nominal value, is not recommended when there are two or more generating units are connected to the same system. Because the generators in the system should have same speed setting and the isochronous governors would try to cancel out each other trying to maintain the system frequency. So the governors with speed-droop a characteristic that is the speed drops as the load increases is used for marinating the stable load sharing between several parallel operating units. The following figure shows the governor block with the transfer function and the gain 1/R.

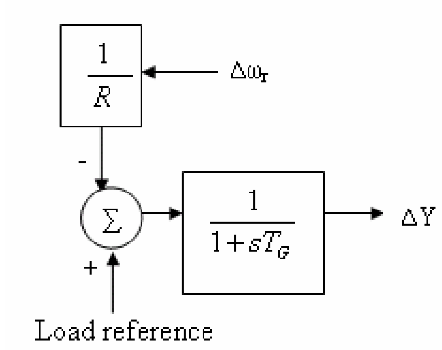


Fig.- 2.5.1 Governor Block

2.5.2 Time response

When a generating unit is subjected to an increasing load, with a speed droop governor, the time response obtained will be as shown in fig. xx. The increase in power output is accompanied by a frequency deviation ($\Delta_{\omega_{ss}}$) because of the droop characteristics. [7]

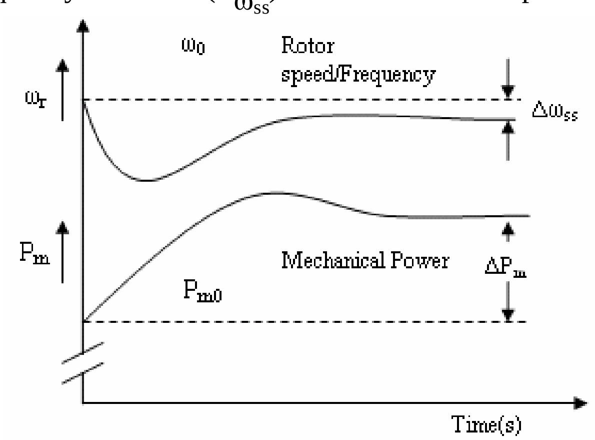


Fig.- 2.5.2 Time response of a generating unit

2.5.3 Controlling Power Output of generating unit

Speed-changer motor -By changing the “load reference set point” the relation between speed and load can be adjusted. In reality this load reference point is changed by using the “speed-changer motor”. The following figure shows the characteristics of a governor associated with the speed changer motor for a 60 Hz system. From the set of 3 parallel curves, effect of speed changer can be analyzed. Characteristic curve A has zero output, while B records an output of 50% and C results in 100%. It can be deduced that for a speed change of 5% or 3 Hz, will result in 100% change in output power. When there is two or more generating units operate in parallel, output of each unit can be varied by varying its load reference for a given system frequency. This makes the speed-droop curves move up and down. [7]

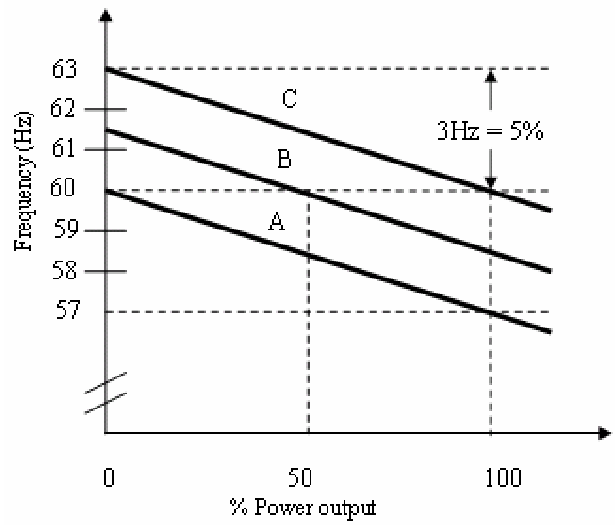


Fig.- 2.5.3 Effect of speed -changer

2.6 Turbine model – Reheat type

The model we consider is of reheating type generating unit and the steam turbine is based on the transfer function $\frac{1+sF_{HP}T_{RH}}{(1+sT_{CH})(1+sT_{RH})}$. This transfer function is the ratio of turbine torque (ΔTm) and control valve position (ΔVcv) and it is assumed that the boiler pressure is constant, Tco is negligible and control valve characteristic is linear. The important time constant is the reheat time constant T_{RH}, which controls the steam flow and turbine power. Therefore reheat type turbines have slower response time than that of non-reheat types.

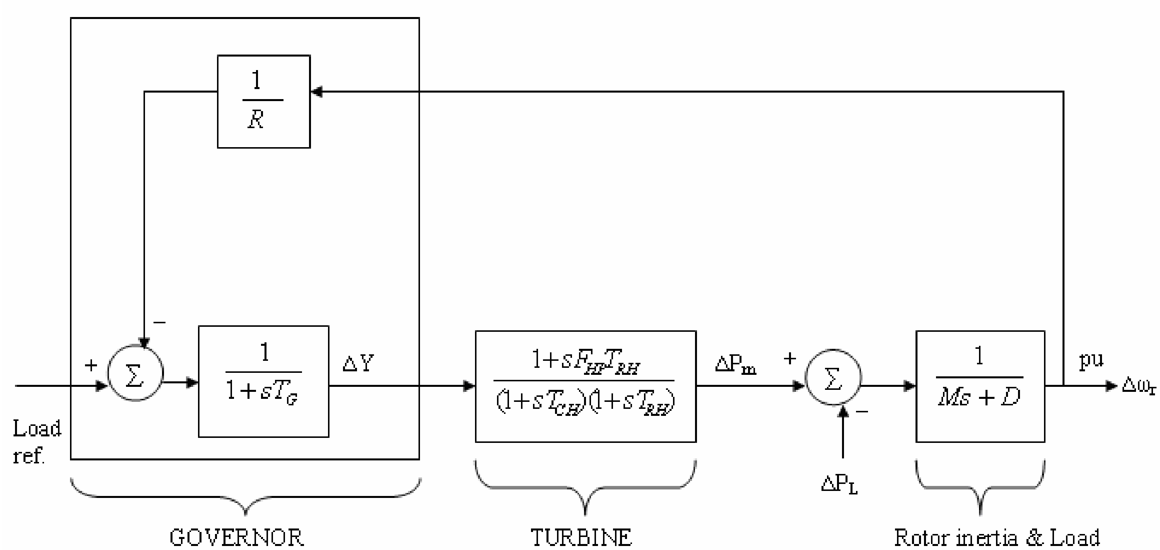


Fig.-2.5 Steam turbine - Reheat type with generating unit

“Control valves” play important part in modulating the steam through the turbine for load / frequency control during normal operation.

2.6.1 T_{CH} – *Charging time constant*

This time constant arises as a result of the opening of a control valve and its response by the steam flow i.e., due to steam chest and inlet piping. Its value is in the order of **0.2 s to 0.5 s** for non-reheat type and **0.1s to 0.4 s** for all reheat types

“Intercept valves” is an effective way of controlling turbine mechanical power during over speed. Intercept valves are located before the reheater section and controls steam flow into Intermediate pressure (IP) and low pressure (LP), where 70% of total turbine power is generated.

2.6.2 T_{RH} – *Reheat time constant*

The steam flowing into the IP and LP sections can be changed only with the build up of pressure in the reheat volume which holds considerable amount of heat and the time constant being T_{RH}. It varies between **5 s to 10 s** irrespective of configurations

2.6.3 T_{CO} –*Crossover piping time constant*

This is a time constant associated with cross-over piping which is **0.3 s – 0.5 s** for all configuration of steam turbines (tandem or cross compound or single or reheat type). This time constant arises because of the steam flowing into the LP section

2.6.4 F_{HP}, F_{LP}, F_{IP} – *Fraction of turbine powers*

These fractions represent the portions of turbine power developed in various cylinders and when the control valve CV is opened fully and has a value 1.0 pu the sum of these fractions is 1.

i.e., $F_{HP}+ F_{LP}+ F_{IP} =1$

F_{HP} Varies from **0.22 to 0.3 s**, F_{LP} varies from between **0.25 to 0.4 s** and F_{IP} vary from **0.26 to 0.5s** depending upon the turbine configuration types. Derivation for determining the power fraction is discussed later under turbine modeling section.

2.6.5 T_G – *Main gate servomotor constant*

Its value used in this steam turbine model is 0.2 s, while it can vary from 0.2 s to 0.4 s

2.6.6 *M – Inertia co-efficient*

'M' is the inertia co-efficient which is equal to twice the inertia constant (H)
M= 2H

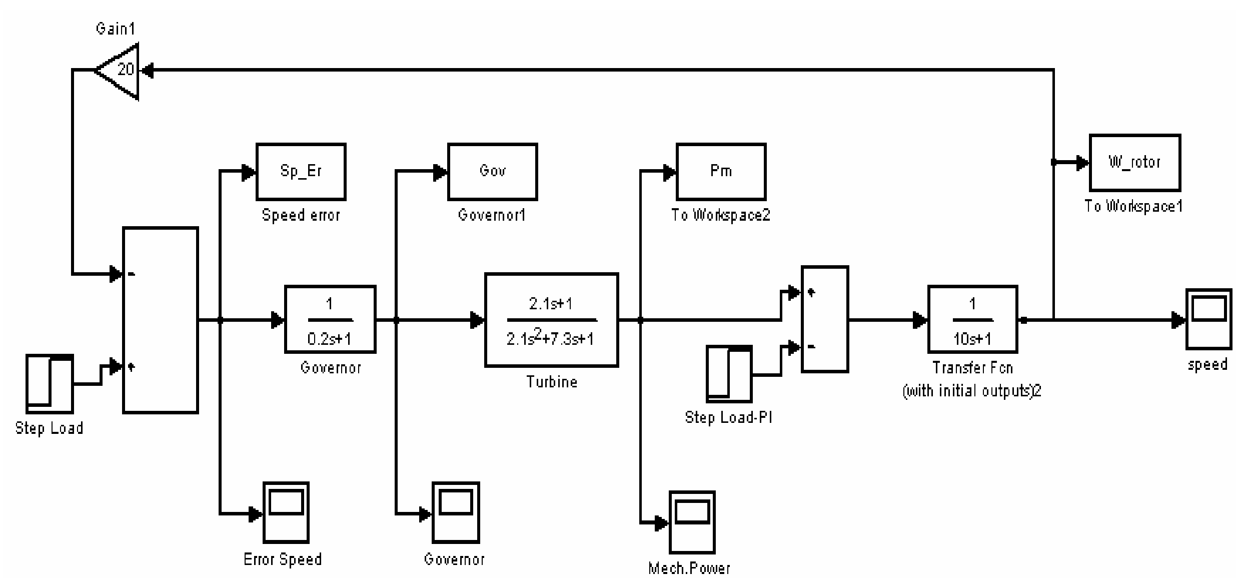
2.6.7 *D – Damping constant*

Damping constant (D) is usually expressed as a percentage change in load for one percent change in frequency. And its value ranges from 1% to 2% which means for 1% frequency change results in 2% load change.

$\frac{1}{R}$ – is the gain factor, where R> 0 for stability. This is a characteristic of a proportional controlled governor model.

2.6.8 MATLAB model:

A matlab model was constructed using 'simulink' with the given parameters. Transfer function for the turbine was simplified into equations by substituting values. A step load is coupled with a gain feedback is given as the input which passes through the 'governor' and the output of the governor is sent through the 'turbine' which results in mechanical power (ΔP_m). This ΔP_m is now coupled with a negative electrical load i.e. ΔP_L a small disturbance and then it is fed to the rotors to obtain the 'speed deviation' and the following outputs were obtained. (For detailed description of the model and matlab program, see appendix. B)



<u>Fig.- 2.6</u> Matlab model

2.6.9 Results

2.6.9.1 OUTPUT WITH LOAD = 5%

For **LOAD= 5%** and with given values of
T_G= 0.2 S
T_{RH}= 7.0 s
T_{CH} = 0.3 s
R= 0.05 s
F_{HP} = 0.3 s
F_{LP}= 0.7s (this model doesn't has an IP section, so F_{IP} is not considered)
M= 10.0 s
D= 1.0 s

Turbine transfer function is $(2.1s+1)/(2.1s^2+7.3s+1)$

As mentioned previously, "governor position" is the input and the output will be "mechanical power" and the "speed deviation". Here, a small increasing step load of 5% is fed.

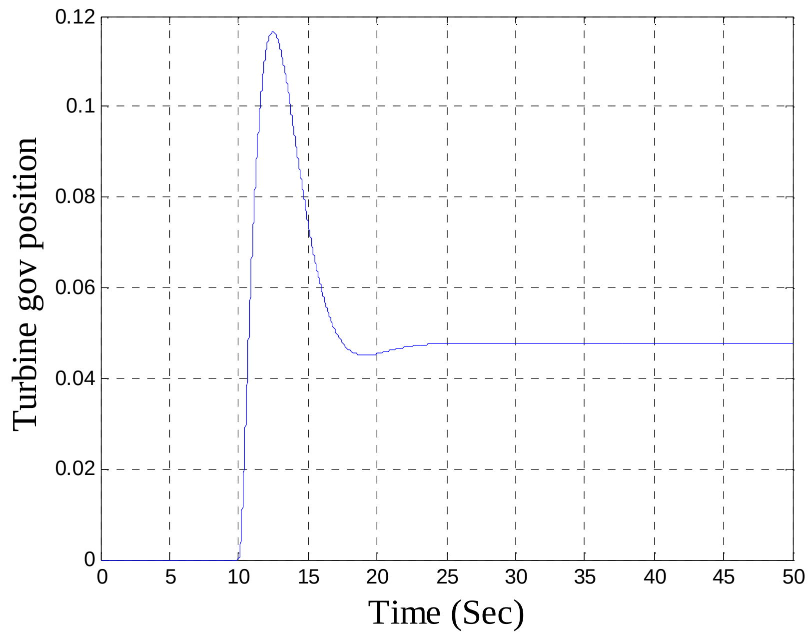


Fig.- 2.6.1a Valve / Gate position of the reheat steam turbine unit for a 5% load

It can be noticed that the input governor position increases initially to increase the power output and when the desired power is reached it drops back to reach the stable position.

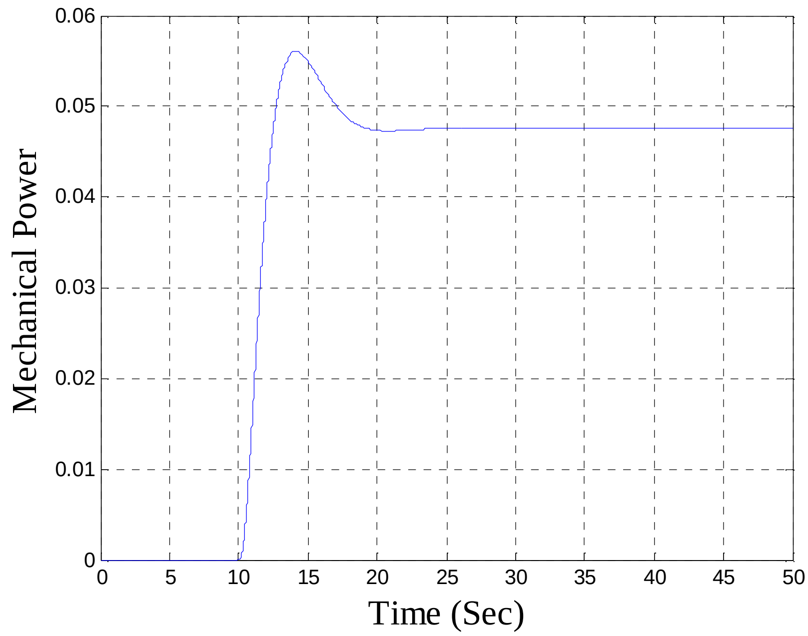


Fig.- 2.6.1b corresponding Mechanical power output of the steam turbine unit

Above graph clearly shows that the mechanical power follows the governor position i.e. when the gate opens, mechanical power output increases to meet the load demand. After reaching its maximum output value mechanical power goes stable proportional to the gate value.

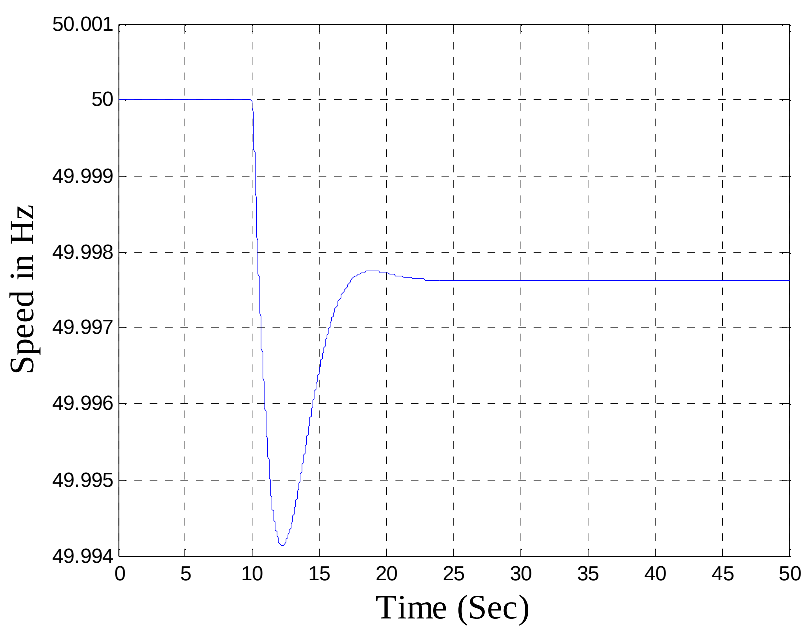


Fig.- 2.6.1c speed deviation/rotor speed of the reheat type steam power unit with a 5% load

It can be noticed that the speed decreases when the gate and mechanical power increases. This implies that speed is inversely proportional to governor position and mechanical power.

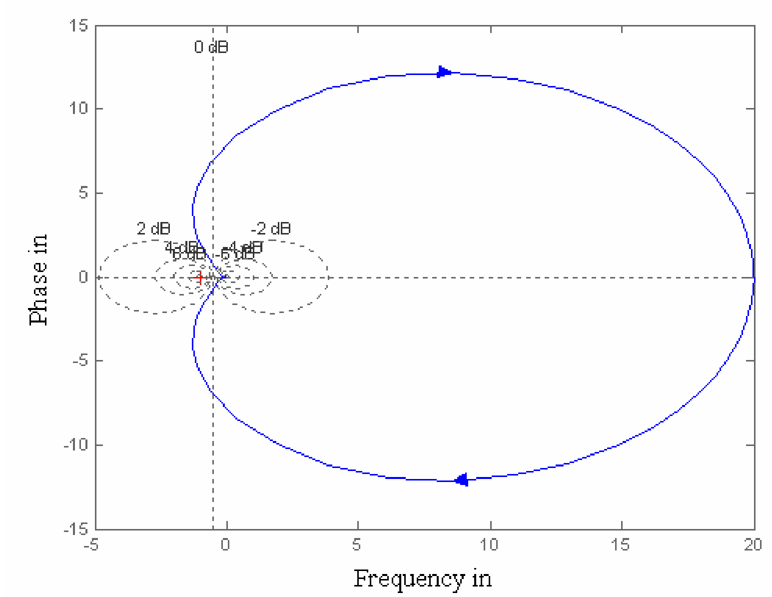


Fig.- 2.6.1d Nyquist Plot for the reheat type steam turbine for a 5% load

The graph shows that the system is stable by satisfying the nyquist criteria for stability (0,-1).and the corresponding phase margin, gain margin is obtained using the margin plot.

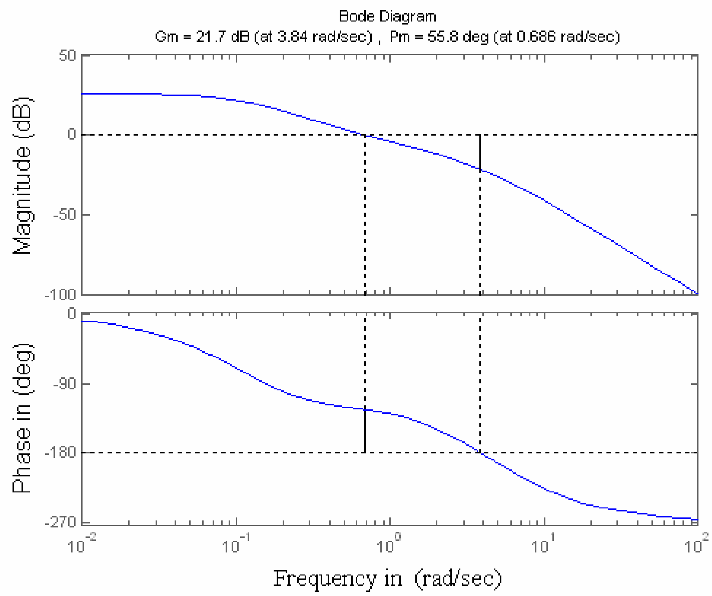


Fig.- 2.6.1e Margin Plot showing the gain margin Gm=21.7db (at 3.84 rad/sec) and phase margin Pm=55.8 deg (at 0.686 rad/sec).

2.6.9.2 OUTPUT WITH LOAD= 10%

For **LOAD= 10%** and with given values of

T_G= 0.2 S

T_{RH}= 7.0 s

T_{CH} = 0.3 s

R= 0.05 s

F_{HP} = 0.3 s

F_{LP}= 0.7s (this model doesn't has an IP section, so F_{IP} is not considered)

M= 10.0 s

D= 1.0 s

Turbine transfer function is $(2.1s+1)/ (2.1s^2+7.3s+1)$

Here, an increasing step load double the time of previous is fed to check the time response. It's because the step load has doubled, output mechanical power also should get doubled according to theory. Let's analyze the results.

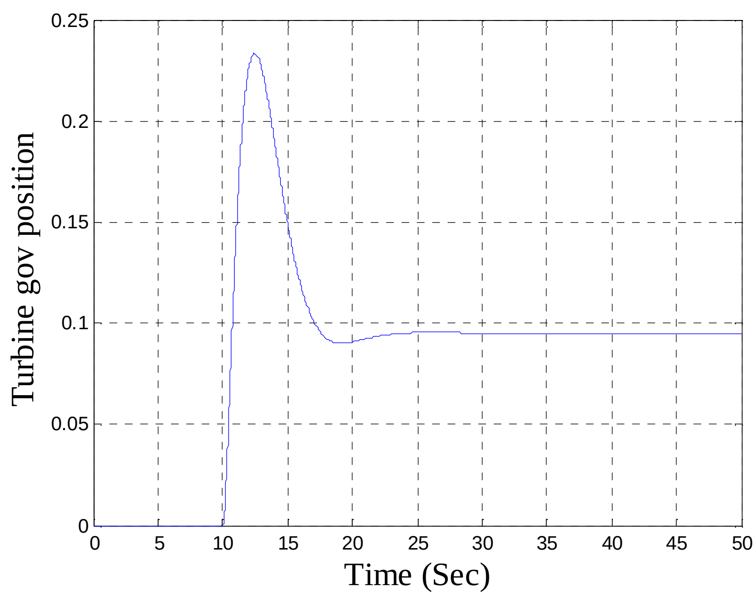


Fig.- 2.6.2a Valve / Gate position of the reheat steam turbine unit for a 10% load

It can be seen that the value of gate position has doubled for the increasing load and the corresponding value has nearly doubled from approx. 0.12 to 0.24. These small variations maybe because of different factors like load limits, valve point, turbine-following or boiler-following mode, etc...) And the mechanical power also increases from 0.06 to approx 0.12 in fig 2.6.2b

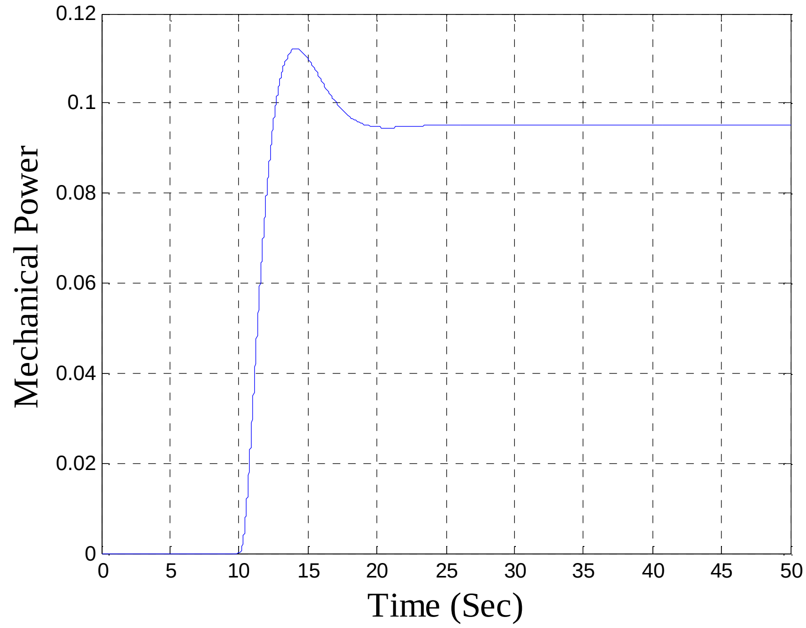


Fig.- 2.6.2b corresponding Mechanical power output of the steam turbine unit

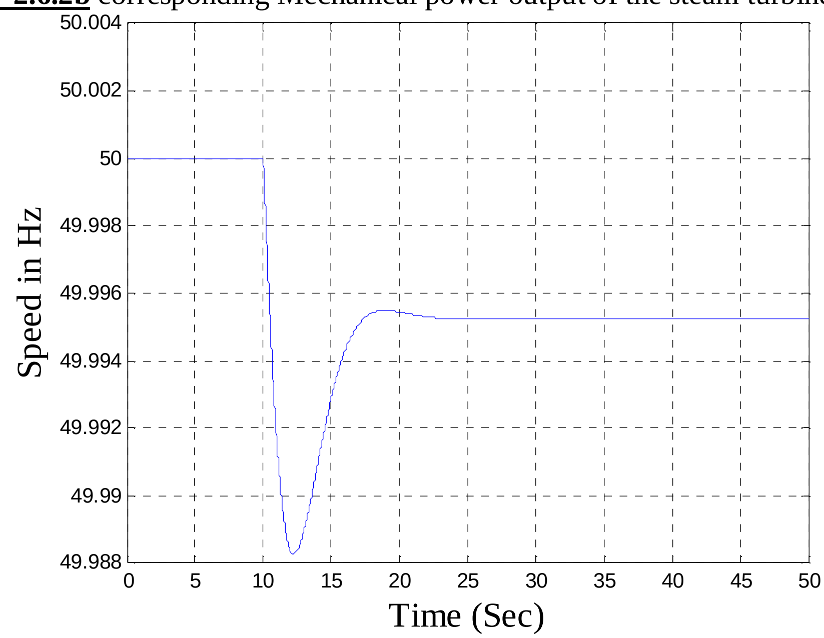
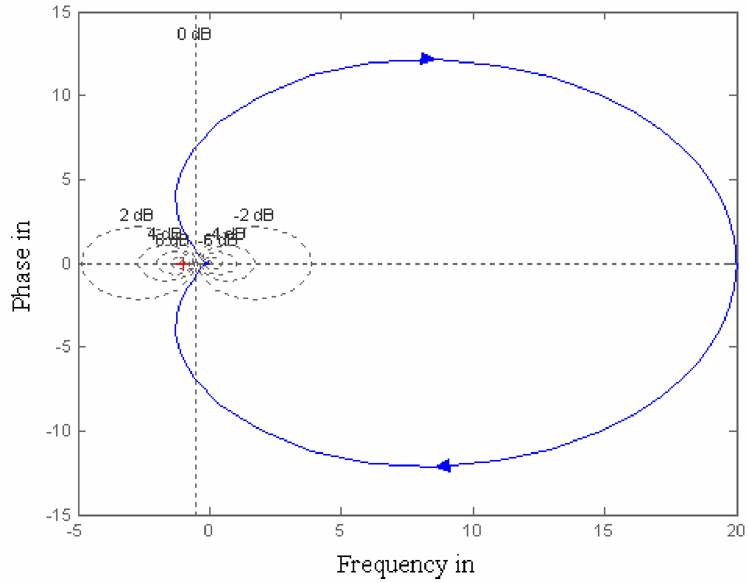
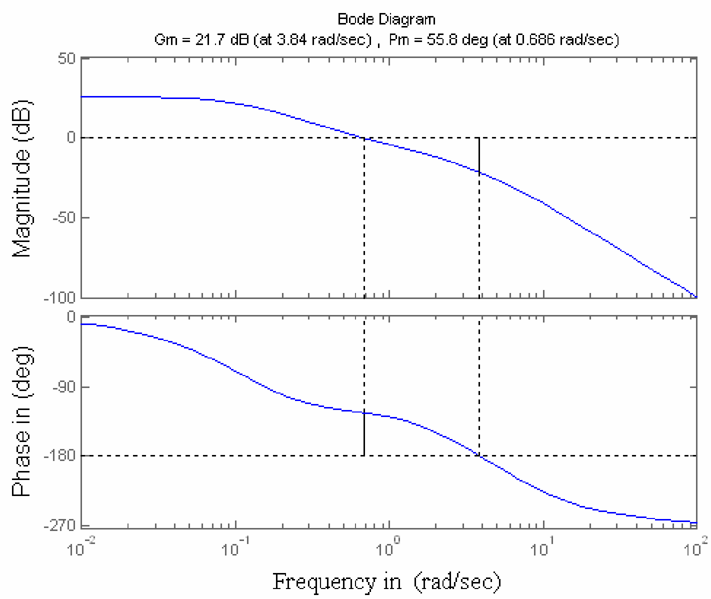


Fig.- 2.6.2c speed deviation/rotor speed of the reheat type steam power unit with a 10% load

It can be deduced that the speed decreases drastically when the input step load is increased. But still it is clear that they follow the standard time response curves to meet the load demand. And from the nyquist plot it can be made clear that the system is stable satisfying the nyquist criteria for a stable system.



<u>Fig.- 2.6.2d</u> Nyquist Plot for a reheat steam turbine with a 10% load



<u>Fig.- 2.6.2e</u> Margin Plot showing the gain margin Gm=21.7db (at 3.84 rad/sec) and phase margin Pm=55.8 deg (at 0.686 rad/sec).

And also the gain margin and phase margin values remains the same for both 5% and 10% load gain margin Gm=21.7db (at 3.84 rad/sec) and phase margin Pm=55.8 deg (at 0.686 rad/sec), which proves that these values doesn't depend upon input step loads and the system remains stable for whatever load.

2.7 Turbine Model – Non-Reheat type

The reheat type steam turbine model used previously, fig.2.5 can also be used a non-reheat type turbine with little modification. For a non-reheat, the reheat time constant T_{RH} becomes zero because of the absence of reheat unit. Thus the turbine transfer function can be re-written as

$$\frac{1}{(1+sT_{CH})}$$ With $T_{CH} = 0.3$.

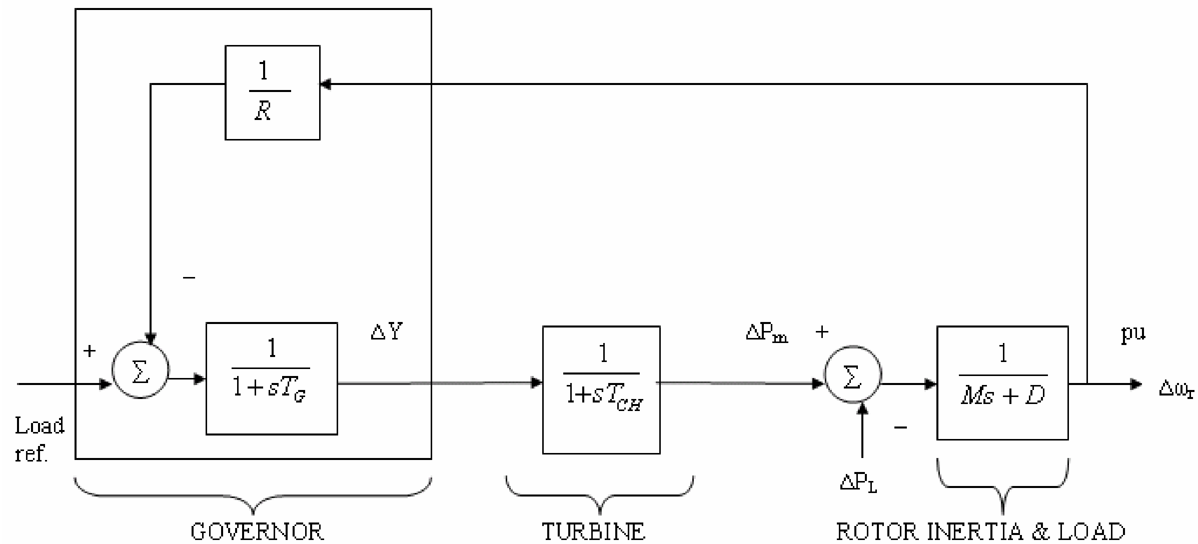


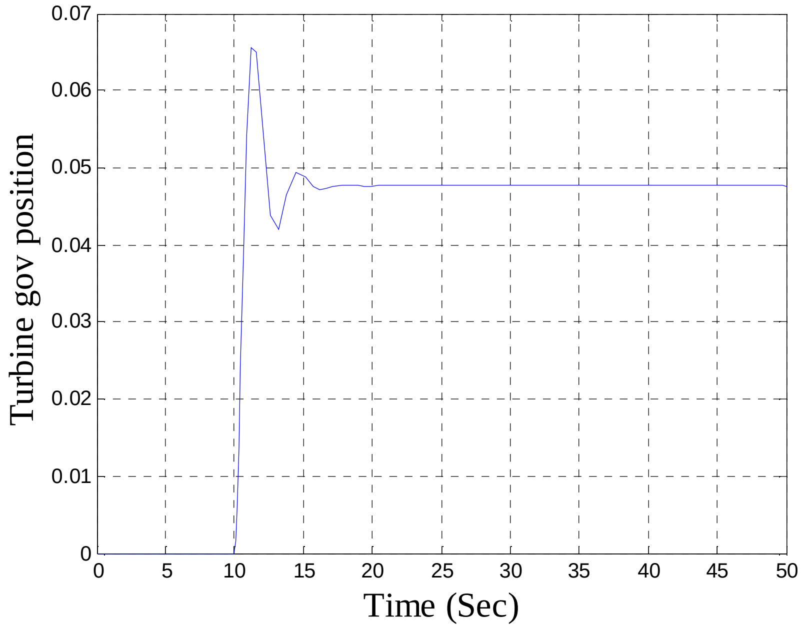
Fig.- 2.7 Steam turbine – Non-reheat model

2.7.1 Results

2.7.1.1 OUTPUT WITH LOAD = 5%

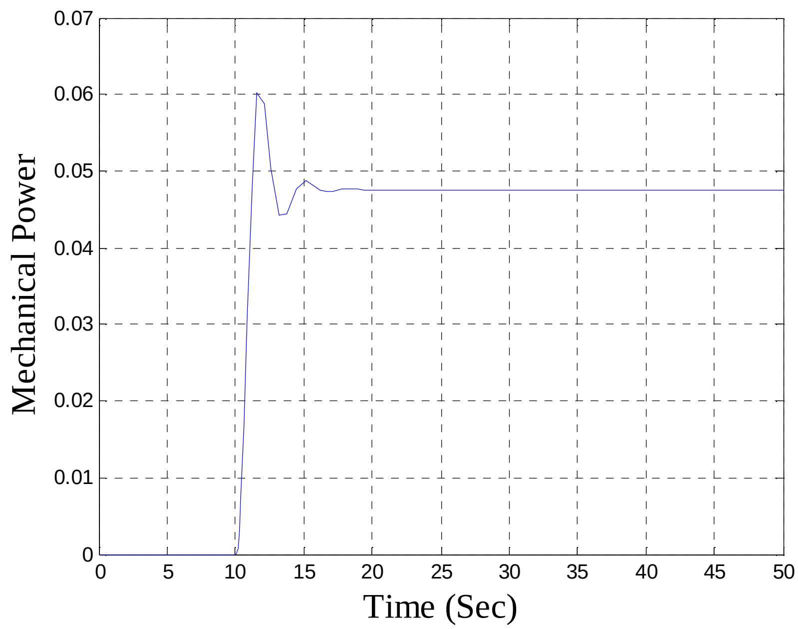
For **LOAD= 5%** and with given values of
T_G= 0.2 S
T_{CH} = 0.3 s
R= 0.05 s
F_{HP} = 0.3 s
F_{LP}= 0.7s (this model doesn't has an IP section, so F_{IP} is not considered)
M= 10.0 s
D= 1.0 s

Turbine transfer function is 1/ (s0.3 +1).



<u>Fig.- 2.7.1a</u> Valve / Gate position of the non-reheat steam turbine unit for a 5% load

The gate opens drastically initially to increase the power output and because it is non-reheat the steam through the gate drops and rises again and then reaches the stable state. This resembles like a fluctuation and then goes to the stable state



<u>Fig.-2.7.1b</u> corresponding mechanical power of the non-reheat steam turbine unit for a 5% load

The output mechanical power follows the steam through the gate. It suffers the same fluctuation in the initial stages before going stable.

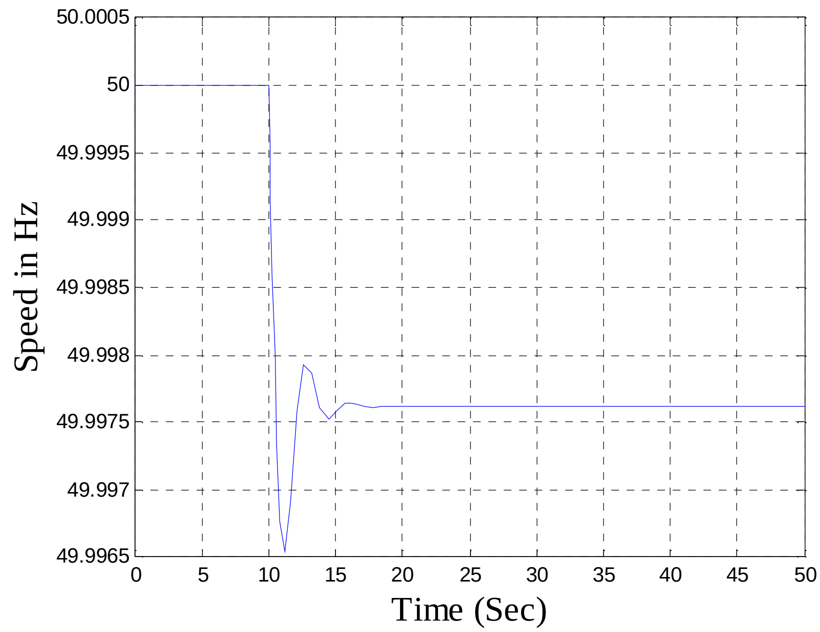


Fig.- 2.7.1c speed deviation/rotor speed of the non-reheat steam turbine unit for a 5% load

This is an interesting behavior of the rotor speed as it fluctuates to negative quadrant drastically for the mechanical power increase and then immediately rises to positive when steam through the gate drops and finally when the power needed is reached, speed goes stable following mechanical power and governor position.

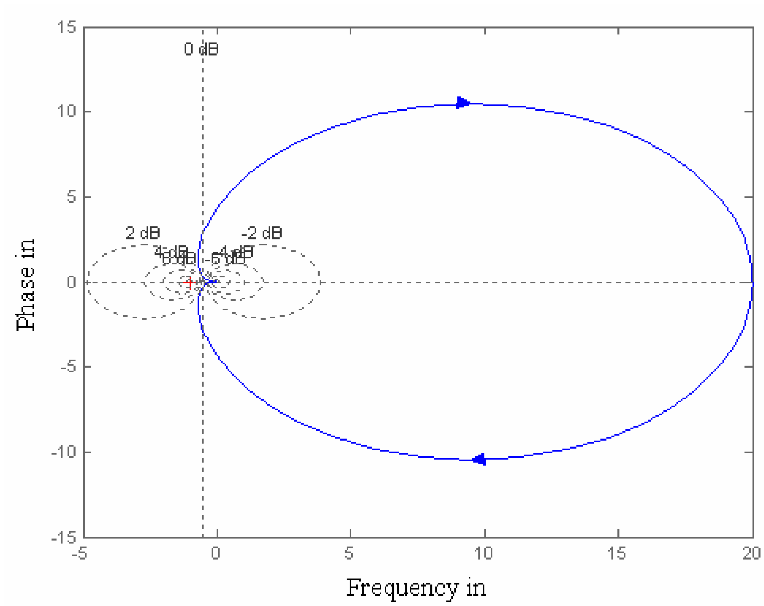


Fig.-2.7.1d Nyquist Plot for non-reheat steam turbine with 5% load

It is clear from the nyquist plot that the system is stable and has a gain margin Gm=12.8db (at 4.18 rad/sec) and phase margin Pm= 47.9 deg (at 1.69 rad/sec).

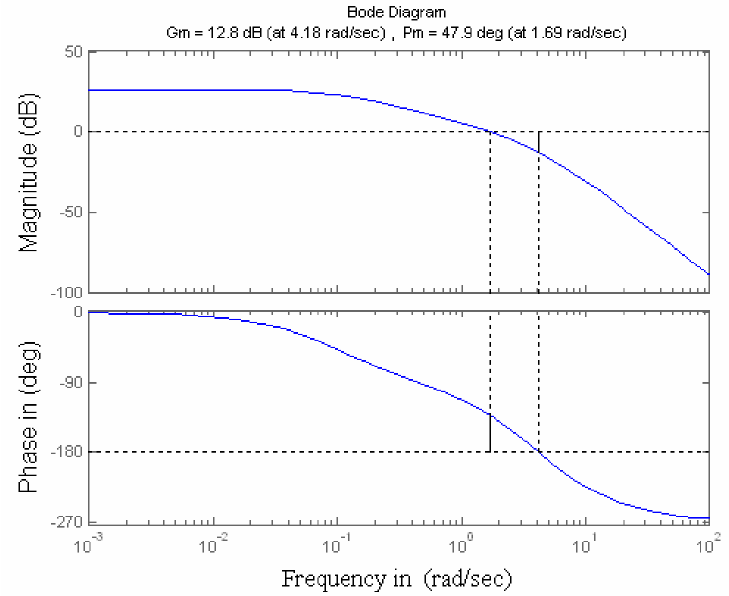


Fig.- 2.7.1e Margin plot for non-reheat steam turbine with 5% load

2.7.1.2 OUTPUT WITH LOAD= 10%

For **LOAD= 10%** and with given values of
T_G= 0.2 S
T_{CH} = 0.3 s
R= 0.05 s
F_{HP} = 0.3 s
F_{LP}= 0.7s (this model doesn't has an IP section, so F_{IP} is not considered)
M= 10.0 s
D= 1.0 s

Turbine transfer function is 1/ (0.3s+1)

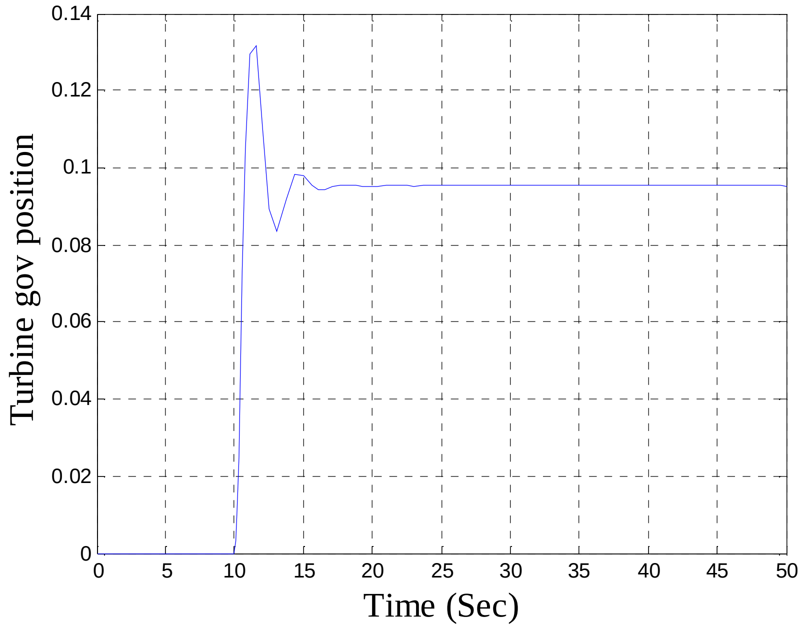


Fig.-2.7.2a Valve / Gate position of the non-reheat steam turbine unit for a 10% load

Governor position reveals that, steam through the gate increases to meet the power demand and the mechanical power curve follows the governor position. Thus it can be deduced that mechanical power is proportional to the governor position. And the mechanical power is nearly doubled for the double increase in the step load from 5% to 10%.

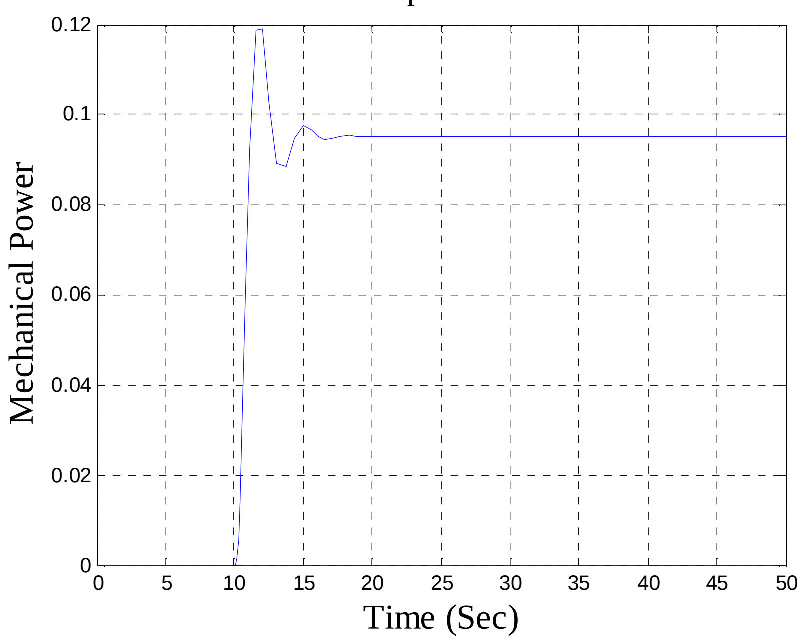


Fig.- 2.7.2b corresponding mechanical power of the non-reheat steam turbine unit for a 10% load

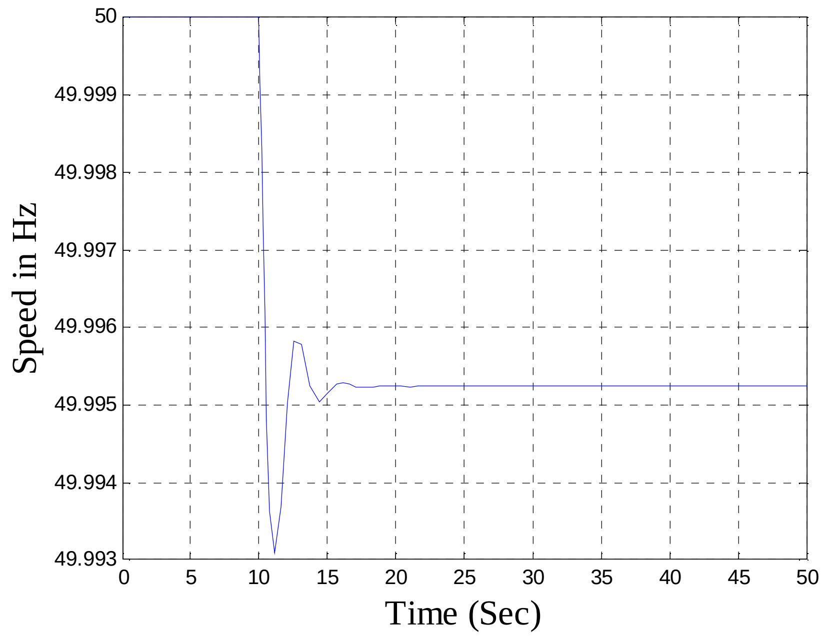


Fig.- 2.7.2c speed deviation/rotor speed of the non-reheat steam turbine unit for a 10% load

It can be noticed that the speed remains in the negative quadrant. It rises and falls before reaches the steady state, when the power demand is met.

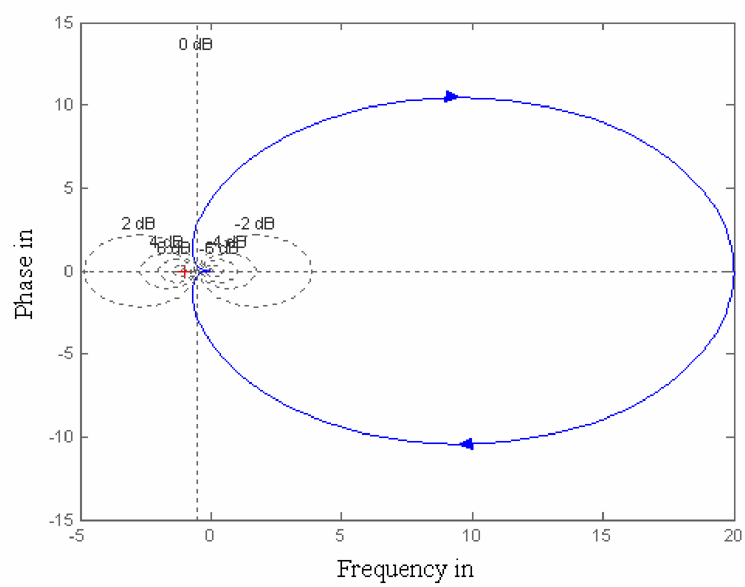


Fig.-2.7.2d Nyquist plot for non-reheat steam turbine with 10% load

The system is proved to be stable using the nyquist plot, which satisfies the nyquist criteria for stability and the values of phase margin and gain margin remains the same irrespective of the step load. And it has a gain margin Gm=12.8db (at 4.18 rad/sec) and phase margin Pm= 47.9 deg (at 1.69 rad/sec).

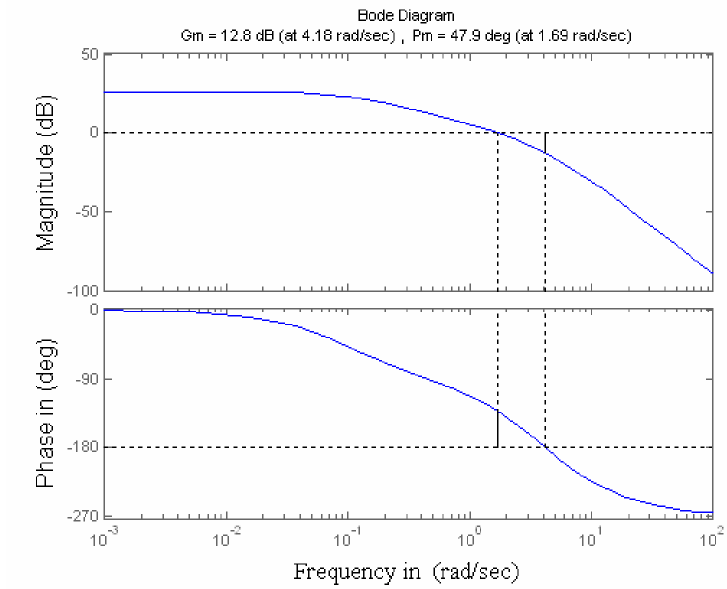


Fig.- 2.7.2e Margin plot for non-reheat steam turbine with 10% load

2.8 Comparison between Reheat and Non-reheat steam turbines

A general comparison between reheat type steam turbine and non-reheat type steam turbine is performed by analyzing the input governor position and the output curves of mechanical power and speed deviation.

This is performed by giving a 10% step load input for both the linear systems and the results are shown below. Boiler pressure has been assumed constant. Responses for steam turbines are usually slower than the theoretical results. And it can be concluded that though steady-state speed deviation remains the same, there exists a notable variation in their transient responses.

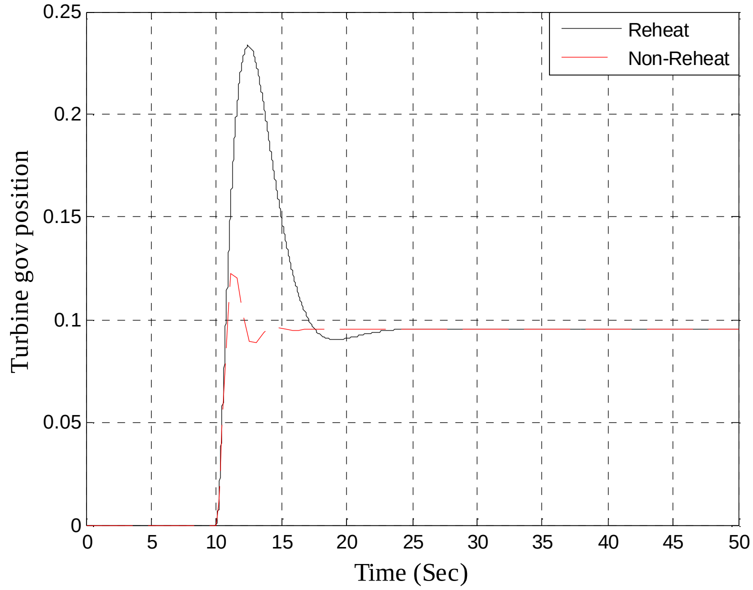


Fig.- 2.8.1 Comparing - Governor Positions

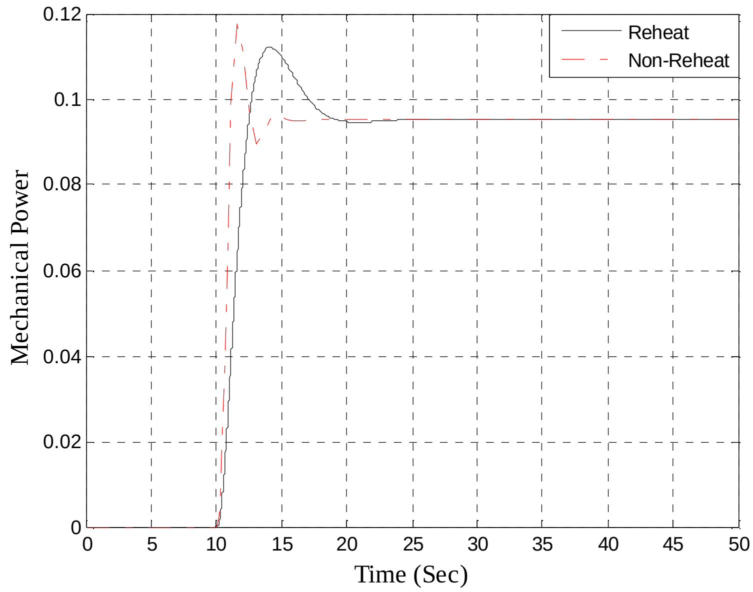


Fig.- 2.8.2 Comparing – Mechanical Power

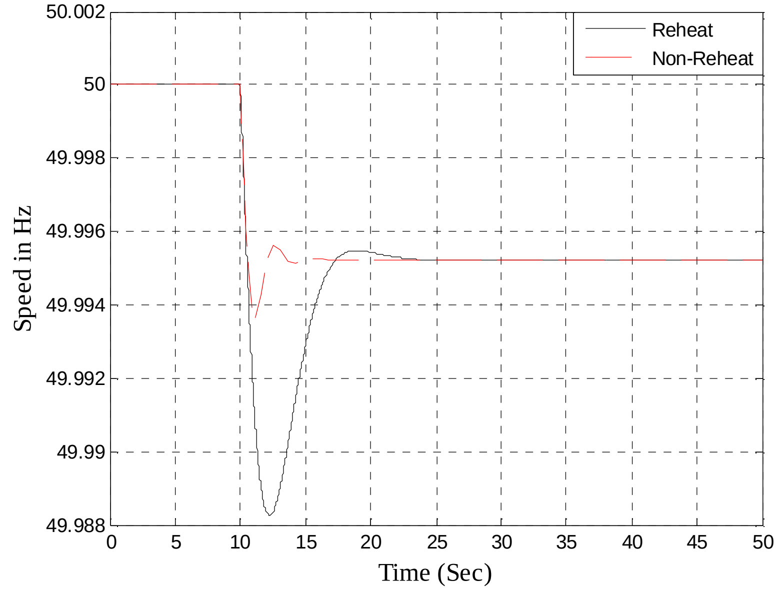


Fig.- 2.8.3 Comparing – Speed Deviation

2.9 Comparison between 5% and 10% step load

The following comparison is made between 5% and 10% step load input for a Reheat type system. The reason for choosing reheat type system is that it is much efficient than the non-reheat type system.

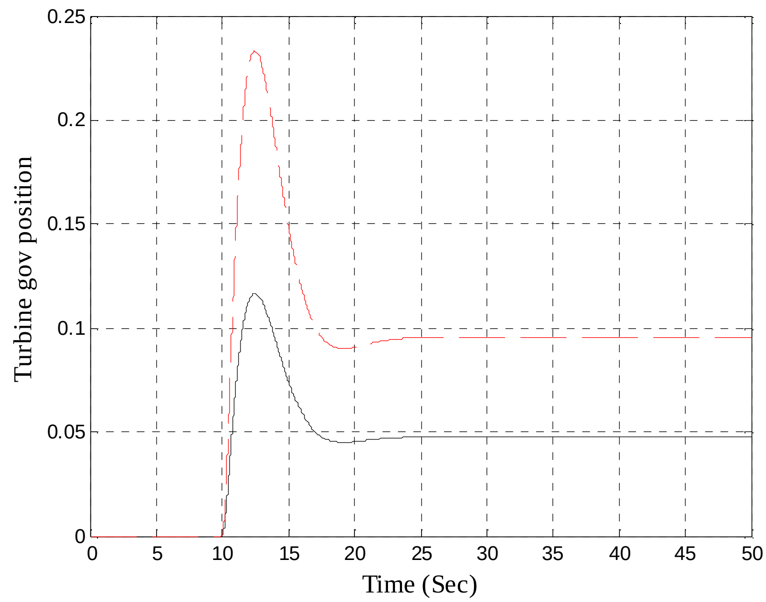


Fig.-2.9.1 Gate positions for 5% and 10% step load

The above graph clearly indicates that the value is doubled as the step input increases. And the corresponding mechanical power also gets doubled thus showing as the step increases the power output increases.

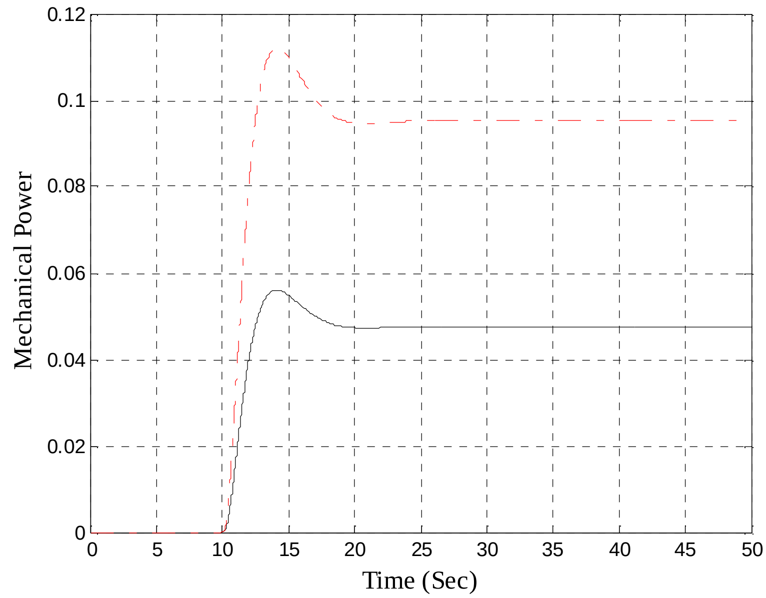


Fig.-2.9.2 Mechanical power output for 5% and 10% step load

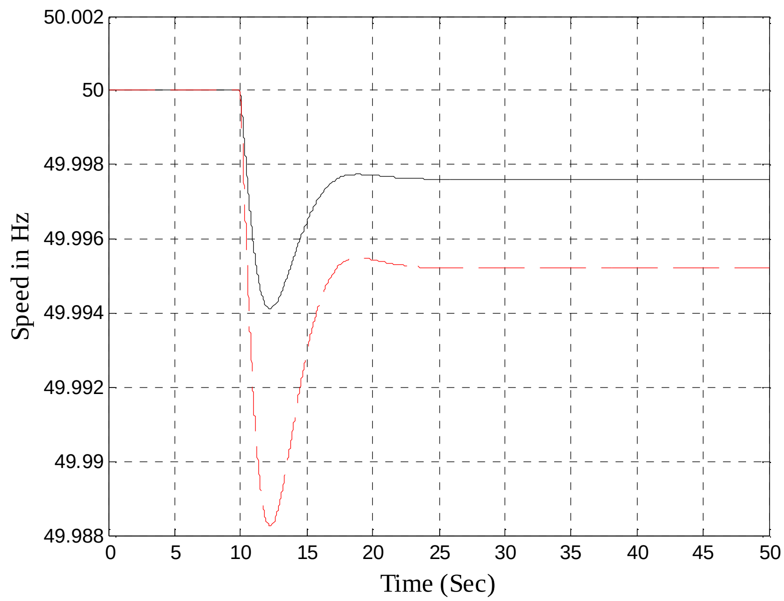


Fig.-2.9.3 Speed of steam turbine for 5% and 10% step load

Chapter-3

Hydroelectric Power

Contents overview

3.1 Introduction:

Hydroelectric power is a renewable technology that converts the high pressure and kinetic energy of water into electrical energy. Hydro power is pollution free energy source and it produces no CO_2 and has little effect on the atmosphere compared to the conventional power plants. The following figure-3.1.1 showed main components of a Hydroelectric power station. Main components are Reservoir, Dam, Gate, Penstock, Turbine and Generator. The following figure shows the necessary components of Hydroelectric power for power generation. [7]

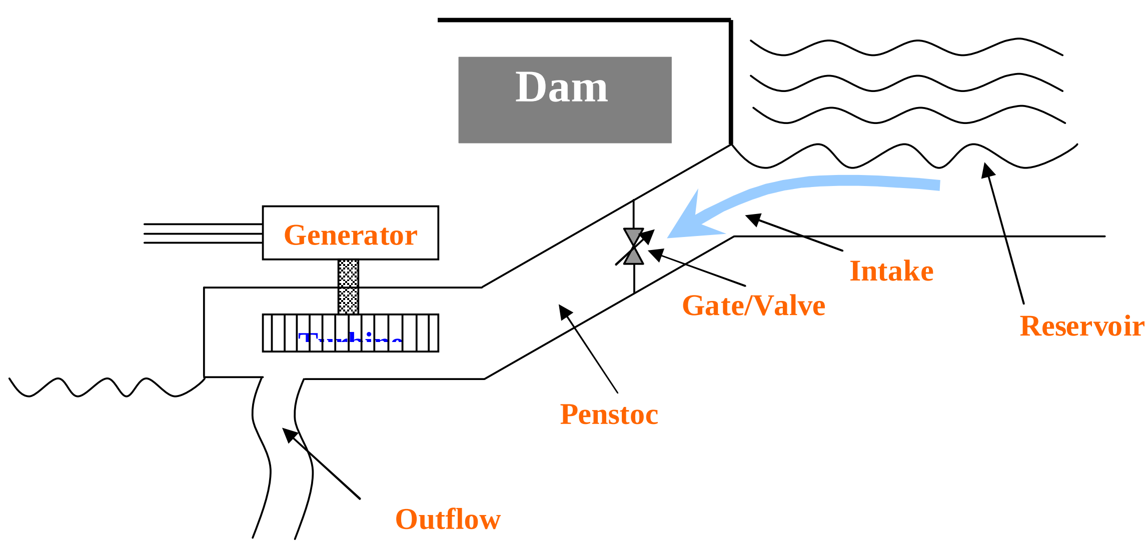


Fig.-3.1. Power generation of Hydroelectric power unit.

3.2.1 Hydro Power Model

Frequency is indispensable constraint and should be constant for a stabilize power systems. Any change of frequency behind limit will affect the speed of motor drives'; hence affect the performance of generating units. Power system frequency depends on active power balance.

Hydroelectric power plants have nonlinear behavior. Here the simulation carried out using the actual nonlinear systems. The linearized model is shown in figure- 3.2 and simulated transferred function of Hydroelectric model in figure- 3.3. Here, it was showed what will be changing phenomena of Turbine mechanical power as well as frequency of power systems by increasing 5% and 10% load. When load is increased from usual value; system frequency decreases rapidly and the speed controller is activated by opening the Gate as input to change the more water flow in the turbine, and consequently, the turbine generates the necessary mechanical power as out put and permit the rotor speed to attain the steady state value. [7]

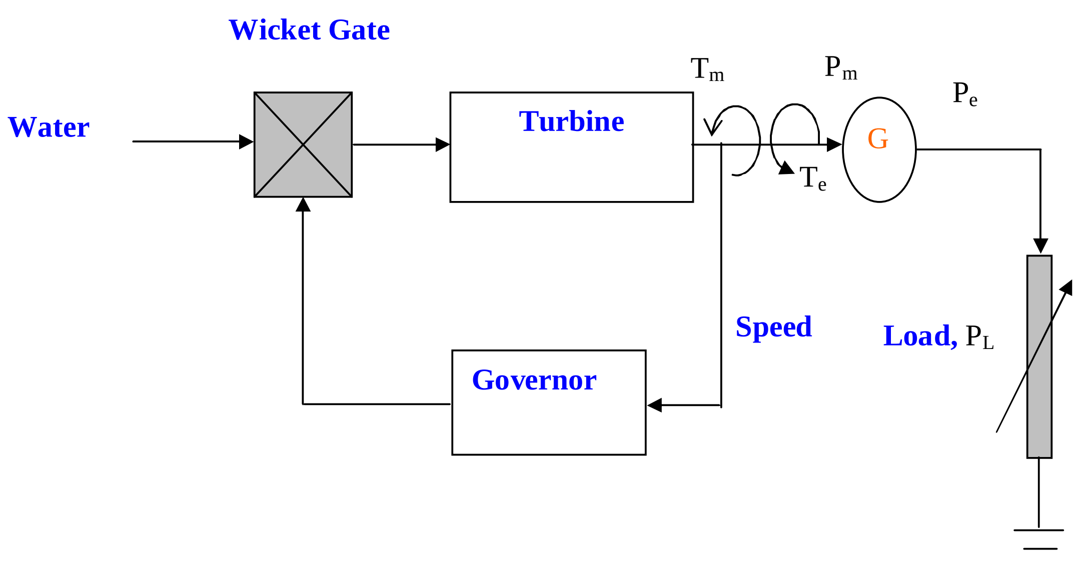


Fig.- 3.2 Block diagram of Hydroelectric Power generation to load.

Hydraulic turbine performance is depend upon following factors:

1. Effect of Water inertia
2. Water compressibility
3. Pipe wall elasticity in the penstock

* Effects of water inertia and compressibility are defined as a water column.
Here, model of the hydraulic turbine and penstock systems developed excluding the

1. Effect of traveling wave
2. Effect of surge tank

For stability studies, we assume the following assumptions:

1. The resistance of hydraulic is insignificant.
2. Inelastic penstock pipe & water is treated as an incompressible fluid.
3. Water velocity varies directly with Valve/gate opening as an input and square root of the net head.
4. Turbine mechanical power is proportional to the product of head and volume of water flow.

3.2.2 Model for simulation studies

Linear model:

This model defined the basic characteristics of hydraulic systems and due to simplicity of its structure it is useful for control systems tuning using linear analysis techniques (frequency response, root locus, etc). [7]

Non linear model:

Where speed and power changes are large such as

1. Governor performance evaluation
2. Islanding operation
3. Load rejection and
4. Systems restoration studies.

Transfer function of hydraulic turbine:
Classical transfer function of the hydraulic turbine is analyzed for ideal turbine and non-ideal turbine.

Ideal turbine:

The basic & general equations of hydraulic systems dynamics are given by:

Flow equation i.e. the velocity of water in the penstock:

$$U = K_u G \sqrt{H}_g \tag{3.1}$$

Where:
U= Velocity of water
H_g= Hydraulic head at Gate/Valve
G= Gate position
K_u= proportionality constant for flow equation.

By introducing the steady state value and partial derivatives then the equation is

$$\Delta\overline{U} = \frac{1}{2}\Delta\overline{H}_g + \Delta\overline{G} \tag{3.2}$$

Turbine mechanical power:

The turbine mechanical power, P_m is proportional to the product of pressure and flow of water:

$$P_m = \eta q \rho g_a H_g \tag{3.3}$$

Final mathematically expression:

$$P_m = K_p H_g U \tag{3.4}$$

$$\Delta\overline{P}_m = 3\Delta\overline{U} - 2\Delta\overline{G} \tag{3.5}$$

Where:
P_m = Turbine mechanical output power
η= Turbine efficiency
ρ= water density
g_a= Acceleration due to gravity
H_g= Hydraulic head at Gate/Valve
Q= Actual turbine flow
U= Water velocity

K_p =Proportionality constant for mechanical power

The acceleration of water column:

When water comes from reservoir to turbine through gate/valve, its head changes at turbine.

Now introducing the Newton's second law of motion:

$$\frac{\partial U}{\partial t} = -g.\frac{\partial H_g}{\partial x} \tag{3.6}$$

Combined equation-

$$(\rho LA)\frac{d\Delta U}{dt} = -A(\rho a_g)\Delta H_g$$

Where:

L= Length of conduit

A=Pipe area

ρ=Mass density

a_g= acceleration due to gravity

ρLA=mass of water in the conduit

ρ a_g ΔH= incremental change in pressure at turbine gate

t= time in second

By simplifying the above equation,

$$T_w = \frac{LU_o}{a_g H_o} \tag{3.7}$$

T_w= water starting time= 0.5 to 4.0 s

For ideal loss less turbine, the classical transfer function of a hydraulic turbine is

$$\frac{\Delta \overline{P}_m}{\Delta \overline{G}} = \frac{1-T_w S}{1+\frac{1}{2}T_w S} \tag{3.8}$$

It shows the turbine out put power changes in response to changes in gate opening.

Non ideal turbine-

For non-ideal turbine, we will consider the following expression of the water velocity and turbine power:

Water velocity equation:

$$\Delta\overline{U} = a_{11}\Delta\overline{H}_g + a_{12}\Delta\overline{W} + a_{13}\Delta\overline{G} \tag{3.9}$$

Turbine mechanical output power:

$$\Delta\overline{P}_m = a_{21}\Delta\overline{H}_g + a_{22}\Delta\overline{W} + a_{23}\Delta\overline{G} \tag{3.10}$$

Where:
$a_{11,}$ a_{13} = partial derivatives of flow with respect to head and gate opening at the operating point

$a_{21,}$ a_{23}= = partial derivatives of turbine power with respect to head and gate opening at the operating point.

Now the final equation for the classical transfer function of a no-ideal lossless hydraulic turbine

$$\frac{\Delta\overline{P}_m}{\Delta\overline{G}} = \frac{1+(a_{11} - a_{13}a_{21}/a_{23})T_w S}{1+a_{11}T_w S} \tag{3.11}$$

3.3 **Basic Plant Equation**

A. Gate servo motor:

$$\frac{1}{1+sT_G}$$

B. Transient droop compensator:

$$G_c(s) = \frac{1+sT_R}{1+s(R_T / R_P)T_R}$$

Governor:

$$\frac{1}{1+sT_w} * \frac{1+sT_R}{1+s(R_T / R_P)T_R}$$

C. Hydro turbine unit:

$$\frac{1-T_w s}{1+0.5T_w s}$$

D. Load and Machine unit:

$$\frac{1}{2Hs+D}$$

E. Droop Characteristic:

$$\frac{1}{R_p}$$

Where:

Parameters	
T_G	**Main Servo time constant**
R_T	**Temporary Droop**
T_R	**Reset time**
R_P	**Permanent Droop**
T_W	**Water Starting Time**
M	**Inertia Coefficient**
D	**Damping Constant**
$\frac{1}{R_P}$	**Gain**

3.4.1 Simulink Model:

The Hydro Electrical Power unit Model for the simulation. The following figure shows the simulation layout of the system

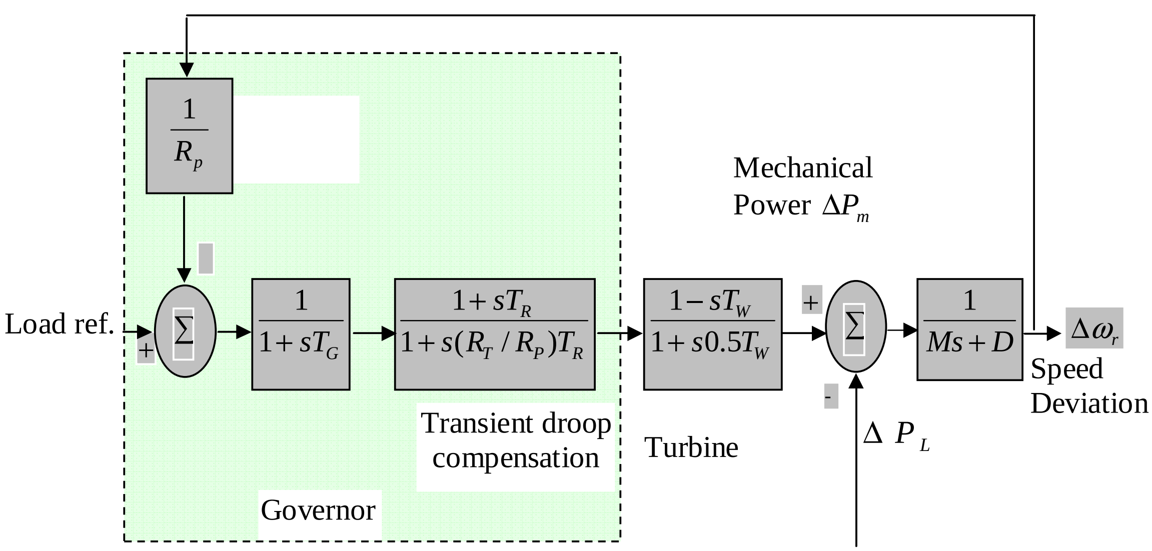
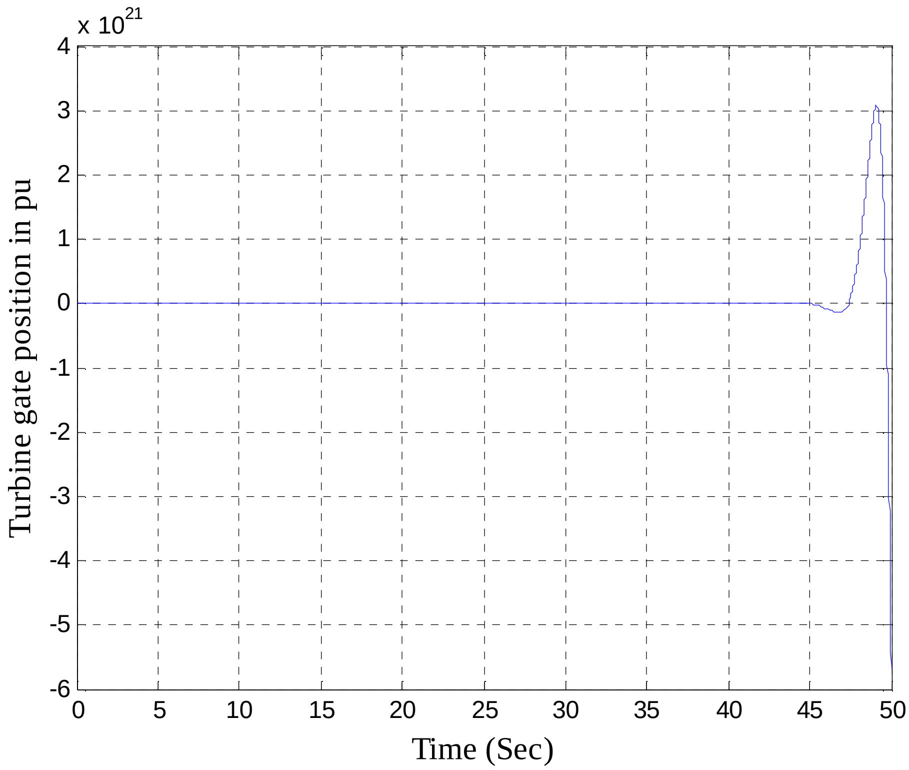


Fig.- 3.3 Simulink Model of Hydroelectric power unit.

3.4.2 Transient Droop Compensator (TDC):

In Hydroelectric power plant, for stable speed control performance, it needs to introduce transient droop compensation in the model. Otherwise it shows the abnormal response due to water inertia. In figure-3.4, 3.5 & 3.6 showed the undesired response of Turbine mechanical power & speed deviation in response to change of Turbine gate opening. ***(Appendix, model-H-04, fig.-3.1.4)***



<u>Fig.- 3.4</u> Gate position of Hydroelectric power unit (without Transient droop compensator) showed abnormal characteristic in this regard it is necessary to include the Transient droop compensator for stability purpose.

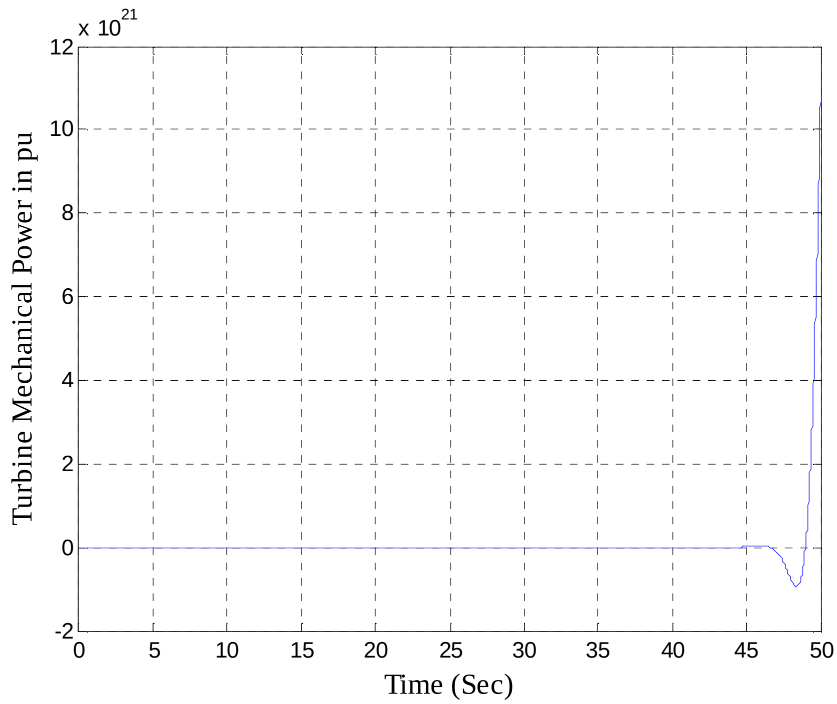


Fig.- 3.5 Turbine Mechanical power of Hydroelectric power unit (without Transient droop compensator) showed abnormal characteristic in this regard it is necessary to include the Transient droop compensator for stability purpose .

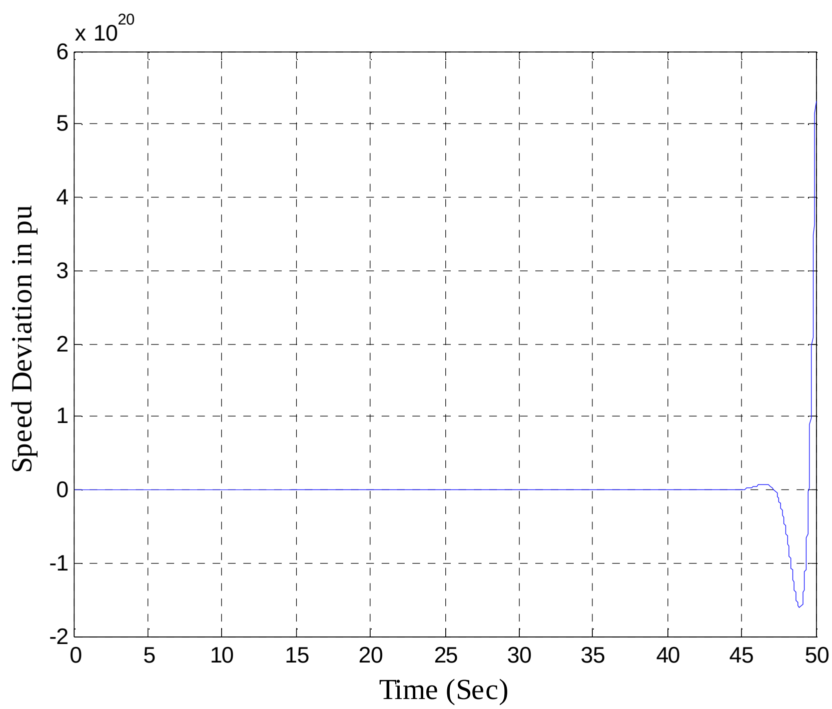


Fig.- 3.6 Speed of Hydroelectric power unit (without Transient droop compensator) showed abnormal characteristic in this regard it is necessary to include the Transient droop compensator for stability purpose .

To meet up the increased power demand, the speed controller is activated by opening the Gate/Valve as input to change the more water flow in the turbine, consequently, the turbine mechanical power suppose to increase but decreasing primarily (figure-3.7 that's opposite to the desired response) and then increasing. In figure-3.7, 3.8 & 3.9 showed response of Turbine mechanical power & speed deviation in response to change of Turbine gate opening with considering transient droop compensator.

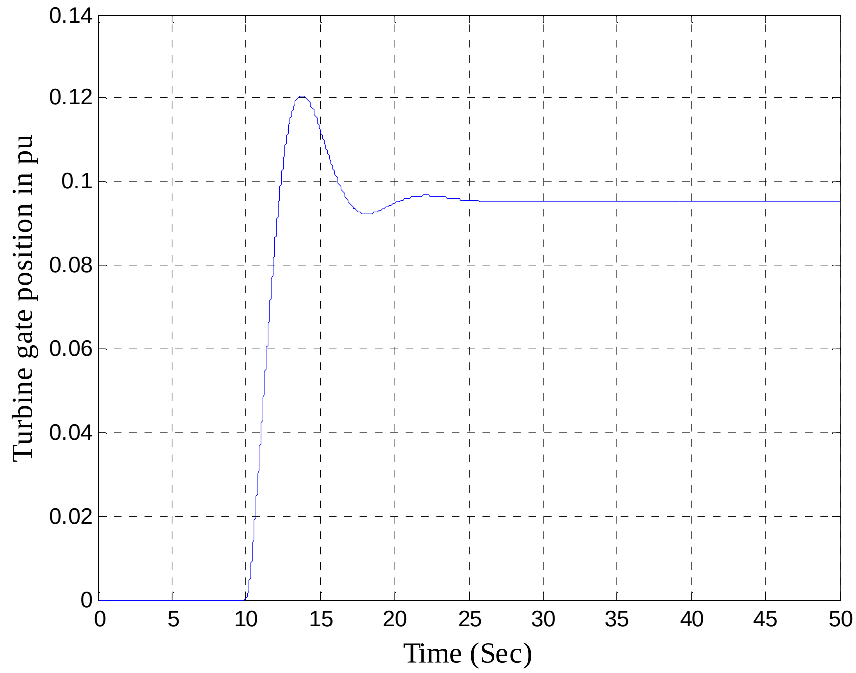


Fig.- 3.7 Gate position of Hydroelectric power unit (with Transient droop compensator).

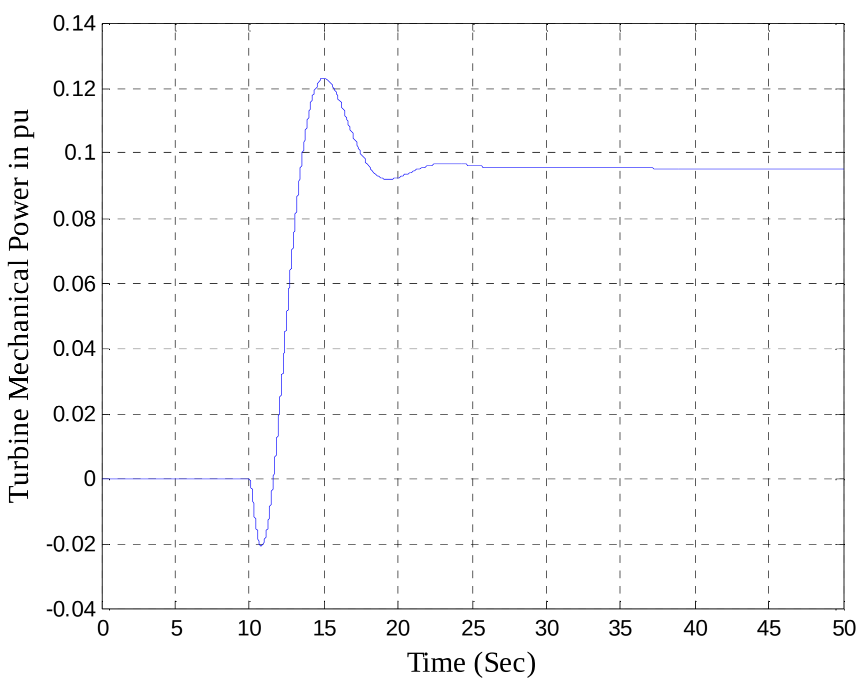


Fig.- 3.8 Mechanical Power of Hydroelectric power unit (with Transient droop compensator).

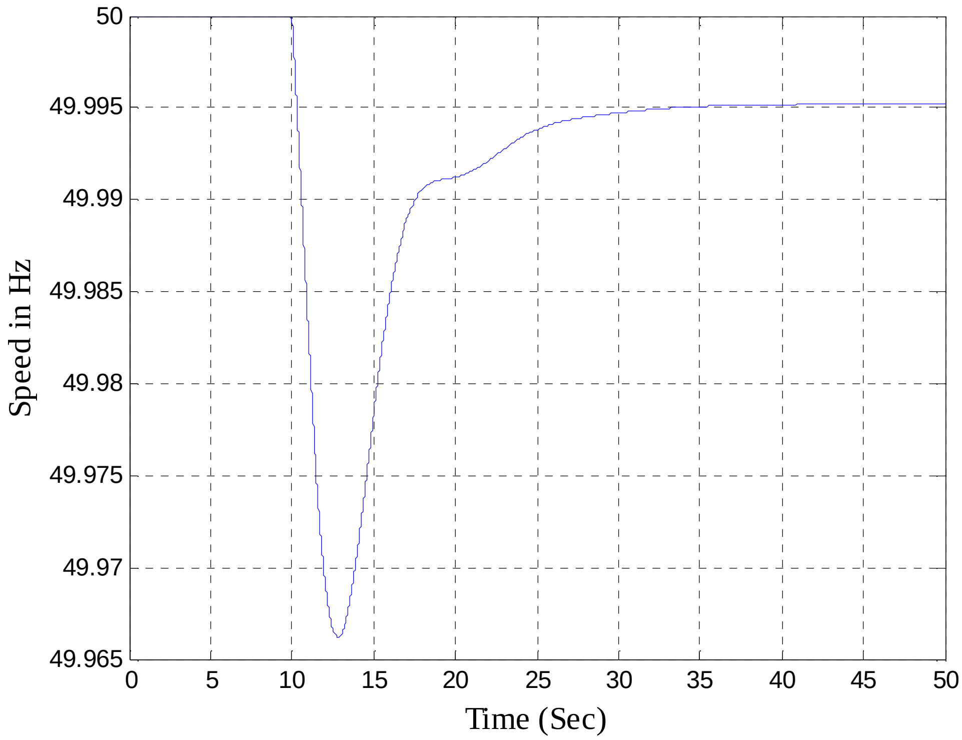


Fig.- 3.9 Speed of Hydroelectric power unit (with Transient droop compensator).

Transfer function of transient droop compensator:

$$G_c(s) = \frac{1 + sT_R}{1 + s(R_T / R_P)T_R}$$

Where (T_R) and (R_T) are defined in the following way:

$$R_T = [2.3 - (T_W - 1.0)0.15]\frac{T_W}{T_M}$$

$$T_R = [5.0 - (T_W - 1.0)0.5]T_W$$

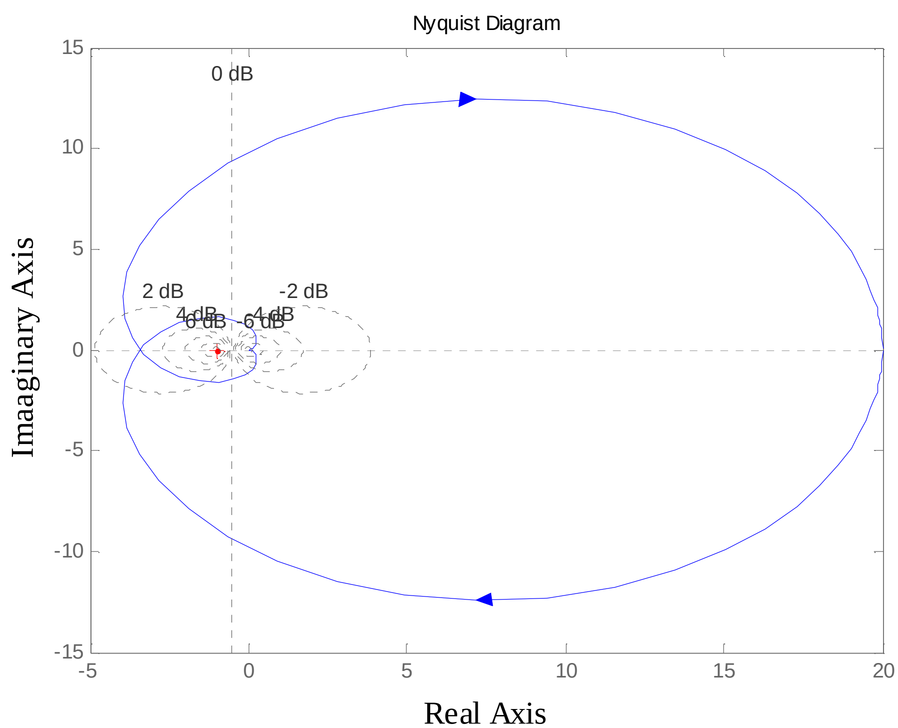
T_W= Water starting time in second
T_M= Mechanical starting time in second

(Note: $T_M = 2H$, H=Inertia Constant or often, T_M=M=2H is used)

3.4.3. Stability performance without and with TDC by Nyquist plot :

Without transient droop compensator, we determined the Nyquist plot to guess the stability and performance of a Hydroelectric power unit.

Without Transient droop compensator Figure 3.10 represents the instable of Hydroelectric power unit and figure-3.11 corresponding Gain margin and Phase margin. ***(Appendix, model-H-04, fig.-3.1.4)***



<u>Fig.- 3.10</u> Nyquist plot of Hydroelectric power unit (without Transient droop compensator).

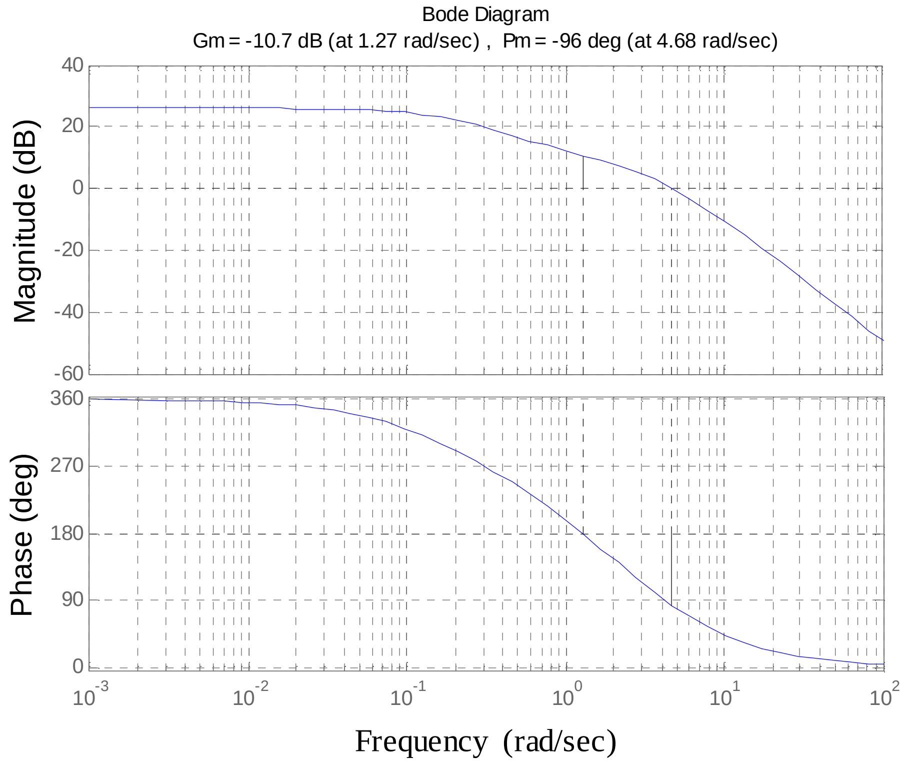


Fig.- 3.11 Gain Margin (-10.7 dB) and Phase Margin (-96 deg) plot of Hydroelectric power unit (without Transient droop compensator).

By considering the transient droop compensator in the model and the Figure-3.12 represents the stability of Hydroelectric power unit and figure-3.13 corresponding Gain margin and Phase margin.

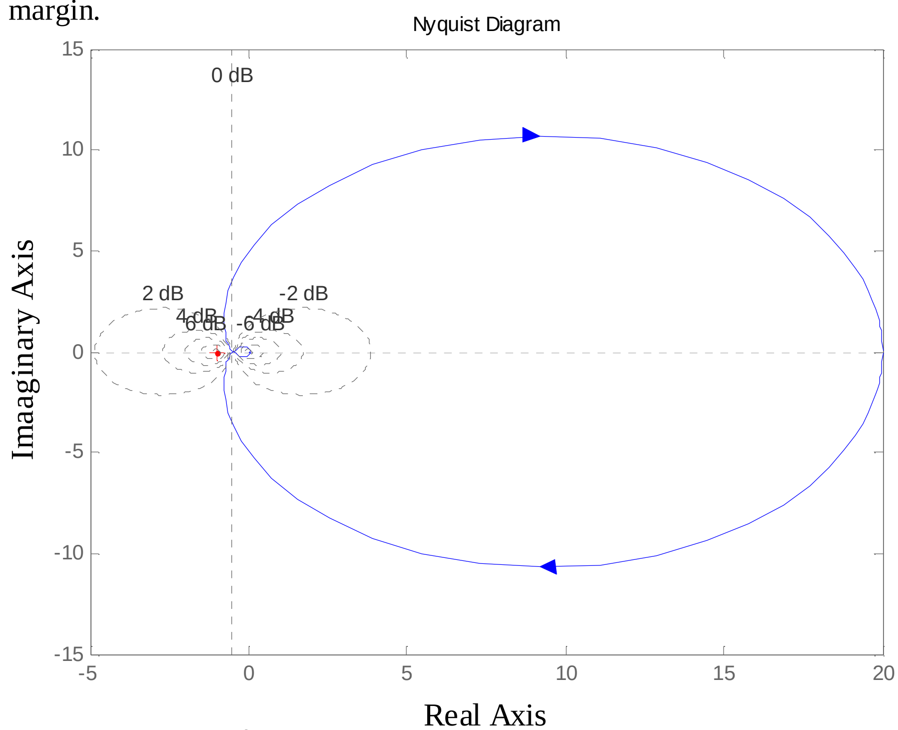
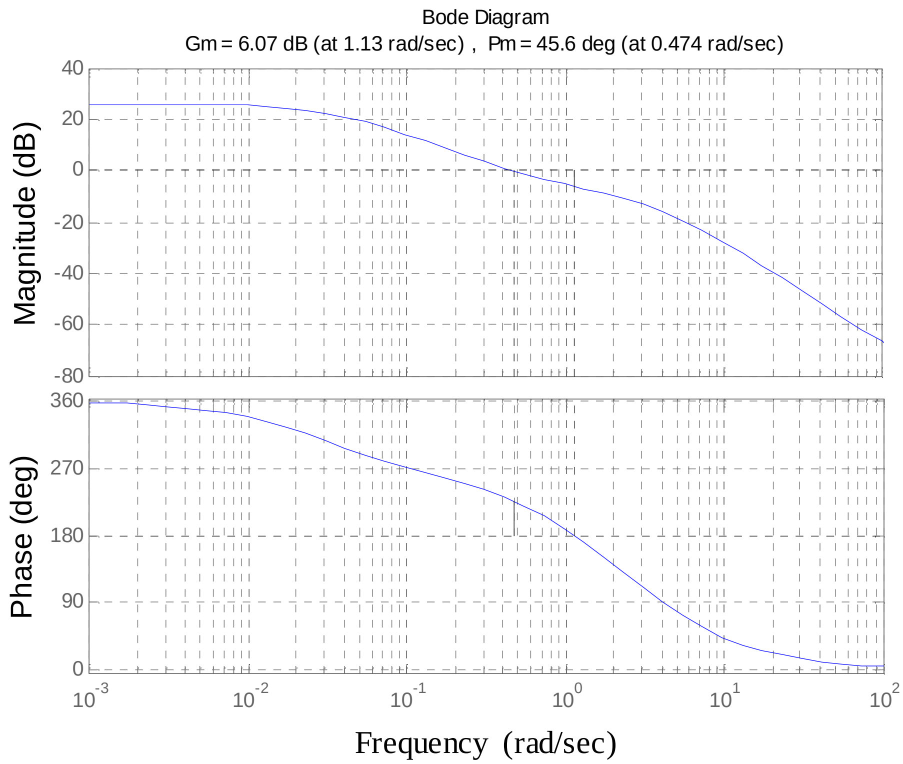


Fig.- 3.12 Nyquist plot of Hydroelectric power unit (with Transient droop compensator).



<u>Fig.- 3.13</u> Gain Margin (6.07dB) and Phase Margin (45deg) plot of Hydroelectric power unit (with Transient droop compensator).

3.5 Characteristic study by varying Load.

3.5.1 Varying load-5% step load:

In Simulink model (Appendix-fig.3.1), we applied 5% step load and corresponding Turbine Gate position and Turbine mechanical power as well as speed deviation are described in the following figure-3.14, 3.15 & 3.16 respectively. ***(Appendix, model-H-01, fig.-3.1.1)***

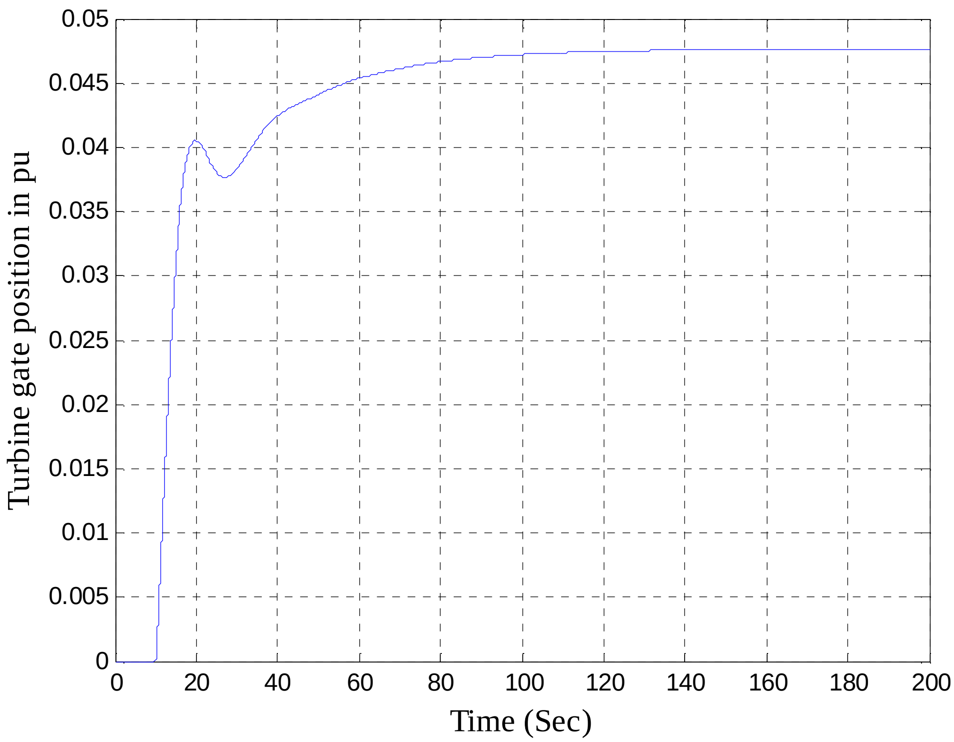
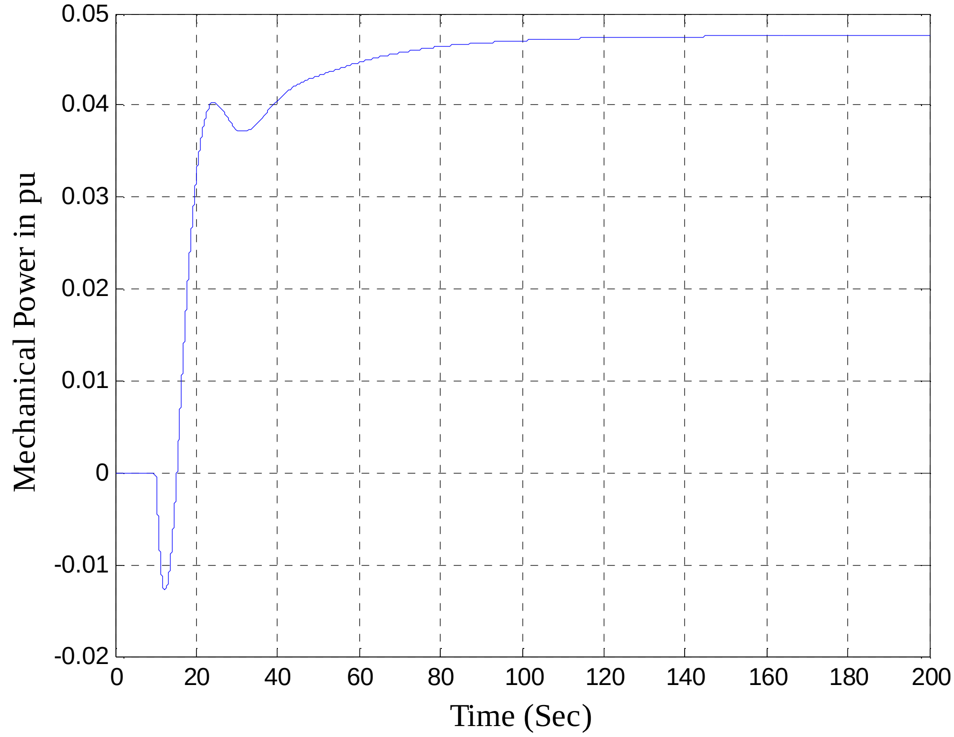


Fig.- 3.14 Turbine Gate position of Hydroelectric power unit with 5 % increased load & values shown are in per unit of step change and its response time and settling time are 45 & 70 seconds respectively.



<u>Fig.- 3.15</u> Turbine Mechanical Power of Hydroelectric power unit with 5 % increased load and values shown are in per unit of step change. Initial step change of gate position; mechanical power changed (decreased) nearly same amount for couple of seconds due to water inertia and increased gradually according to step change of gate position and its response time and settling time are 45 & 70 seconds respectively same as gate opening behavior.

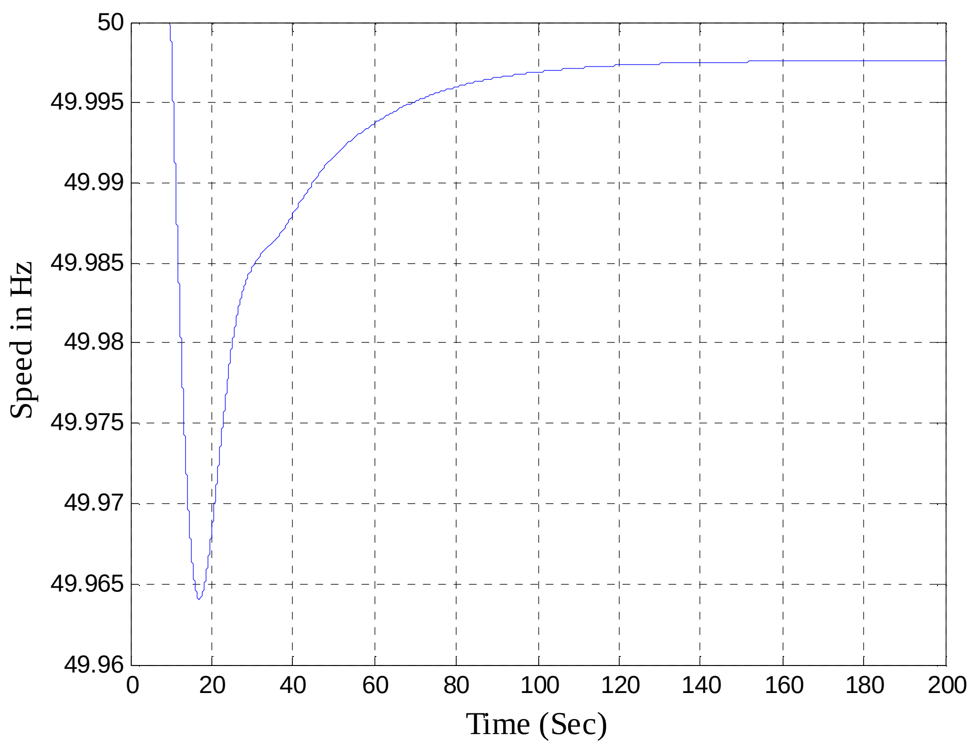


Fig.- 3.16 showed the Speed of Hydroelectric power unit with 5 % increased load. The speed decreased very rapidly due to initially decreased of turbine mechanical power due to water inertia at the time of gate opening and its response time and settling time are 45 & 90 seconds respectively. In 5% load varying the speed does not cross the standard operating limits of frequency 50±0.2 Hz (for Sweden-50±0.1 Hz).

3.5.2 Varying load-10%

In simulink model (Appendix-Model-1), we applied 10% step load and corresponding Turbine Gate position and Turbine mechanical power as well as Speed deviation are described in the following figure-3.17, 3.18 & 3.19 respectively.

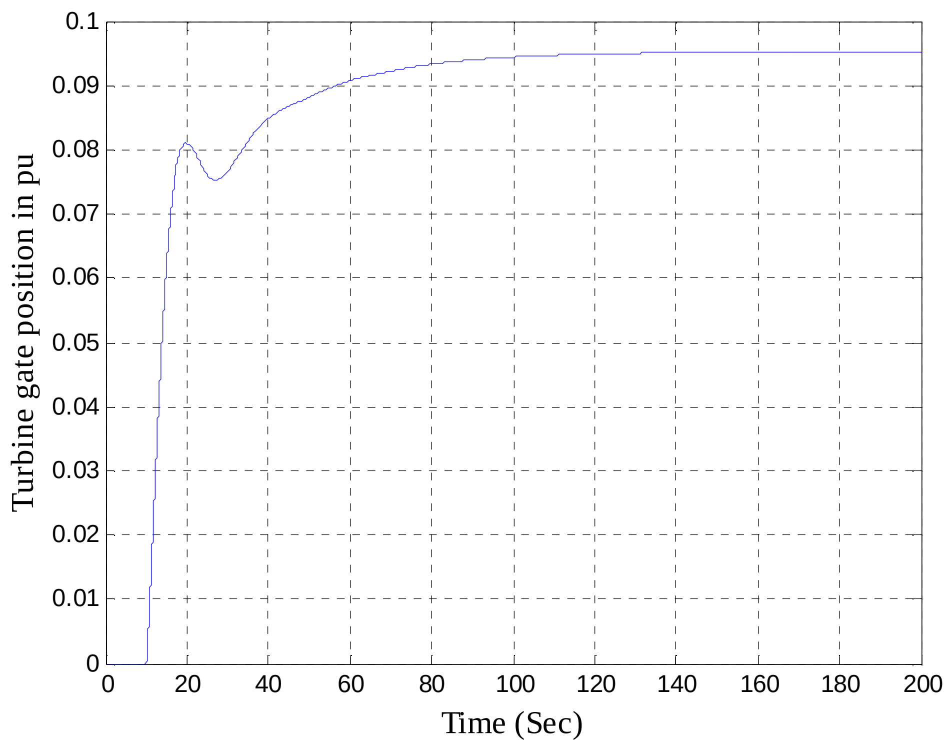


Fig.- 3.17 Turbine Gate position of Hydroelectric power unit with 10 % increased load and values shown are in per unit of step change and its response time and settling time are 45 & 70 seconds respectively. Here, the gate position opened 2 times according to 2 times increased of step load. Both cases the response time and settling time are nearly same.

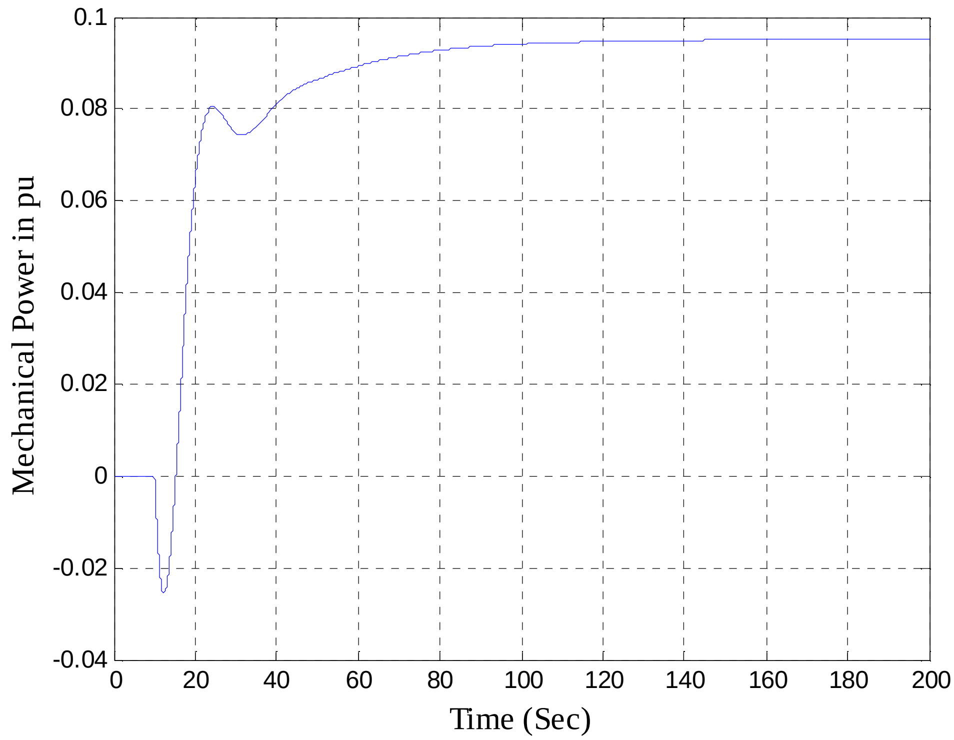


Fig.- 3.18 Turbine Mechanical Power of Hydroelectric power unit with 10 % increased load and values shown are in per unit of step change. Initial step change of gate position; mechanical power changed (decreased) nearly same amount for couple of seconds due to water inertia and increased gradually according to step change of gate position and its response time and settling time are 45 & 120 seconds respectively. Here, mechanical power needs two times according to two times increased of step load. Both cases the response time and settling time are nearly same.

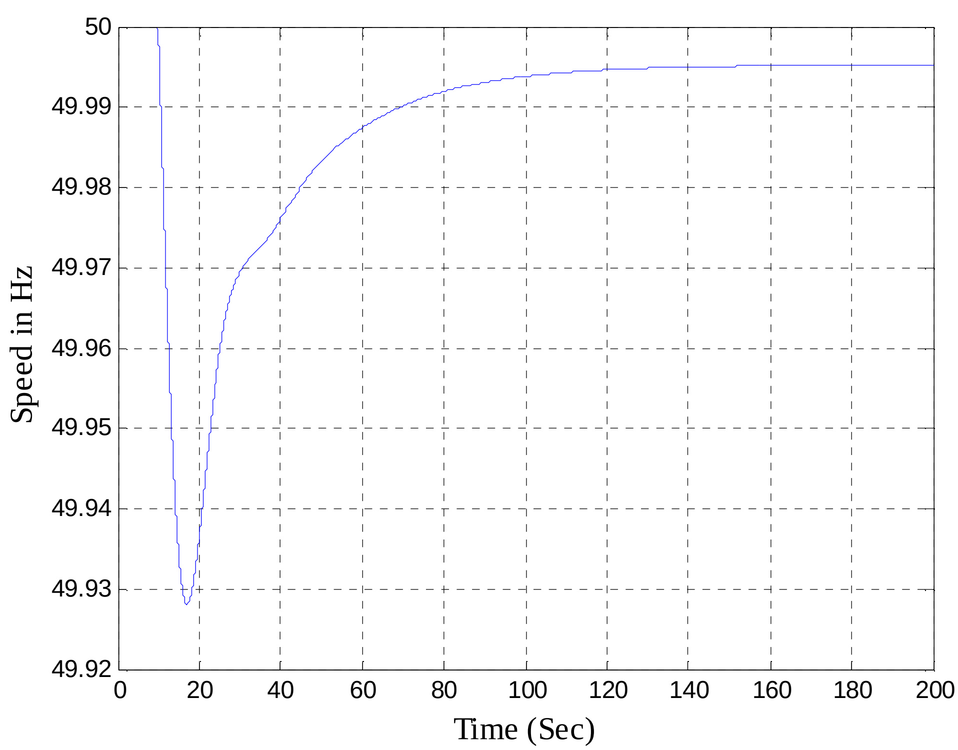


Fig.- 3.19 showed Speed of Hydroelectric power unit with 10% increased load. The speed decreased very rapidly due to initially decreased of turbine mechanical power due to water inertia at the time of gate opening and its response time and settling time are 45 & 110 seconds respectively. In 10% load varying the speed does not cross the standard operating limits of frequency 50±0.2 Hz (for Sweden: 50±0.1 Hz). Both cases the response time is same but settling time for this case is 20 sec higher.

Comparison:

Now the following figures show the comparison of Turbine Gate position and Turbine mechanical power and corresponding speed between 5% to 10% step load. ***(Appendix model-H-01, fig.-3.1.1).***

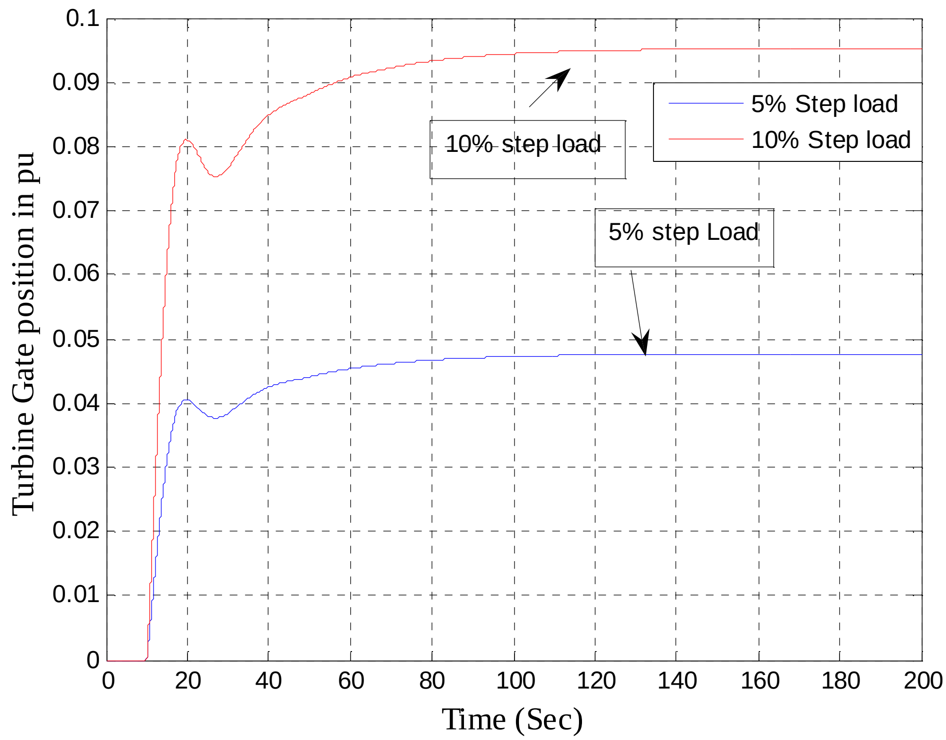


Fig.- 3.20 Turbine Gate position of Hydroelectric power unit with 5% -10 % step load.

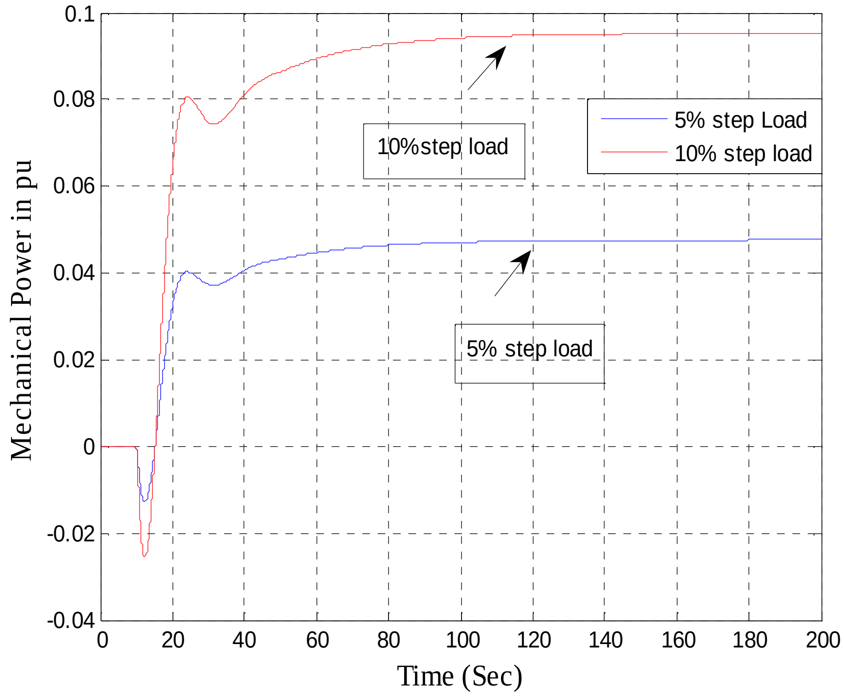


Fig.- 3.21 Turbine Mechanical Power of Hydroelectric power unit with 5% -10 % step load.

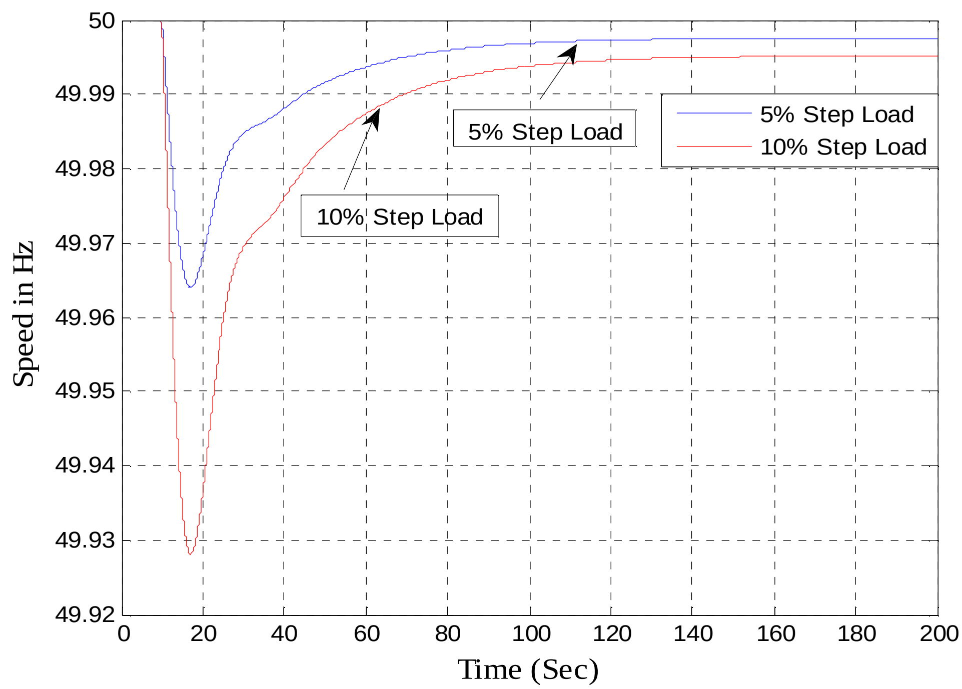


Fig.- 3.22 shows Speed of Hydroelectric power unit with 5% -10 % step load.

3.6.1 Non-minimum phase systems:

Hydroelectric Turbine behaves a non-minimum phase phenomena due to water inertia. It means that a change in the Gate/valve opening creates an initial change in the Turbine mechanical power that is opposite to our opinion. [7]

The turbine mechanical power, P_m is proportional to the product of pressure and flow of water:

$$P_m = \eta q \rho g_a H$$

And

Water velocity in the penstock:

$$U = K_u G \sqrt{H}$$

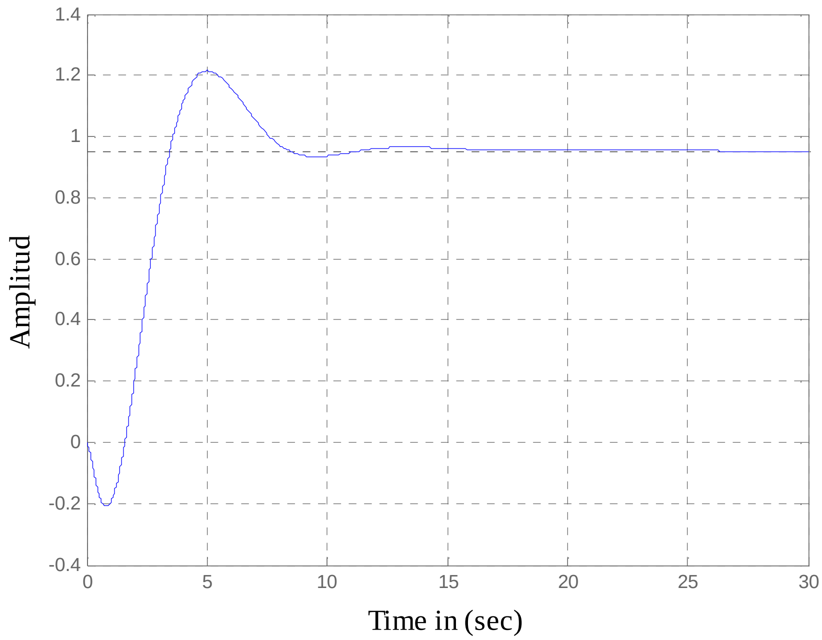
$$P_m = K_p H U$$

The classical Transfer function will of hydroelectric power unit will be the following way, the Turbine mechanical power deviate by small deviation in gate opening.

$$\frac{\Delta \overline{P}_m}{\Delta \overline{G}} = \frac{1 - T_w S}{1 + \frac{1}{2} T_w S} \qquad (3.12)$$

Equation (3.12) characterizes the change of mechanical power with small deviation of gate that represents a non-minimum phase system of Hydroelectric power system.

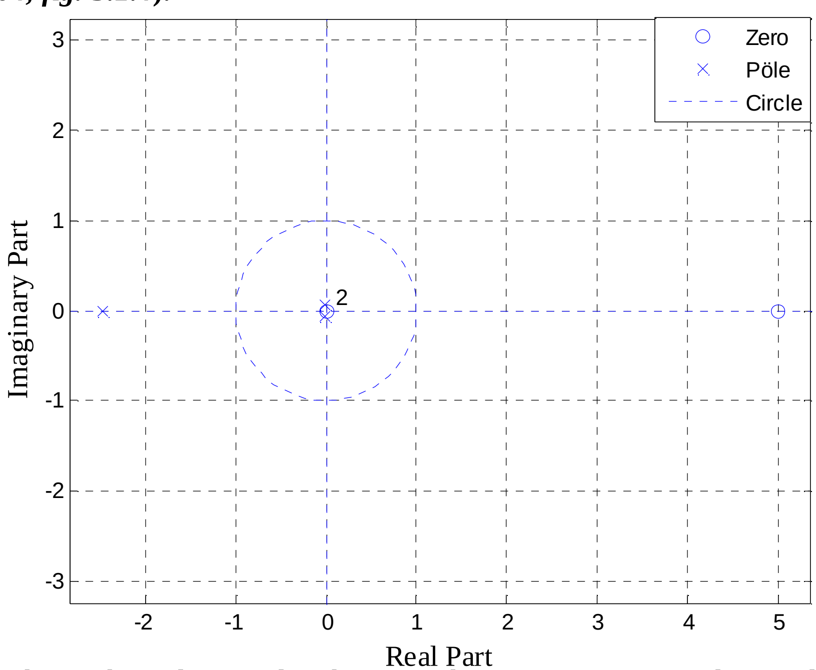
The step response of hydroelectric power system ***(Appendix-the model-H-04, fig.-3.1.4)*** is as follows:



<u>Fig.-3.23</u> Step response of hydroelectric power plant.

The other characteristic of the non-minimum phase system of Hydroelectric Power Plant is that the some of its zeros inside the unit circle and others outside the unit circle and must be in the right half of the s-plane.

The following figure shows the pole/zero of the Hydroelectric power system **(*Appendix model-H-04, fig.-3.1.4*).**



<u>Fig.- 3.24</u> shows the pole/zero distribution; where some zeros resides inside the unit circle and some outside the circle to the right half of the s-plane, of Hydroelectric power plant model.

3.6.2 Minimum phase response of steam power plant:

The pole/Zero plots of minimum phase systems and the step response of steam power plant is as follows: ***(Appendix model-S-01, fig.-2.1).***

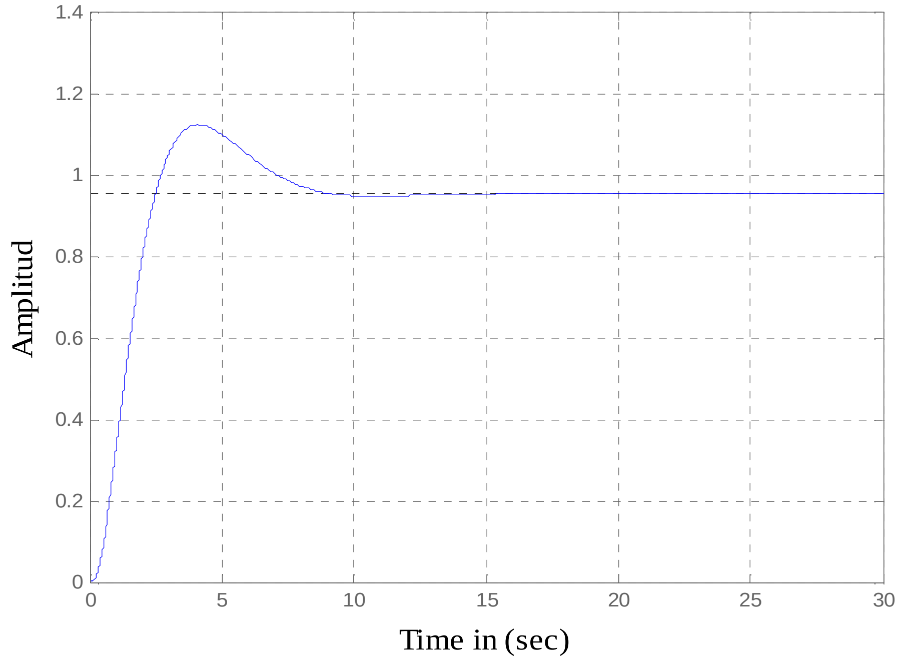


Fig.- 3.25 Step response of Steam Power plant unit.

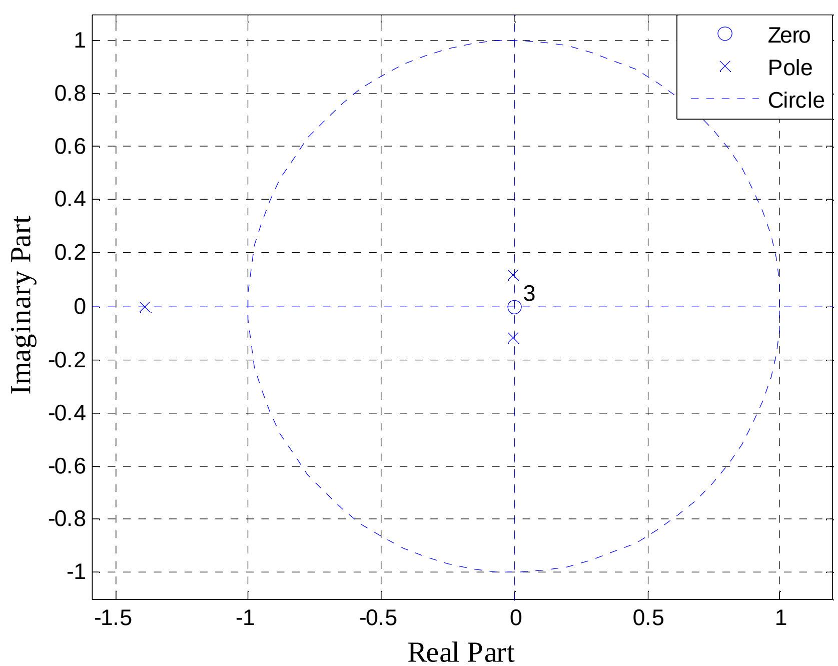
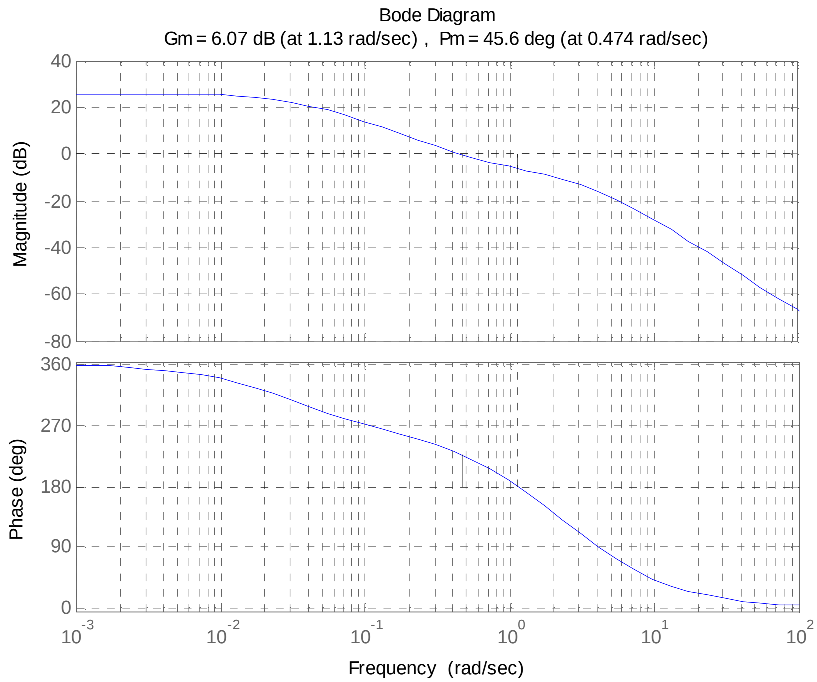
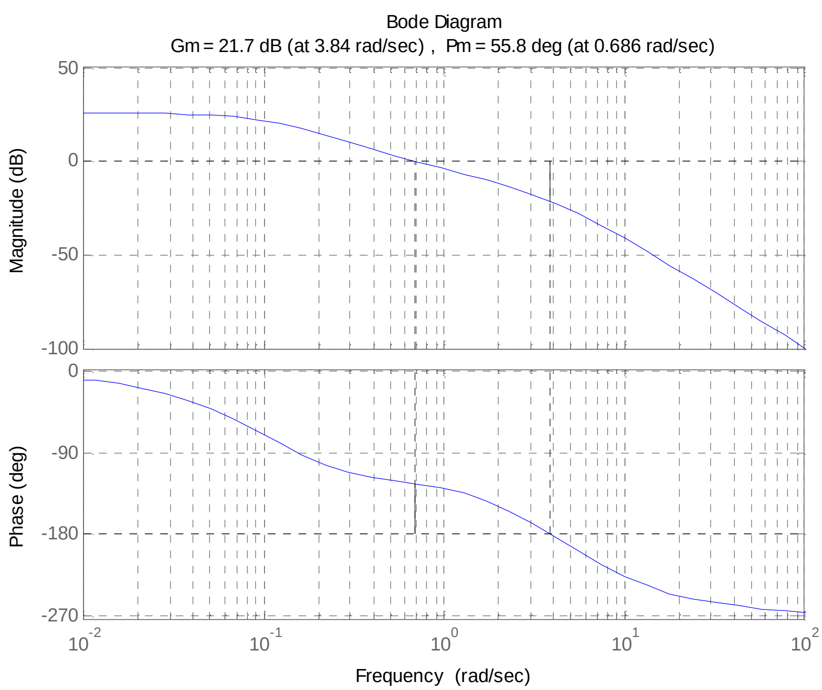


Fig. - 3.26 represent the pole/zero distribution all zero resides inside of the unit circle of steam power plant model.

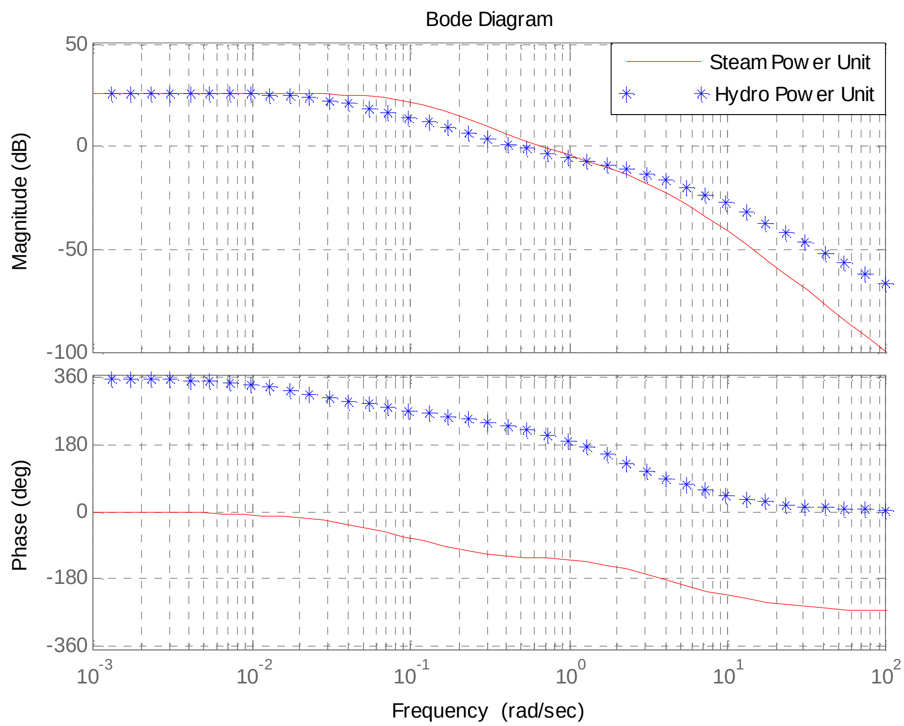


<u>Fig.- 3.27</u> Gain and phase margins of Hydroelectric power plant ***(Appendix model-H-04, fig.-3.1.4).***



<u>Fig.- 3.28</u> Gain and phase margins of steam Power Plant ***(Appendix model-S-01, fig.-2.1).***

In a magnitude plot, Hydroelectric power plant and steam power plant (they have different Gain & phase margins showed) have no minimum phase shift. In fig. - **3.29** showed there is no minimum phase shift in magnitude plot.



<u>Fig.- 3.29</u> Gain and phase margins of steam Power Plant and Hydroelectric power plant where no minimum phase shift in magnitude plot.

Chapter-4

THERMAL POWER SYSTEMS

Contents overview

4.1 Introduction

Load frequency control plays a vital role in electric power production as it offers the most important generation control of power plants. Here, we are to study a thermal power plant which is suitable for controlled load frequency and it is performed under normal condition of the plant. During the period of less demand, power plants with thermal energy systems like nuclear or fossil – fuelled (coal) is used. It is necessary to use the thermal point under load frequency control to meet these demands.

Coal, oil or gas are the commonly used as fuels for fossil – fuelled power plants to produce heat by combustion which is then converted to superheated steam. Then it is fed through the turbine to convert this superheated steam to mechanical energy then into electrical energy by the generator coupled to the turbine. Thermal power plants operation is much similar to the steam turbine power plant. The block diagram of its operating principle is shown in figure 4.1. It can be identified that the block diagram is much similar to the operating principle of steam turbines (figure 2.1).

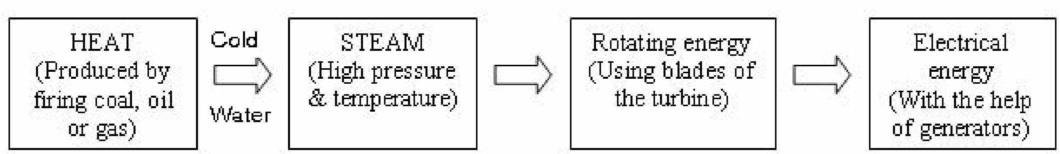


Fig.- 4.1 representation of principle of Thermal power systems

This process of conversion is also accompanied by condensers with large cooling pipes; the condensate is then again fed back to the boilers. This is done to improve the energy conversion efficiency. [7][17]

4.2 Plant Description

A fossil – fueled power plant has three main parts of the plant. They are

4.2.1) Primary Fuel component
4.2.2) Steam Production & utilization component
4.2.3) Condensate and feed-water component

4.2.1 Primary Fuel component

This is the part of the plant, where the primary fuel is converted into thermal energy. This component consists of (1) A Furnace (2) The Fuel system (3) Secondary air system and (4) Flue gas system. See figure 4.2 for the entire configuration of thermal power system. [7]

4.2.1.1 Furnace:

A "furnace" Is used to convert the fuel used into heat energy. A mixture of fine particles of coal, oil or gas and air is injected for a complete combustion and to achieve efficient output of high temperature heat. This is then passed over the walls of the drums carrying water or to the steam carrying re – heaters.

4.2.1.2 The Fuel system

This system is responsible for supplying the fuel to the furnace. Talking about fuel, coal needs more attention as it should be pulverized and dried before using it for combustion. Hence, one has to understand that coal fired units respond much slower when compared to oil and gas fired units.

4.2.1.3 Secondary Air system

The injected fuel into the furnace must be combusted properly in order to extract most of the heat out of it. To satisfy this need we use 'secondary air system' which supplies the furnace with sufficient amount of air and ensures proper combustion of the injected fuel. A 'fuel draft fan (FD)' is used to inject the air and the demand of the air sent in depends upon the fuel and air controller.

4.2.1.4 Flue Gas system

Flue gasses from the furnace to the chimney travel through the 'flue gas system' where the gas passes through re – heater sections (primary and secondary) and economizer. This is done to extract the heat from the flue gas which otherwise would be wasted through the chimney. An 'Induced draft fan (ID)' is used to facilitate this exit activity.

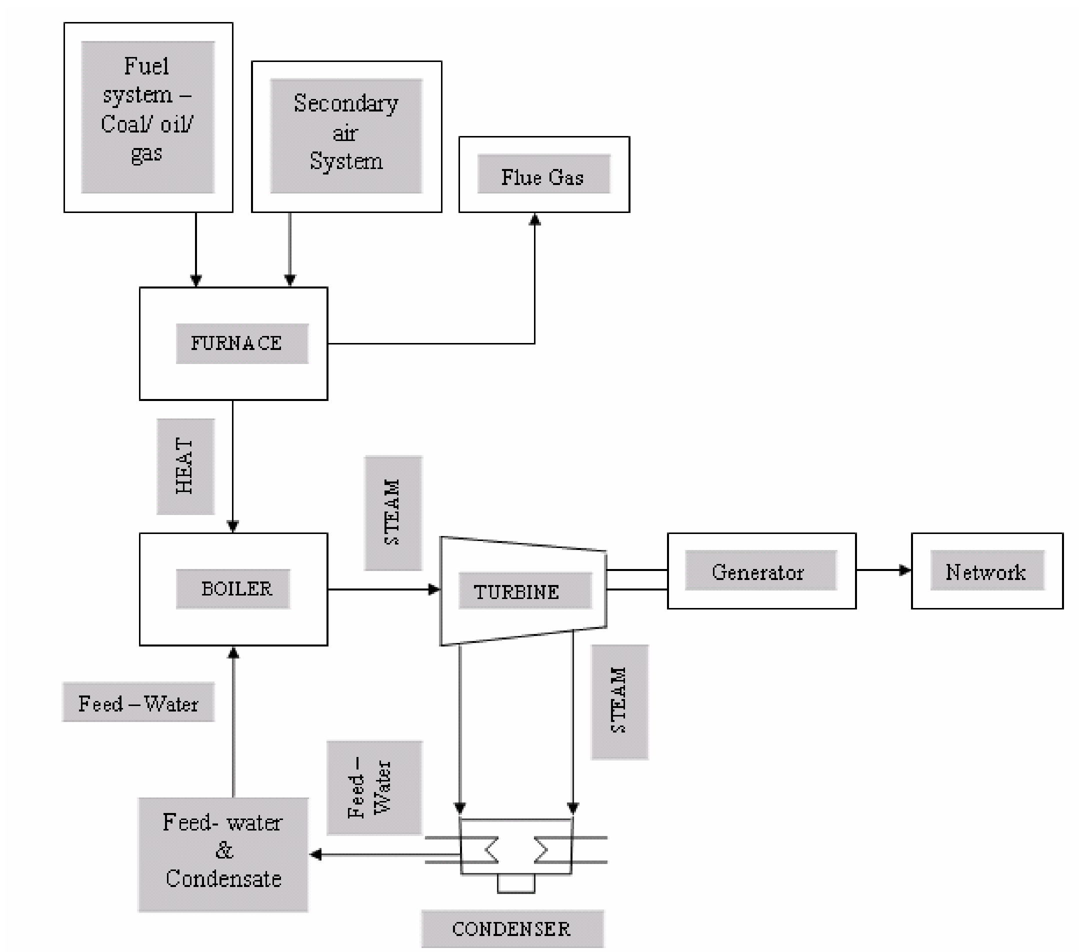


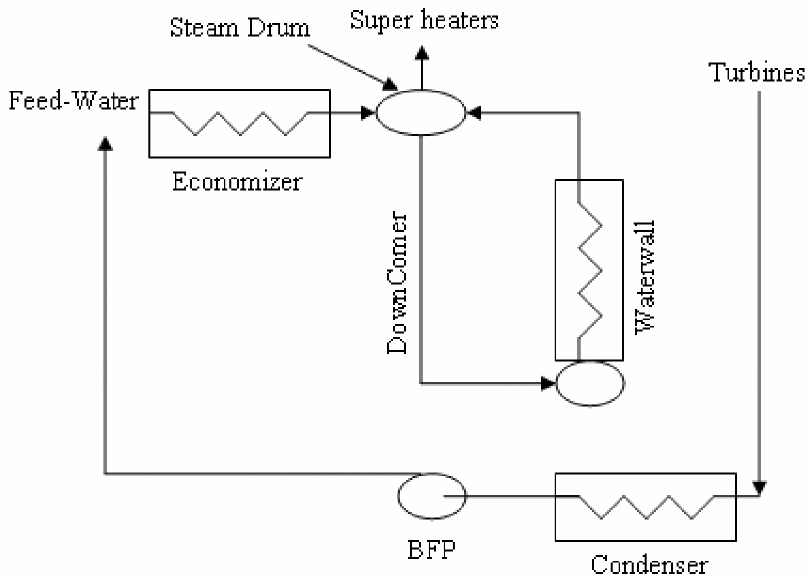
Fig.- 4.2 fossil- fuelled power plant

4.2.2 Steam Production and utilization component

As known, 'a boiler' is responsible to produce steam which is then heated to high temperature and pressure by super –heaters and re –heater sections. This steam is converted to mechanical energy by turbine. Boiler design plays a vital role in the effective steam production. There are two types of boiler suitable for this kind of power plants, they are [7]

4.2.2.1) Drum type boilers
4.2.2.2) Once – through boilers
4.2.2.1 Drum type boilers

This type of boilers use a drum, which separates the steam from re – circulation water and the separated steam is sent through different re – heaters (ref. figure 4.3). Hence it is called as ‘drum type boilers or recirculation boilers’. The operating principle of these boilers depends upon the natural or forced flow of water through the wall, where it is converted into steam by the high pressure steam. And it is suitable for operation at sub critical pressure. Energy stored in this kind of boiler is more then the once - through boiler, so they are capable of supplying power even when the fuel flow is stopped. But its response to changes is slower.



<u>Fig.- 4.3</u> Drum type boilers

<u>4.2.2.2 Once through Boilers</u>

These kinds of boilers are characterized by not re – circulating water within the furnace. But the feed–water directly flows through the waterwalls, where it is converted into steam by absorbing the heat produced. Then it is passed through the super heaters and then to high pressure turbines. A boiler feed pump (BFP) is required to ensure the thorough flow of feed–water and a turbine bypass system is used for disposing the residue without wasting any of the heat or work fluid. It is suitable for operation at supercritical range (i.e., above 22,120 kPa)[1], which is the reason for not using a separate drum to obtain steam, as the operating temperature is very high. Energy stored in this type of boilers is very less when compared to the drum type, so they are very quick responding to changes. But it cannot supply power for some more time without any fuel, like drum – type boilers.

[1] Reference Power system stability and control by Mr.Prabha Kundur.

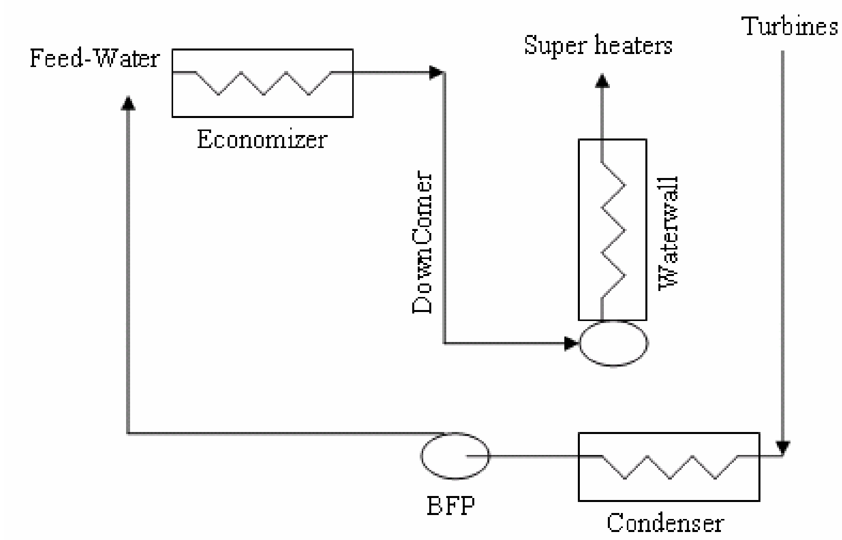


Fig.- 4.4 Once – through Boilers

4.2.3 Condensate and feed water component

The feed – water is system which supplies enough water to the boiler which is in turn converted to the steam. The excess water from the furnace is sent back to the boiler to improve the efficiency of the system. See figure 4.2. [7]

4.3 Control Systems

Control variables for fossil – fuelled turbines vary with manufacturers. Most commonly used parameters of controls are the rate of firing, rate of pumping and throttle valve settings. While temperature, pressure, power and speed are output controlled parameters. And also it is designed in such a way to reduce power production or trip when the safe limit exceeds. There are two types of control systems, they are

4.3.1 Overall Unit control
4.3.2 Process parameter control

This overall unit control is further sub divided into four types of control, which are 1) boiler following 2) turbine following 3) integrated control and 4) sliding pressure control. And the process parameter control includes parameters like steam pressure, feed – water, air that regulate the unit output

4.3.1.1 Boiler following control system

In this type, ‘turbine control valves’ play the main role by making the changes in generation. The steam produced is varied by the change in steam flow and the boiler pressure varies accordingly to the difference between the steam produced and the steam demand. An error signal sent by the varying throttle pressure is used to control the fuel and air input to the furnace. This type is called a boiler following or turbine leading way of control.

In this mode of operation, energy stored in boiler is used to meet the initial steam demand and hence the power output is rapidly increasing. See figure 4.5

4.3.1.2 Turbine following control system

Here the control is simply performed by varying the input to the boiler, which in turn controls the generation. Combustion controls are driven by the demand signal (MW) while the boiler pressure is controlled by the turbine control valves. This type is also called as boiler leading way of control.

In this mode of operation, energy stored in the boiler is not used unlike boiler following mode, hence the power output curve from figure 4.5 shows that it is following the steam produced.

4.3.1.3 Integrated boiler control

As the name says, this mode of control is the combination of both turbine – leading and boiler – leading way of controls. Hence it ensures the benefits and flexibility of both the mode. The unit response graph (figure 4.5) clearly indicates, this type of control provides fast response and also safety to boilers.

4.3.1.4 Sliding Pressure control

In this mode, throttle pressure value is made dependent on the unit load instead of keeping it constant and the output is controlled by controlling the throttle pressure which is in turn controlled by the boiler controls. Hence it can only be advantageous in boiler – leading mode of operation. In this method temperature in high pressure turbines remains almost constant because the throttle value doesn’t change during load variation.

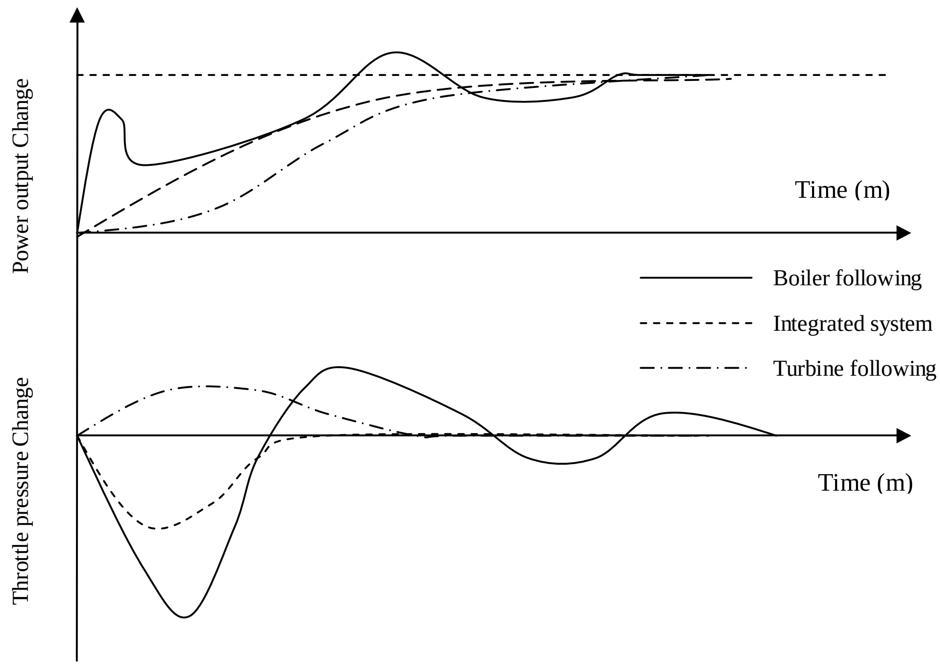


Fig.- 4.5 unit responses of different modes of boiler control

4.4 Modeling of Thermal Power plant

The thermal model considered here, is selected in such a way similar to the steam turbine model considered previously in chapter 2.6, for easy execution and comparison. We already know that thermal power plant operation, components are much similar to steam power plant. From figure 4.1 it can be deduced that the steam produced in boiler passes through the turbine blades, where it is converted into mechanical energy which is then converted into electrical energy using a generator. Hence the modeling of thermal power plant also deals with steam turbine which is already discusses in steam turbine chapter under the section 2.4. [7]

4.5 Governor – Turbine Model

The process of simulating Load frequency control (LFC) under normal conditions is to evaluate the daily performance and to suggest improvements considering different plant effects. And also study of coal - fired thermal power plants under LFC is increasing in several electric power companies to make use of thermal plants during light load conditions. The turbine-governor model is always added with the rate limiter and time delay in the conventional thermal model for dynamic simulation of load frequency control. In this model, effects related to boiler steam's sliding pressure control, turbine load reference control by coordination of boiler-turbine control, steam pressure changes because of control valve movement in turbine are considered to be null.

4.5.1 Governor Model

Governor model used here is very similar to steam turbine model. The following block shows the governor block with a gain 1/R.

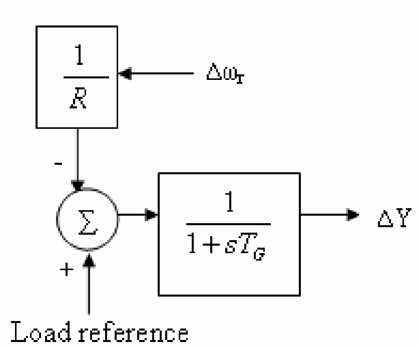


Fig.- 4.6 Governor Block of thermal power plant

4.5.2 Turbine Model – Reheat type

The transfer function which is considered for the thermal power model is $\frac{1}{(1+sT_1)} * \frac{1+sK_RT_R}{(1+sT_R)}$,

this can be simplified to:

$$\frac{1+sK_RT_R}{(1+sT_1)(1+sT_R)}$$

This is similar to the turbine transfer function used in steam turbine used in 2.6. This is a reheat type thermal turbine and the reheat time constant (T_R)[2] takes a value of 10.0s and the fraction of turbine constant (K_R)[3] takes a value of 0.5s.while (T_1)[4] is the charging time constant and has a value of 0.3 s. The model we use is a "boiler – following or turbine – leading type"[5]. [7] [18]

[2 ,3, 4] - see chapter 2.6 for definition

[5] - see 4.3.1.1

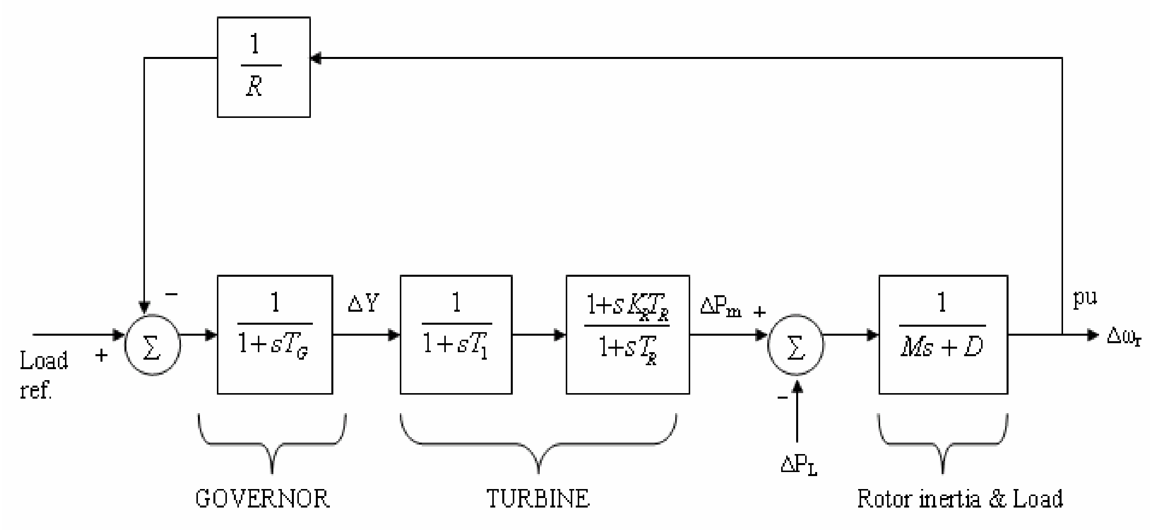


Fig.- 4.7 Thermal Power Units

4.5.2.1 Matlab Model

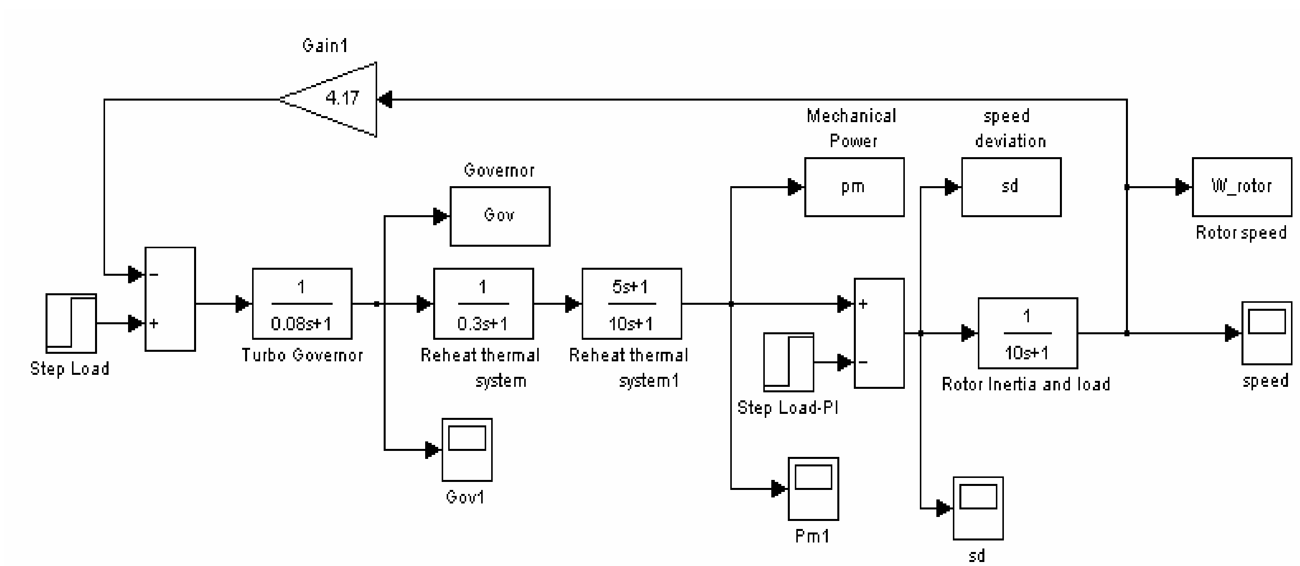


Fig.- 4.8 Mathlab Model – Thermal Power plant

4.5.2.2 Results

4.5.2.3 OUTPUT WITH LOAD = 5%

For **LOAD= 5%** and with given values of
T_G= 0.08 S
T_R= 10.0 s
1/R= 4.17 s
K_R = 0.5 s
T_1= 0.3s
M= 10.0 s
D= 1.0 s

Turbine transfer function will be (5s+1)/ ($3s^2$+10.3s+1)

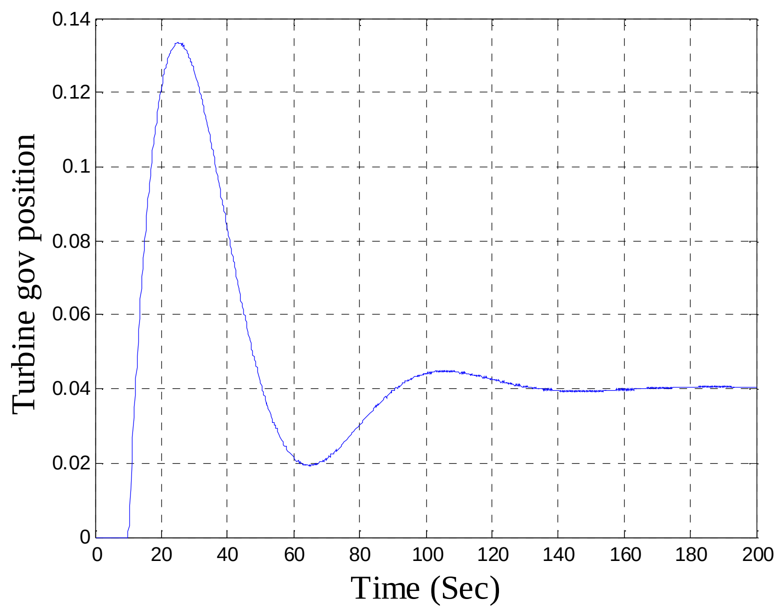
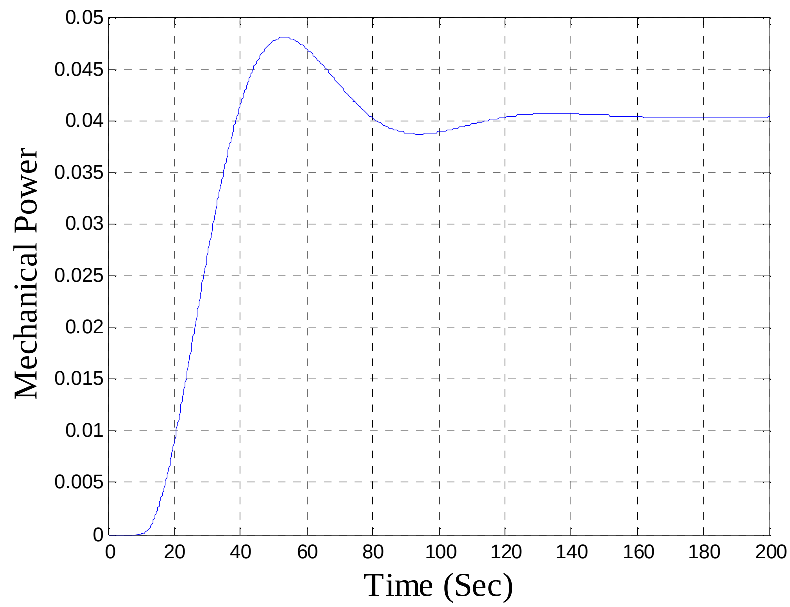
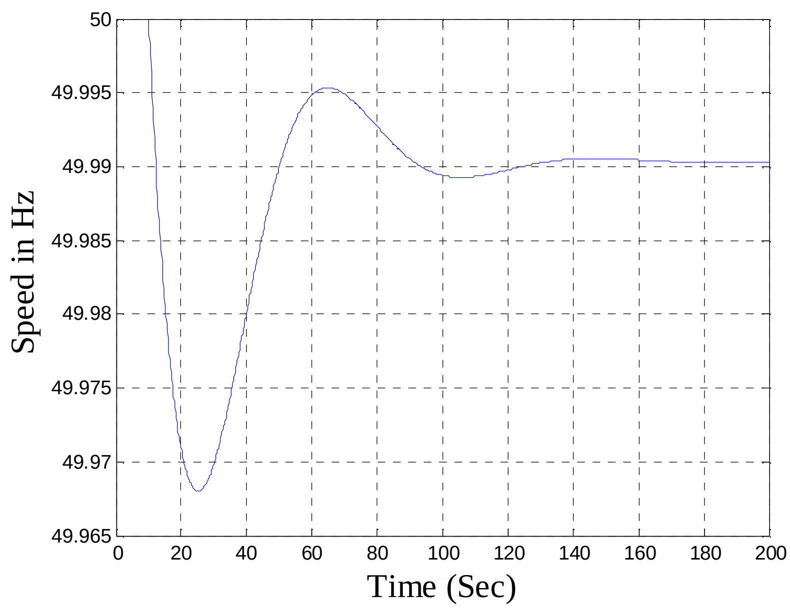


Fig.- 4.9.1a Valve/gate position of thermal turbine at 5% load

Governor gate is opened to let the steam flow through it which increases the power output. Hence it can be noticed that the governor position increases to the peak in figure 4.9.1a, to which correspondingly the mechanical power increases to its peak value in the figure 4.9.1b. It is interesting to note that when the desired power output is reached the gate falls down rapidly to reach stability while the power decreases slowly to reach stability.



<u>Fig.- 4.9.1b</u> Mechanical Power output of thermal power plant



<u>Fig.- 4.9.1c</u> Speed deviation of thermal power unit with a 5% load

It can be noticed that the speed decreases as the power and gate curves increases. As the model used is "boiler – following" type all curves perfectly resembles the theoretical curves explained in figure 4.5 earlier in this chapter.

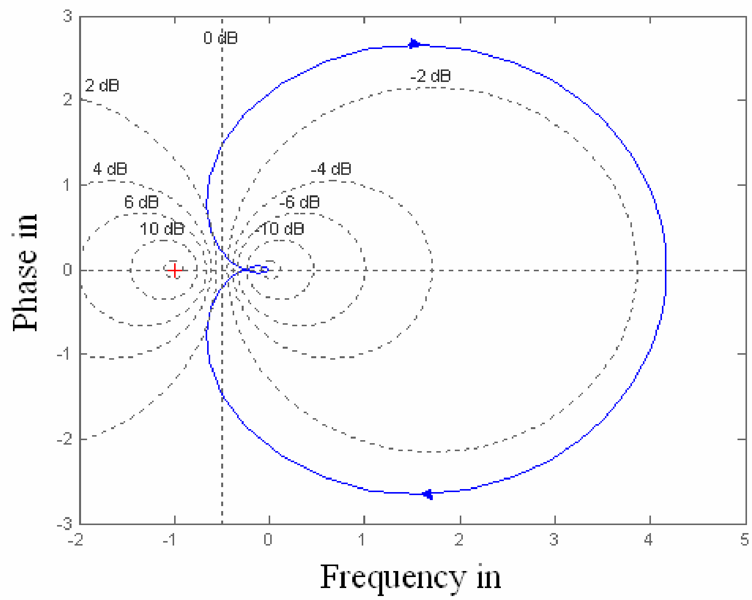


Fig.- 4.9.1d Nyquist Plot

The above graph shows that the system is stable by satisfying the nyquist criteria for stability (0,-1).and the corresponding phase margin, gain margin is obtained using the margin plot.

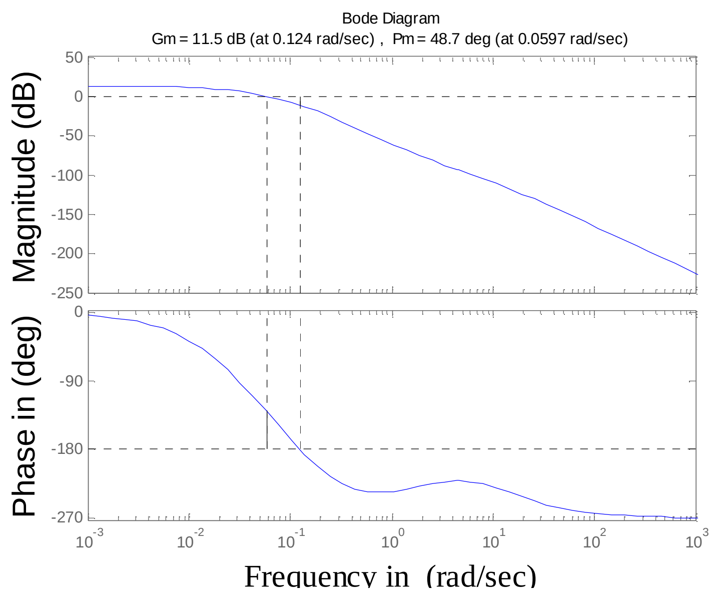


Fig.- 4.9.1e Margin Plot for thermal power unit with a gain margin Gm=11.5 db (at 0.124 rad/sec) and phase margin Pm= 48.7 deg (at 0.0597 rad/sec)

4.5.2.4 OUTPUT WITH LOAD = 10%

For **LOAD= 10%** and with given values of

T_G= 0.08 S

T_R= 10.0 s

1/R= 4.17 s

K_R = 0.5 s

T_1= 0.3s

M= 10.0 s

D= 1.0 s

Turbine transfer function will be $(5s+1)/(3s^2+10.3s+1)$

Here an increasing step load double the time of the previous step is fed to check and analyze if the power output has doubled according to theory.

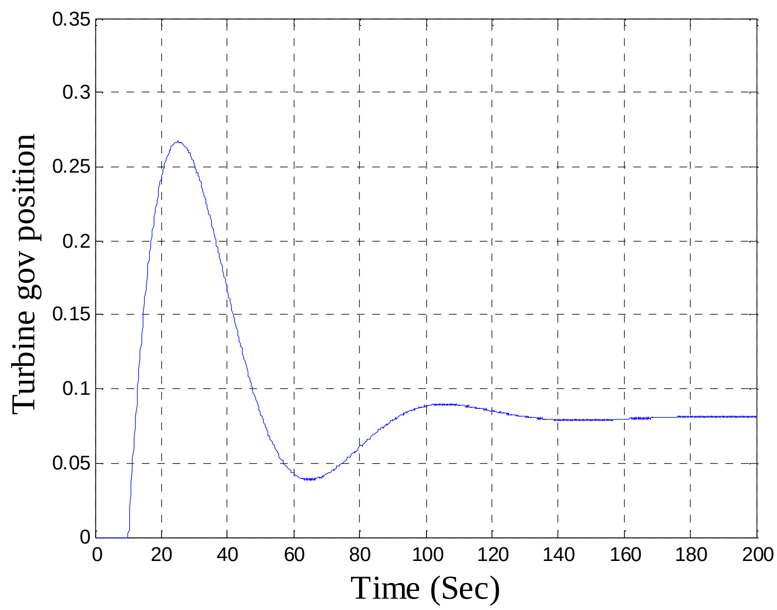


Fig.- 4.9.2a Valve/Gate position of thermal turbine at 10% load

It is visible that the gate position has doubled from 0.17 from figure 4.9.1a to 0.34 in figure 4.9.2a, which is exactly double the time of the previous one and the corresponding mechanical power is also doubled from 0.06 in figure 4.9.1b to 0.12 in figure 4.9.2b. Thus it can be explained that when the step load increases the gate position also increases to meet the increasing power demand.

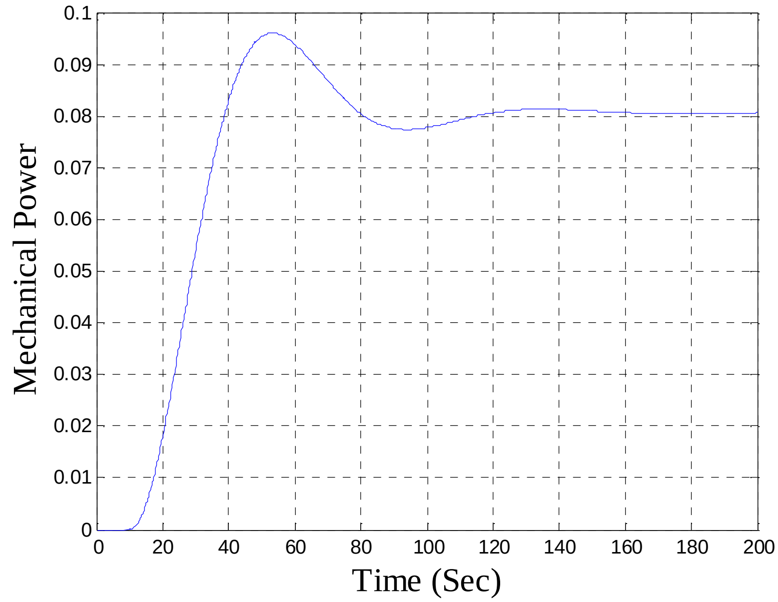


Fig.- 4.9.2b Mechanical Power output of thermal power plant at 10% load

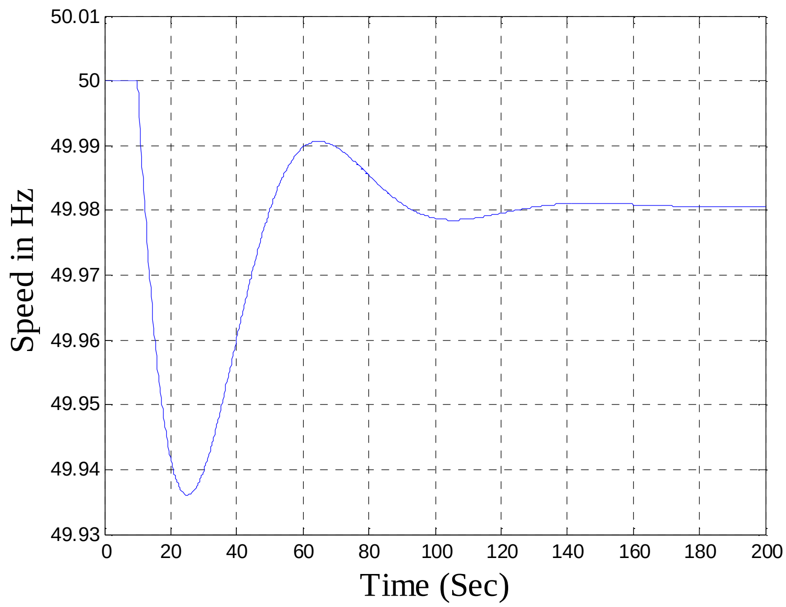
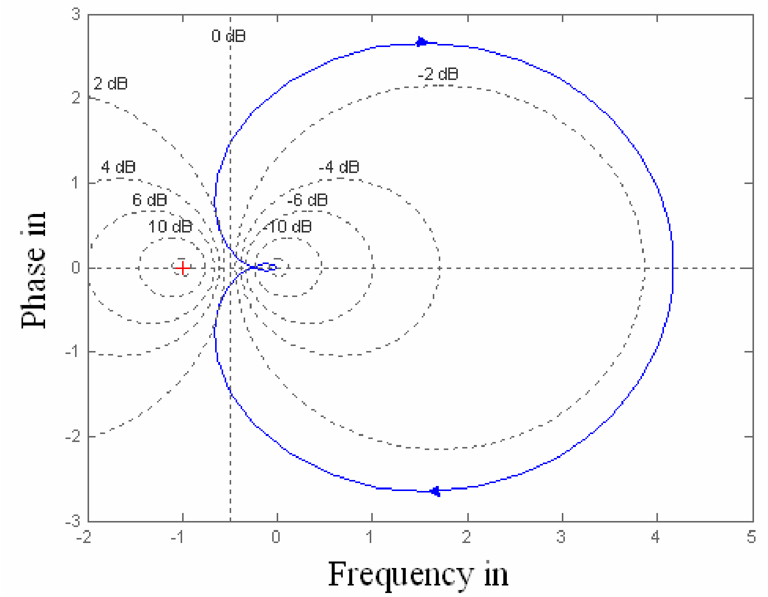
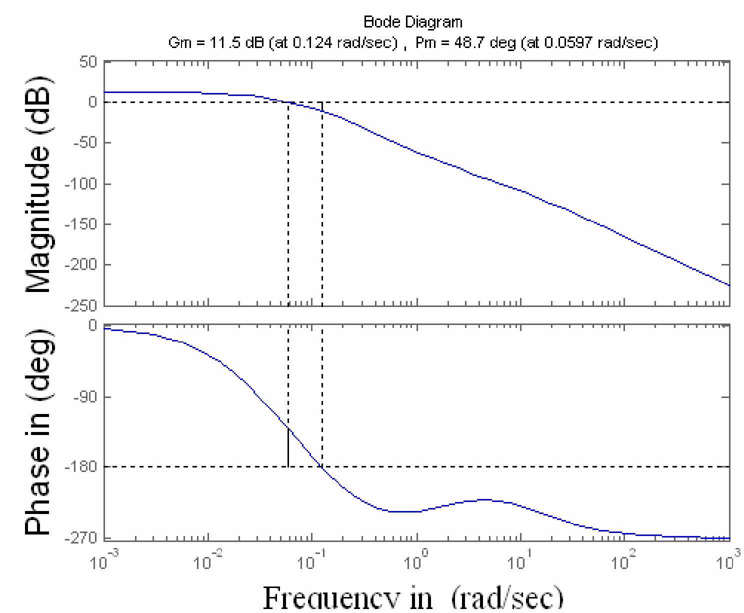


Fig.-4.9.2c Speed deviation of thermal turbine power plant

Decrease in speed is also doubled, when the load is doubled and also the curves follow the theoretical explanation given earlier in this chapter. And the Nyquist plot in figure 4.9.2d shows that the system is totally stable satisfying the criteria of stability (0, -1) and the phase and gain margins are obtained using the margin plot.



<u>Fig.- 4.9.2d</u> Nyquist Plot for thermal unit at 10% load.



<u>Fig.-4.9.2e</u> Margin Plot for thermal turbine with 10% load having Gain margin Gm=11.5 db (at 0.124 rad/sec). Pm= 48.7 deg (at 0.0597 rad/sec)

4.5.3 Thermal Turbine – Non – Reheat type

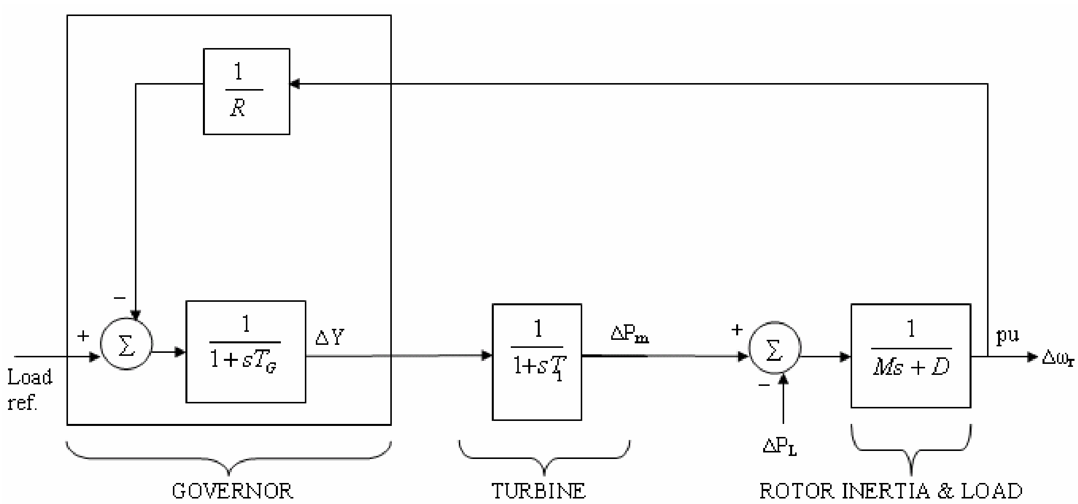


Fig.- 4.10 Thermal turbines – Non – reheat type

For a non – reheat type thermal turbine, the reheat constant T_R becomes zero, thereby reducing the turbine equation

$$\frac{1+sK_R T_R}{(1+sT_1)(1+sT_R)} \quad \text{With } T_R = 0\text{, becomes}$$

$$\frac{1}{1+sT_1}$$

Thus the turbine equation holds only the charging time constant T_1 in it.

4.5.3.1 Results

4.5.3.2 OUTPUT WITH LOAD = 5%

For **LOAD= 5%** and with given values of
T_G= 0.08 S
1/R= 4.17 s
T_1= 0.3s
M= 10.0 s
D= 1.0 s
Turbine transfer function will be 1/ (1+0.3s)

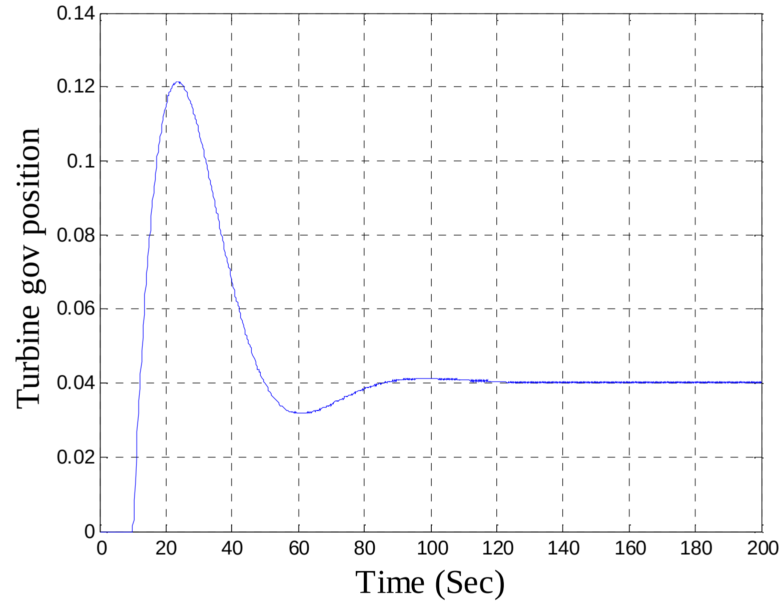


Fig.- 4.10.1a Valve/gate position of non-reheat type thermal turbine for 5% load

One can clearly visualize that, as the valve of the governor position increases letting the steam to flow through the turbine blades, corresponding mechanical power increases to its peak depending upon the load requirements

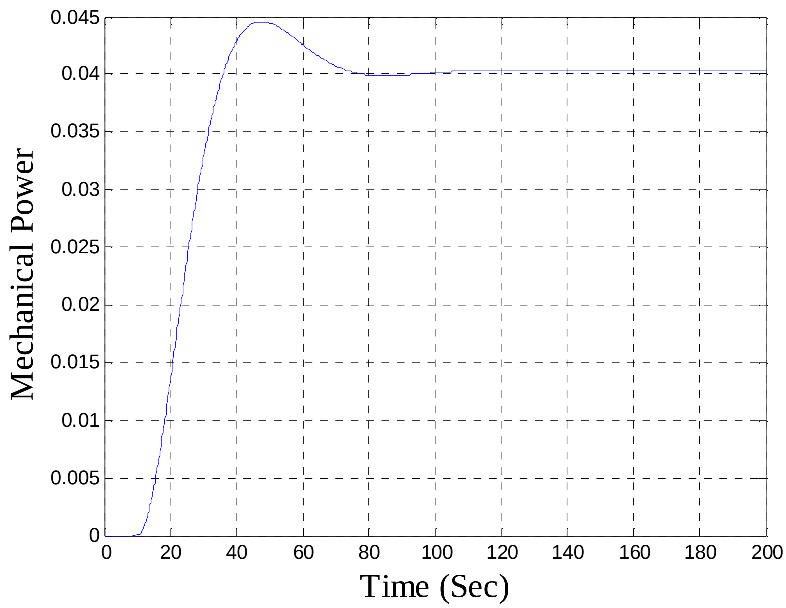
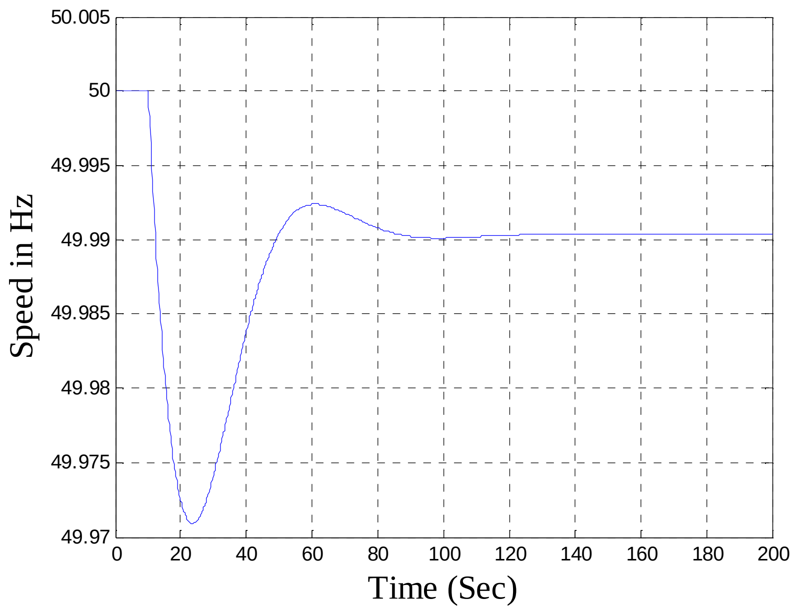
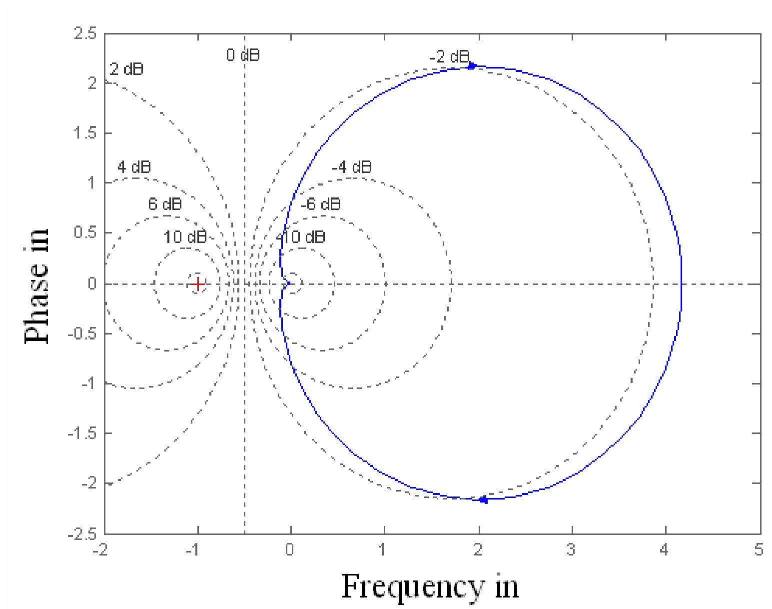


Fig.- 4.10.1b Mechanical power output of non-reheat type thermal unit



<u>Fig.- 4.10.1c</u> Speed deviation for non-reheat type thermal power unit

As the power increases the rotor speed decreases with respect to gate position and mechanical power. And then it gets stabilized when the power becomes stable and following nyquist plot shows that the system is stable.



<u>Fig.- 4.10.1d</u> Nyquist Plot of non-reheat type thermal unit with 5% load

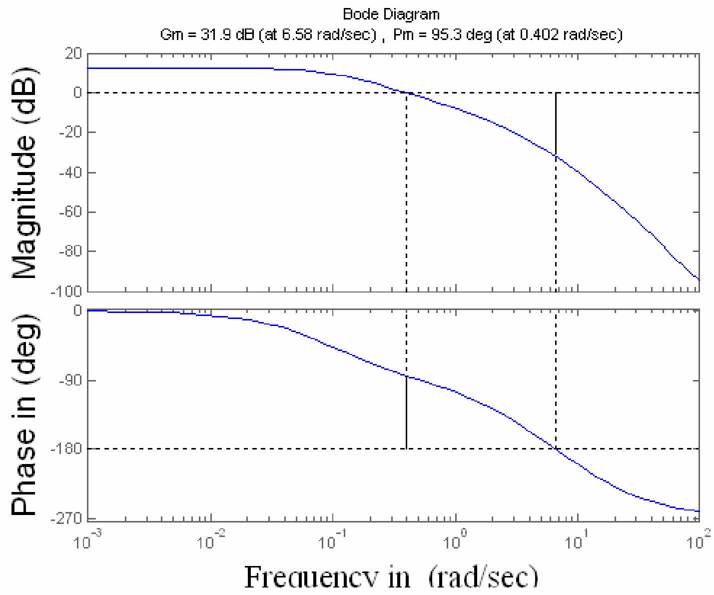


Fig.- 4.10.1e Margin Plot of non-reheat type thermal unit with Gain Margin Gm= 31.9 db (at 6.58 rad/sec) and Phase margin Pm=95.3 deg (at 0.402 rad/sec)

4.5.3.3 OUTPUT WITH LOAD = 10%

For **LOAD= 10%** and with given values of
T_G= 0.08 S
1/R= 4.17 s
T_1= 0.3s
M= 10.0 s
D= 1.0 s

Turbine transfer function will be 1/ (1+0.3s)

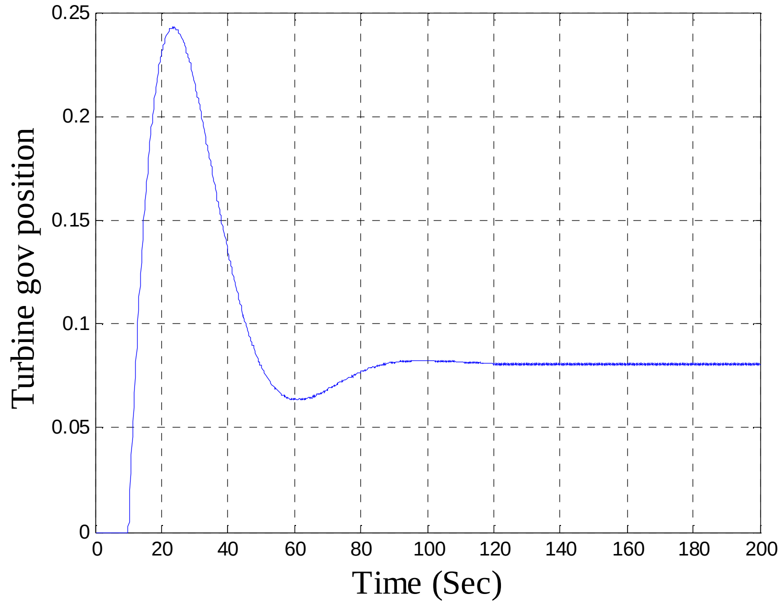


Fig.- 4.10.2a Valve/gate position of non-reheat type thermal turbine for 10% load

As the load increases it can be seen that the gate position gets doubled and the mechanical power in the below figure gets nearly doubled. It is because the system is non-reheat, and this proves that the efficiency of a non-reheat system is less when compared to a reheat system.

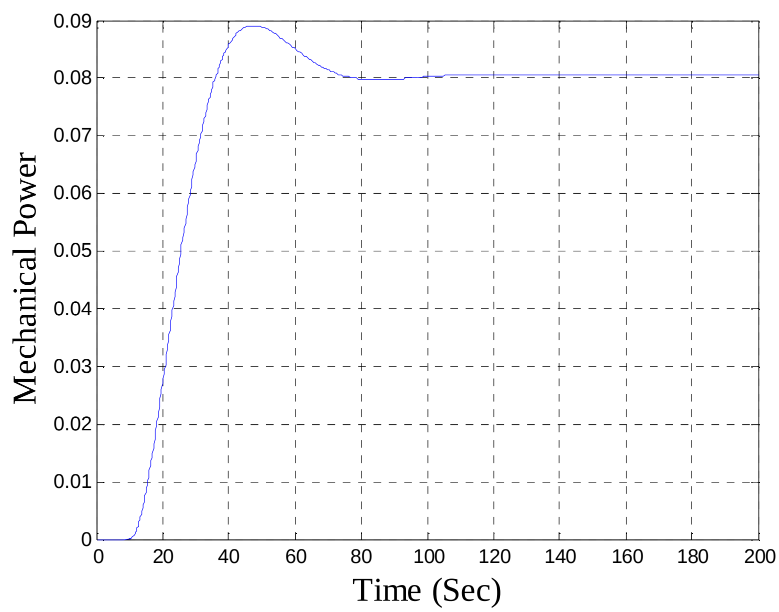


Fig.- 4.10.2b Mechanical power output of non-reheat type thermal unit

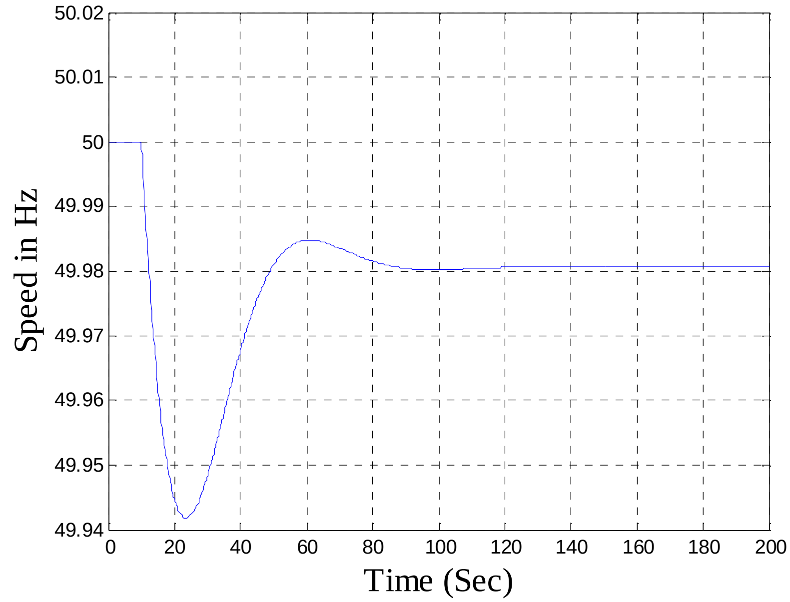


Fig.- 4.10.2c Speed deviation for non-reheat type thermal power unit

The speed deviation curve shows that the speed decreases as the valve position increases to increase the power output. The nyquist plot shows that the system is stable it is proved to be in-efficient when compared to the reheat type thermal turbine.

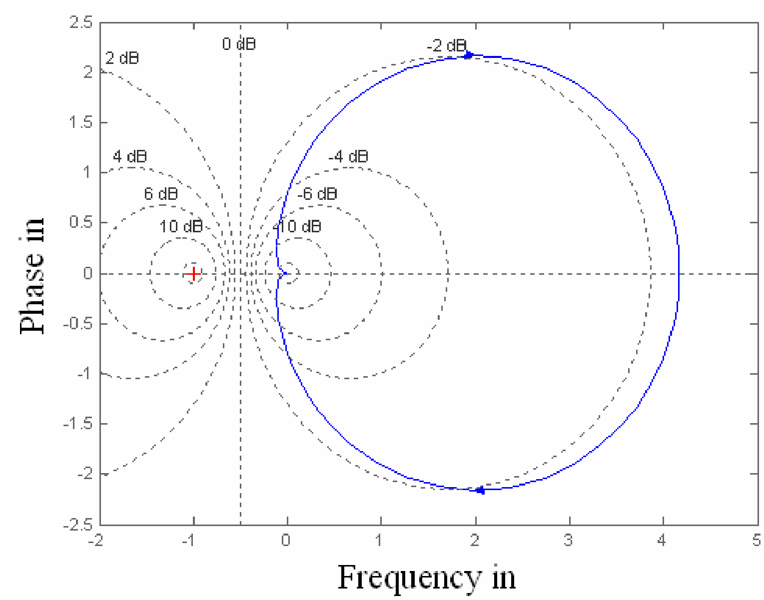


Fig.-4.10.1d Nyquist Plot of non-reheat type thermal unit with 10% load

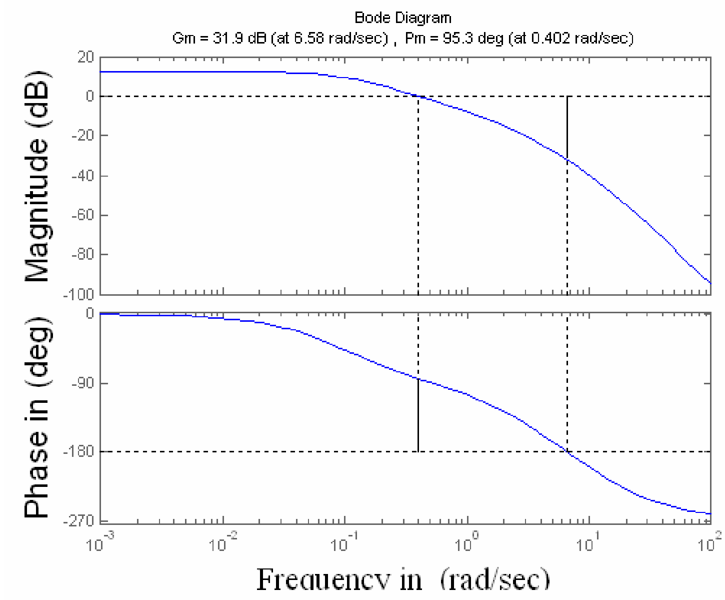


Fig.-4.10.1e 1e Margin Plot of non-reheat type thermal unit with Gain Margin Gm= 31.9 db (at 6.58 rad/sec) and Phase margin Pm=95.3 deg (at 0.402 rad/sec)

4.5.4 Comparison of reheat and non – reheat type of thermal turbines

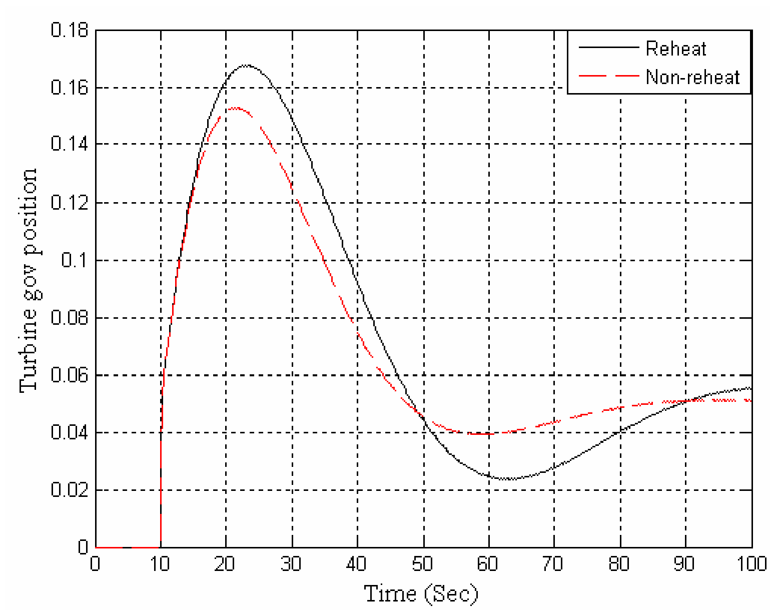


Fig.-4.11a Valve/gate position comparison

The following comparison is made to show the output achieved by using a reheat and non-reheat system. It is visible that with the same input, mechanical power output for the reheat thermal power system is higher than that of non-reheat. Hence in practice a re-heat system is used to extract more energy out of the input.

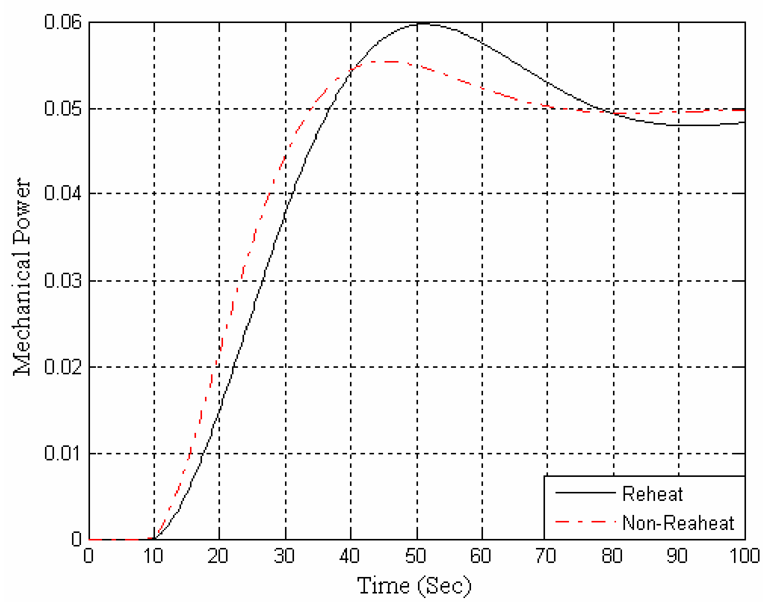


Fig.-4.11 b Mechanical Power comparisons

In the figure it is noticed that the mechanical power output of reheat turbine is 0.06 for a 5% load input whereas the non-reheat gives an output lesser than the reheat model.

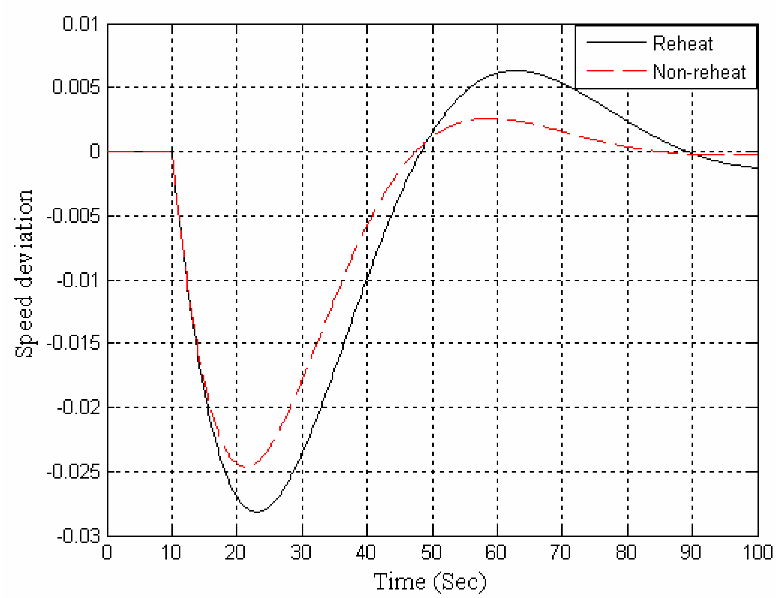


Fig.- 4.11c Speed deviation comparison

Chapter 5

Cost of Frequency Control & Spinning Reserves

Contents Overview

In the previous chapters we have been discussing about frequency control. Here we discuss about the cost associated with the frequency control and the amount of spinning reserves an individual system operator (ISO) should provide for meeting the variation of frequency during increasing demand or contingency. We will learn about mostly used cost models for frequency control and allocation of spinning reserves. Calculations are not performed for any of the plants here because of lack of sufficient data required.

Frequency deviation arises in the power system as a result of temporary power variation. In order to maintain the frequency in the target value, controlling of active power generated and/or consumed is necessary. This way demand and the generation can be met with proper balance. This is provided by 'frequency control reserve', which is a reserve of certain amount of active power. When a frequency drop occurs it is compensated by positive frequency control reserve to increase the frequency and alternatively when frequency increases, negative frequency control reserve is used to cut the frequency value.

5.1 Types of frequency control

To sustain the balance between load and generation, three levels of frequency controls are used. [21]

1) Primary frequency control
2) Secondary frequency control
3) Tertiary frequency control

In this thesis we concentrate mainly on *primary frequency control*, which is an automatic type of control that adjusts the active power generation and/or consumption based on frequency deviation and restores the balance between load and generation quickly. Speed governor plays an important role in this type of control and has response time less than 30 seconds.

Secondary frequency control ensures the re-establishment of primary frequency control capability i.e. to bring back the frequency to its nominal value and thereby minimizing the power flow imbalance in neighboring control areas. This control is usually carried out automatically by Automated Generation Control (AGC). This type of control is slower with a response time of 15 min.

Tertiary frequency control is done manually through telephone calls or faxes between control centre and generation centre. In some power systems, this tertiary control is divided into tertiary 'minute' reserves which can be spinning reserve or back up reserve and tertiary 'hour' reserves.

5.2 Primary frequency control

When large generation or load outage occurs, this will result in system imbalances. It is crucial for the system to maintain stability rapidly. Hence primary frequency control is adopted to perform this function. Generators built-in with speed governors within the synchronous zone will perform his frequency control automatically. Though demand side contributes towards frequency control by connecting or disconnecting loads during frequency deviation, it is not taken into account during calculation of frequency response. [20] [21]
As mentioned earlier in primary frequency control, speed governors play a vital role. These governors are basic controllers with four factors affecting them, they are

5.2.1 Accuracy of frequency measurement

Accuracy is obtained from the rotational speed of the shaft. This accuracy factor seems to be of less importance for a System operator (SO). In Europe, an accuracy of $\pm$10mHz ($\pm$ 0.02% of nominal frequency) is adopted

5.2.2 The speed droop

Speed droop is usually specified by the independent system operator (SO) and in Europe according to UCTE (Union for the co – ordination of Transmission of Electricity in Europe) the value ranges between 3% and 20% depending upon the country.

5.2.3 The active power limiter

This is nothing but the primary frequency control reserve and to define this reserve methods based on heuristics are commonly used. For UCTE a constant loss of production value is determined which is 3000MW and primary frequency reserves to compensate this value is usually set. Heuristics system doesn't take risks into account but it is practically efficient.

5.2.4 The insensitivity of the controller

A controller here is the speed governor attached in the generator. This generator in the synchronous zone doesn't take part in the primary frequency control when it lies in the insensitivity band. Hence restricting the insensitivity band to low values will increase the participation of these generators during frequency deviation. UCTE has set a value of total insensitivity less than $\pm$ 10 MHz ($\pm$0.02% of nominal frequency).

All generating units do not respond to the above commands instantaneously as these factors are related to command settings. Hence system operator (SO) takes the responsibility of specifying the deployment time. In Sweden, and several other counties like Great Britain, New Zealand which has a small system and undergoes large frequency deviation needs a fast responding primary frequency control reserve. And the deployment time is usually 30 seconds for UCTE and it varies depending upon the system operator.

5.3 Cost of frequency control

As mentioned earlier primary frequency control adjusts itself automatically to maintain the rated frequency and stability in the system. Thus it is evident that the cost will be associated with the power plants operational cost, fixed cost, maintenance cost, etc… for example capital cost is high in hydro power plant than the thermal power plant while variable operating cost is higher in thermal than the hydro power plant. In practice some generating units are involved in primary, Secondary and tertiary (to some extent) controls which contributes to the plant operational costs.

For calculating the costs involved with secondary frequency controls, several models are proposed and are used in practice. Now we are going to look at three models used in Slovenian power system which falls under the norms of UCTE. These models used for the Slovenian system discard the value of investment costs assuming these costs are provided by the generating units involved in the secondary control. However, these costs can be considered depending on the system. As previously mentioned these calculations are always based on 'heuristic' estimations. [20]

5.3.1 Energy price probability distribution and power plant's incremental cost model

Energy reserves are set by the system operator which incurs the power plant an opportunity cost. These energy reserves are the secondary reserves and the annual cost for this reserve depends on the generators opportunity cost, which is given by

$$C_{SR} = g(c_e, P_{SR}) = \sum_{i=1}^{365} \sum_{j=1}^{24} P_{resSR,ij}(c_{eij} - \lambda) \tag{5.1}$$

Where,

C_{SR} - Annual cost for secondary reserve

$P_{resSR,ij}$ - Average secondary control power reserve / hour

c_{eij} - Average energy price/ hour (in electricity market)

λ - Incremental cost of power plant

$P_{resSR,ij}$ And c_{eij} are functions of time. In any power system the reserves are never provided by a single unit. Hence the incremental cost depends on the bunch of units which provides the power reserves. To calculate the cost associated with secondary reserve, probability distribution of energy price c_e and required power reserves P_{resSR} must be known. Gamma distribution technique is used to determine the energy price distribution and normal distribution for the required power reserves. Other distribution techniques like chi – square, F – distribution, Rayleigh are not suitable.

The probability density function (PDF) of the energy price is calculated using the equation

$$p(c_e) = f(c_e \alpha, \beta) = \frac{1}{\beta^{\alpha} \tau(\alpha)} x^{\alpha-1} e^{-\frac{c_e}{\beta}} \tag{5.2}$$

The values for the Slovenian system was found out to be $\alpha = 45$ and β =0.2, which gives the mean energy price to be 4.5$cent/kWh. And the PDF for the power reserve is calculated by the equation

$$p(P_{SR}) = f(P_{SR} \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(P_{SR}-\mu)^2}{2\sigma^2}} \tag{5.3}$$

Where μ =0 and σ = 10. After calculating (2) and (3), the cumulative density function (CDF) and (PDF) of the costs of power reserves is calculated by

$$P(C_{SR}) = \int_0^{\infty}\int_0^{g^{-1}} f_{c_e} P_{SR}(c_e, P_{SR}) dc_e dP_{SR} \tag{5.4}$$

And

$$p(C_{SR}) = dP_{C_{SR}} \frac{C_{SR}}{dC_{SR}} \tag{5.5}$$

The function g^{-1} represents the energy price, which is affected by the power reserve costs and used power reserves. The value of λ for the Slovenian system was found to be 2.5$cent/Kwh. Here the cost tend to be negative denoting that the incremental cost can be higher than energy price forcing the producer to have more reserve capacity to avoid financial loss. This is however not feasible.

5.3.2 Energy price difference between day and night model

In electricity market with fluctuating demands it is obvious that the costs might vary between day and night. If we assume that the variable cost is low in the day than energy price and vice versa then the producer tend to sell the energy during the day and buy it in the night only. And also in order to provide the secondary control reserve an annual opportunity cost is incurred, which is given by the equation

$$C_{SR} = \frac{5}{7} * \sum_{i=1}^{365}\sum_{j=1}^{24} P_{resSR,ij}(\lambda - c_{nightij}) \tag{5.6}$$

Where,

λ - Negotiated price of energy (through bilateral contract)

$c_{nightij}$ - Average price of energy at night/hour

The factor 5/7 is obtained by assuming that the producer operates for 12 hours a day and rest of the time he buys electricity. And this is applied only during the weekday and not in the weekends. Like the previous method, gamma distribution and normal distribution is used to calculate the probability distribution of energy price and required power reserves, respectively. The negotiated price (λ) was set to 4$cent/kWh. This method proves to be expensive for secondary frequency control.

5.3.3 Band power price model

The way of estimating the cost of frequency control is based on band power assuming that the off – peak power is sold during the day when the energy price is high i.e. P_{max} to P_{min} and during the night the band power P_{min} is sold. And if the producer reserves some energy then the off – peak power is reduced to P_{max} -P_{min} -P_{resSR} and the band power is reduced from P_{min} to P_{min} + P_{resSR}. The annual opportunity costs is given by

$$C_{SR} = \sum_{i=1}^{365} P_{resSRi}\left[t_{bandi}c_{bandi} - t_{off-peaki} * (2c_{off-peaki} - c_{bandi})\right] \tag{5.7}$$

Where,

C_{SR} - Annual cost for secondary frequency control

P_{resSRi} - Power reserves for secondary control

c_{bandi} - Energy price for the band power

$c_{off-peaki}$ - Energy price for off – peak power

t_{bandi} - Time taken in the band system

$t_{off-peaki}$ - Time taken in off – peak system = 24h - t_{band}

The index '*i*' the average values per day. It was calculated that if $t_{band\ is}$ 12h then $c_{off\text{-}peak}$ is 3.8$cent/kWh. C_{band} is 2.5$cent/kWh and P_{resSR} is 80MW which brings up the annual cost of secondary frequency control reserve to be 8.5M$

From the three estimation models it can be seen that the third model gives a very expensive result while the 1st and the 2nd models were reasonable. This maybe because in different bidding strategies. The only way to get an accurate result is consider the bidding strategies of power reserve providers which is a combination of several types of bidders. For the Slovenian power system these information's are kept confidential. Hence an approximate figure is shown to explain the models.

5.4 Cost – model for Tertiary Frequency Control

As mentioned earlier tertiary control is divided into tertiary 'minute' and tertiary 'hour' control. Tertiary minute takes the same time as secondary control but initiated manually being the only difference. While tertiary 'hour' takes approximately 15 minutes to get initiated. A cost model for the tertiary minute control is explained in this section. In this method operational costs, investment costs and start – up costs are considered. The probability distribution of operational costs is determined heuristically by taking average number of start ups and its average duration. The annual cost can be defined by the following equation,

$$C_{TMR} = A_{fix} + A_{inv} + W_{test}\lambda + n(C_z + 1000P_{TMR}t_z\lambda) \tag{5.8}$$

Where,

C_{TMR} - Annual cost for tertiary 'minute' frequency control reserves

C_z - start up costs

A_{fix} - Power plants fixed cost

W_{test} - Energy produced during test – runs

n - Start – ups expected/year

P_{TMR} - Tertiary control power reserve

λ - Power plants incremental costs

t_z - Mean operational time after start – up.

A_{inv} - Yearly annuity of investment costs; this is calculated using the equation

$$A_{inv} = C_{inv} \frac{p(1+p)^n}{(1+p)^n - 1} \tag{5.9}$$

Where,

C_{inv} - Investment cost in the year of construction

n - Power plants expected life (in years)

p - expected annual income

In Slovenian power system this control is offered by a 300MW gas thermal power plant and a much smaller power plant which has high operating costs. These power plants able to reach their nominal values in approximately 15 minutes, making them best suited for tertiary 'minute' frequency control. In (8), fixed cost (A_{fix}) was estimated to be 5 M$ and if the investment costs for the building of 300MW is 18M$, the expected annual income (p) is 8% for a life (n) of 25 years, then the annuity is 16.88 M$. To check the readiness of the power plant, it has to be test run on monthly basis at least for 10 hours a day. The cost associated with this test run depends on the incremental cost (λ). For gas power plant it is 10$cent/kWh. Which gives the annual test run cost to be 3.6 M$ and start – up cost to be 5k$ which is insignificant.

For calculating the tertiary 'minute' control power reserve's operating cost, probability distribution of the expected start – ups/year and its mean duration must be defined. Gamma distribution can be used to calculate these values. The parameters are chosen heuristically. During the calculation of operation costs, energy tariff is not considered, which implies that the power plant is not getting paid for the energy produced.

CDF and PDF of the tertiary control reserve costs can be calculated by the following equations,

$$P(C_{TMR}) = \int_{-\infty}^{\infty} \int_{-\infty}^{g^{-1}} f_{nt_z}(n, t_z)\, dn\, dt_z \tag{5.10}$$

And

$$p(C_{TMR}) = dP_{C_{TMR}} \frac{(C_{TMR})}{dC_{TMR}} \tag{5.11}$$

The function g^{-1} represents the expected number of start- ups per year, which in turn depends on the mean operational time of each start up and the incremental costs. The incremental cost is 10$cent/kWh, which brings the expected annual operating costs to nearly 1.23M$. Using (8), the total annual tertiary 'minute' power reserve cost is 25.35 M$ for the 300MW Slovenian power system. This shows that operational costs stand for a very small percentage of total costs.
It can be thus deduced that tertiary frequency control is expensive than the secondary control. This might not be the same for all power systems, because here the tertiary control was provided by an expensive 300MW system. The models specified can be used to calculate the secondary and tertiary 'minute' frequency control thus providing a base for analyzing the alternative solutions for power reserves.

5.5 Spinning reserves

Spinning reserves are the energy reserve capacity of a power system. Lack of sufficient energy reserve to meet the alarmingly increasing load will result in system overloading. Hence spinning reserves plays a vital role in frequency control. These spinning reserves are unused capacity which is synchronized to respond to frequency changes in the system with less time to respond. We will discuss about the management of spinning reserves and its effects on load shedding. [22] [23]

The operator can start and stop the turbines to maintain sufficient spinning reserves and also able to set the maximum and minimum values of reserves. Turbine starts automatically when the minimum value of spinning reserve reached and it is shut down from its operation when spinning reserves reaches it maximum value. Spinning reserves for each turbine is calculated on the basis of its load, ambient temperature, age and time since last service. The calculation of spinning reserves is always made on basic principles and simple so that it can be applied to any working conditions. Test results from field testing performed on turbine - governor model is used to calculate availability of the spinning reserves. There are 3 types of reserves

1) Primary reserves
2) Secondary Reserves
3) 10 – minute reserves

5.5.1 Primary reserve capability

These reserves aim to seize the immediate frequency deviation after a contingency like loss of large supply unit. Artificial test conducted on these units determines the ability of each unit to discharge primary reserves. It is defined as the units change in power output with respect to change in system frequency and it is determined that the time taken is 30seconds.

5.5.2 Secondary reserve capability

These reserves aim to bring back the frequencies to the acceptable limit following contingency i.e. is to restore the primary frequency control. Secondary reserve discharge ability is determined by extending the tests conducted on units for primary reserves and the time taken for this discharge is from 30 seconds – 15 minutes. Secondary response is responsive to few factors like ambient temperature and loading levels. Hence tests on turbine units at different loading levels are performed to determine the sensitivity level for secondary reserve capability.

5.5.3 Ten minute reserves

In North American electricity market a new concept is proposed called Acceptable Area Control Error (ACE) where each unit is encouraged to return to zero every 10 minutes. This way, units compensate for a major loss on its own within the time limit. It is perfectly working for American market and it is certified by NERC (North American Reliability Council).

5.6 Allocation of spinning reserves

A pre-allocation step is to determine the requirements and capability of each generating units and to select the applicable candidate to allocate the reserves. This allocation also considers the economical impact of re-dispatching for instance gas turbines provides excellent primary reserves but operating cost is much high while hydro power plant has low re – dispatching costs but not suitable for primary reserve. To solve this issue ‘Reserve Calculation’ can be used where the optimization model is modified and the constraints (primary, secondary and 10 minute reserve) itself varies among the units. Hence all three constraints can be considered for each contingency. This method is not only applicable to systems with economic dispatch but also to systems where the generation dispatch is determined by market forces.

5.7 Choice of power plants

For providing sufficient spinning reserves, choosing the power plants plays an important role. For a hydro power plant primary response is limited by water columns and faster response depends on governor loop stability. Thus making it inefficient for primary reserves. Where as gas turbine power plant provides excellent source for primary and secondary spinning reserves. But one needs to compromise the fact that by running not at base loads will result in high operating cost. Contribution from a steam turbine power plant towards primary and secondary reserves seems minimal because of the fact any frequency change will effect the exhaust heat and the heat time constants directly. However, operating steam turbine with partially closed steam control valves is a reasonable alternative to the use of thermal power systems.

5.8 Spinning reserve and load shedding

When there is an overload in a system it is essential to trip loads that are of least importance to avoid major consequences. Feeders are rated with level of importance and when the spinning reserve goes negative, feeders of lower importance starts to trip. This way minimum value of spinning reserve is maintained for the system to be on the run.

In a nut shell, finding the spinning reserve requirement is complicated because of the frequency dynamics affected by the governor response, which in turn affected by the frequency input. Though computer simulations can be used to predict the frequency performance it is hard for employing it practically. But the worst case scenario can be identified and the required spinning reserve can be calculated. And simple calculation is used to determine the individual unit capability to allocate the amount of reserves. This kind of method is easily applicable for a small system. For a large system frequency deviation occurs only when there is loss of large generating units. But still it remains essential to calculate the spinning reserve requirements and distribute within the available units. [23]

Chapter-6

Wind Power

Contents overview

6.1 Introduction:

Recently, renewable energy resources have attracted considerable interest due to day by day the fuel for power generation from nonrenewable energy decreasing dramatically. For next 50 years, nonrenewable resources are will be limited in most country of the world and cost for power generation will be increased so high.

It is true and obviously no double that the current civilization depends on energy. After second world war within 60 years the current population in the world nearly 6 billion and next 50 years it will be nearly double. So large amount of energy consumption will not be supported from nonrenewable energy resources due to lack of renewable energy resources.

Now it is very essential to move on nonrenewable energy resources for power generation. One drawback of the nonrenewable energy resources can not provide the constant energy supply & can't store directly, consequently, secondary energy storage systems require. Renewable energy included water energy, solar energy, wind energy, geothermal energy and biomass. Among of them water energy, solar energy, wind energy are available to use and current researcher & scientist are developing more reliable system of wind energy for power system. So, researcher & scientist and investor in Scandinavian country and California doing research to develop the wind energy (when many wind power will be connected to the power systems) as a reliable sources.
The suitable condition for installing the wind power in remote area or open place. [10]

6.2 Formation of moving Wind:

To produce Electric power from wind needs to its continuation from steady state to couple of velocities. This wind is renewable energy resources. The wind is moving to and fro due to some reasons. Wind above oceans, hills and continents are moving due to temperature difference around the world. Some places of the world receiving direct sunlight from sun than north & south poles of the earth. Consequently, vertically some distances from ground level of the air over these areas warms up rapidly and then rise. And near cooler air comes to fill the space left by the rising air and then create the surface. Normally, the warm up air is lighter than cooler air. The following figure-6.1. Shows the assumption of formation of moving wind. [12]

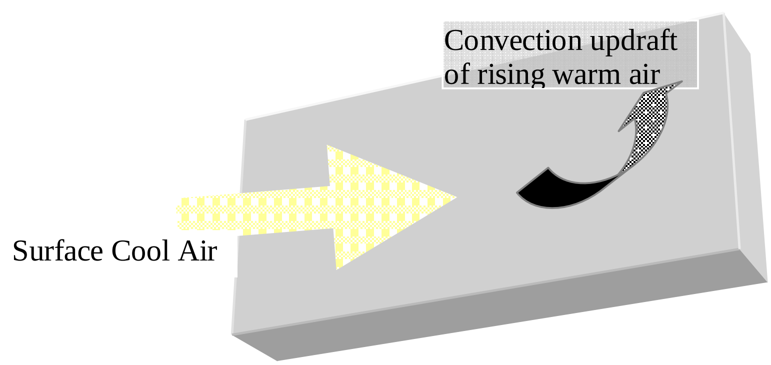


Fig.-6.1 Surface cool air is filling the vacant position and warm air is going up.

From the above assumption we can express the wind power density, P_w

$$Pw = \frac{d}{dt}(q_d x)$$
$$= 0.5\rho U^2 \frac{dx}{dt} = 0.5\rho U^3 \qquad (6.1)$$

Where:

P_w =Wind power density (w/m^2)

q_d = Dynamic pressure of the wind (N/ m^2)

x = moving wind in a given point (m)

ρ=Air-density (kg/ m^3)

U=Horizontal component of the mean-free stream wind velocity (m/s)

6.3 General Wind Turbine Model:

Due to recent development of wind turbine creates the wind technology more complex and advanced constructions. Different simulation programme of wind turbine have different model and different data. In most cases, for modeling purpose, generic model are considered with six blocks. The following figure-6.2 represents the general wind Turbine model.[1]

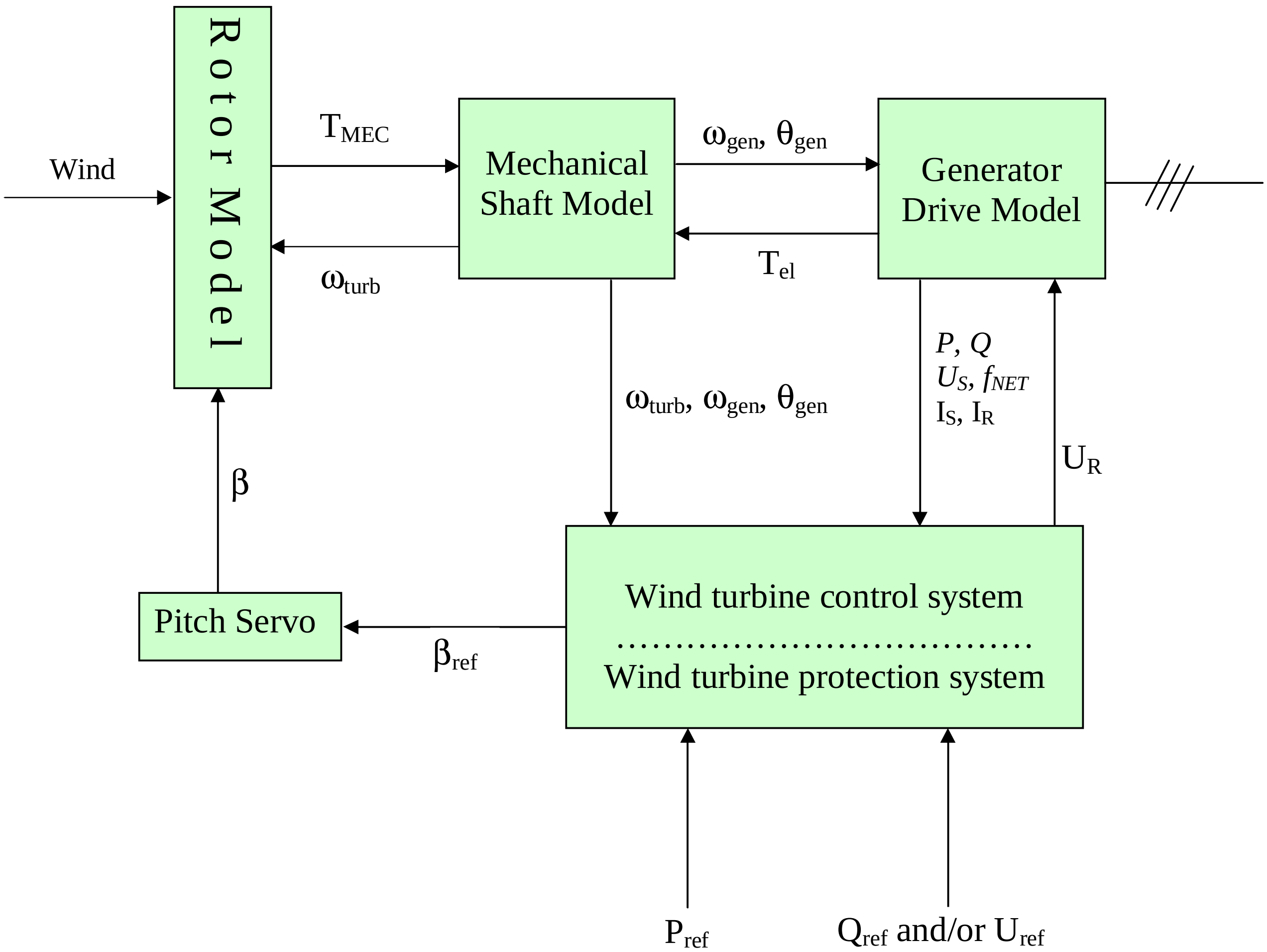
1. **Aerodynamic systems block:** Aerodynamic systems means the turbine rotor i.e. blades of the wind turbine. The number of blades i.e. turbine rotor reduces the air pressure/speed and contrary it gain the kinetic energy from air and convert it to mechanical power, P_w. Turbine mechanical power depends on 3 main factors are wind speed, the blade angle, β of turbine blades and rotational speed, w_{turb}.

2. **Mechanical Systems block:** The mechanical systems of wind turbine are combination of turbine rotor, connecting shafts, gear systems and generator rotor.

3. **Generator Drive:** The generator drive is the combination of generator itself and electronic converter. In fixed –speed wind turbines, the generator drive is only induction generator itself. In variable-speed wind turbines, the generator enables the control systems to adjust rotational speed of the turbine rotor to the instantaneous wind speed over a wide speed range.

4. **Pitch control:** In variable-pitch wind turbines, the pitch servo controls the blade angle, β. The pitch servo limits the angle from β_{min} to β_{max}.

5. **Wind turbine control systems:** This is main control systems of wind turbine and is defined by manufacturer for specific wind turbine or same type of wind turbine. The main task of the control system is to control the power and speed of the wind turbine. For fixed type wind turbine, the generator is treated as a passive power producing component and turbine blade angle is only controllable in the whole turbine systems. In variable-speed wind turbine the generator is treated as controllable element and the turbine blade element is an additional factor for control element.



<u>Fig.-6.2</u> Block diagram of a generic wind turbine model.

Where:

f_{NET}=*Grid Electrical Frequency*

I_s=*Stator current*

I_R= *Rotor current*

P=*Active power*

P_{ref}=*Active power reference*

Q=*reactive power*

Q_{ref}= *reactive power reference*

U_S=*Stator voltage*

U_R=*Rotor voltage*

U_{ref}=*stator voltage reference*

T_{el}=*Electrical torque*

T_{MECH}=*Mechanical torque*

ω_{turb}=*Rotational speed of turbine*

ω_{gen}=*Rotational speed of generator rotor*

θ_{gen}= *Generator rotor angle*

β=*Pitch angle*

β_{ref}=*Blade reference angle*

6. **Protection systems of the wind turbine:** The three quantities voltage, current and rotor speed are the main protection scheme of the wind turbine system.

6.4 Power curve:

Electricity is produced from wind turbine by conversion of kinetic energy of wind. Equation 6.1 described the power produced from wind where the available power varies with cube in wind speed. Available power in wind can not extracted completely by wind turbine. The power curb depends on the air pressure. Wind is moveable and it has different speeds (m/s) in different time. So, constant wind speed can not possible due to Global environmental nature that described in figure-6.2. To produce the electricity it will need minimum wind speed and in high wind speed the power production should be stop due to turbine safety. It is clear that the power production should be available from wind turbine in certain range of wind speed. The following fig-6.3 shows the power in pu verses wind speed (m/s. depend upon the design of wind turbine the power curb of the specific wind turbine follows the relationship between cut-in wind speed and rated capacity. [1][6]

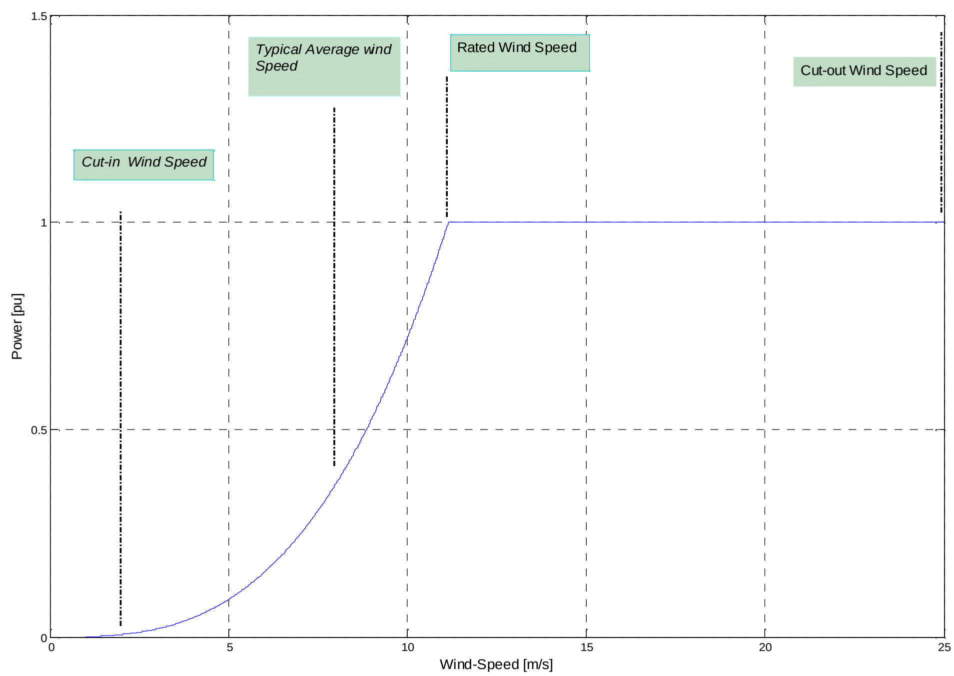


Fig.- 6.3 Typical power curve of a wind Turbine system in different wind speed.

Cut-in Wind Speed: The cut-in wind speed is the speed at which the wind turbine starts to produce electricity and wind velocity nearly 3 to 5 meters per second. In figure-6.3 shows the cut in wind speed of 3.6 MW GE wind turbine. Below the cut-in wind speed the turbine doesn't produce electric power. In figure 6.3 shows the cut-in wind speed range.

Average wind speed: The typical average wind speed lies between below rated wind speed (12 to 16 m/s) where the maximum power is produced and above the cut-in wind speed (3 to 5 m/s) and it's value between 8 to 12 m/s. In figure 6.3 shows the average wind speed range.

Rated wind speed: when the wind speed lies between 12 to 16 m/s, the wind turbine reaches its rated capacity i.e. maximum capacity. After the rated capacity, if the wind is increased in certain level the power production will be same. In figure 6.3 shows the rated wind speed range.

Cut-out Wind Speed: the wind speed at value 25 m/s is treated as a cut-out wind speed. When wind velocity is reached in such position the wind turbine is programmed to stop rotating for avoiding damaging the turbine and its surrounding. In figure 6.3 shows the cut-out wind speed range.

6.5 Power equation of wind turbine:

Wind turbine is electro-technical component like others in electrical power systems. Here we will describe in briefly some basic equations for aerodynamic modeling of wind turbines. For modeling the wind turbine systems it should be included the Generator, Electronic Converters, Mechanical shaft systems and Turbine control systems. [1] [2]

Equation of the turbine rotor:

Electricity is produced from wind turbine by conversion of kinetic energy of wind. So, turbine blade can't extract all kinetic energy from wind. The following equation represents the total wind power, P_{wind} within the rotor swept area of the wind turbine. Turbine rotor, R can be represented by the relationships between total power in the wind and mechanical power, P_{MECH}. The kinetic energy of a cylindrical air of radius, R traveling with wind speed V_{wind} and corresponding total wind power will be:

$$P_{WIND} = \frac{1}{2} * \rho_{AIR} * \pi * R^2 * V_{WIND}^3 \tag{6.2}$$

Where=

$\rho_{AIR} =$ Air density (kg/m^3) =1.225 kg/m^3

$R =$ Rotor Radius (m)

$V_{WIND} =$ Wind speed (m/s)

From the equation we realized that rotor radius; *R* can't hold all energy in the moving wind. The speed of the wind can be reduced by wind turbine which is treated as a fraction of power in the wind. This fraction is denominated the power efficiency coefficient, C_p of the wind turbine. The performance coefficient, C_p can be described by the relationships between the total wind power, P_{wind} and mechanical power, P_{MECH} in the following equation:

$$\mathrm{P_{MECGH}} = \mathrm{C_P} * P_{WIND} \tag{6.3}$$

According to the Betz's limit, theoretically, the mechanical power, P_{MECH} can be extract nearly 59% of the kinetic energy of the wind. In practically, C_P can be determined in the center of the turbine which optimal value lies between 0.52-0.55 for three blades wind turbine. Some cases, the optimal value C_P lies between 0.46-0.48 when it is counted to the electrical power at the generator terminal instead of mechanical power at the center of the turbine.

So, equations (6.2) and (6.3), we can describe the Mechanical power, P_{MECH}:

$$\begin{aligned} P_{MECH} &= C_P * \frac{1}{2} * \rho_{AIR} * \pi * R^2 * V_{WIND}^3 \\ &= \frac{1}{2} * \rho_{AIR} * \pi * R^2 * C_P * V_{WIND}^3 \end{aligned} \tag{6.4}$$

The relation between power and torque of wind turbine is:

$$T_{MECH} = \frac{P_{MECH}}{\omega_{turb}}$$

$$P_{MECH} = T_{MECH} * \omega_{turb} \tag{6.5}$$

Where:

w_{turb}=Turbine rotational speed

From equation (6.4) & (6.5), it is clear that P_{MECH} is depend upon rotational speed, w_{turb} wind speed, V_{wind} and turbine blade angle, β. So, it can be expressed in the following way:

$$P_{MECH} = f_{P_{MECH}}(\omega_{turb}, V_{WIND}, \beta)$$

Here, the incoming energy that extract from wind depend upon the angle of incidence,φ between plane of the moving rotor blades and relative wind speed, V_{rel} *(*$=V_{tip}+V_{WIND}$*)*. By considering two dimensional geometry, wind turbulence is omitted that created by the blade tip and related to the angle of incidence; φ is determined by the incoming wind speed, V_{wind} and speed of the blade by the following equation (6.7):

Tip speed ratio, commonly used term in the aerodynamics of the wind turbines, is defined as the ratio of the rotor blade tip speed ($V_{tip}= w_{turb}*R$) and the wind speed (V_{wind}).

So,

$$\lambda = \frac{V_{tip}}{V_{WIND}} = \frac{\omega_{turb} R}{V_{wind}} \tag{6.6}$$

$$\varphi = \tan^{-1}(\frac{1}{\lambda}) = \tan^{-1}(\frac{V_{WIND}}{\omega_{turb} * R}) \tag{6.7}$$

Where:

V_{tip}=Rotor blade tip speed (m/s)

wtur=Rotor speed (rad/s)

R=Rotor Radius of turbine blades (m)

V_{wind}=Wind speed (m/s)

When the tip of the blades moves 8 to 9 times faster than incoming wind speed, C_P will be the optimal. The angle of incidence, φ is depend on the position along the length of the blade.

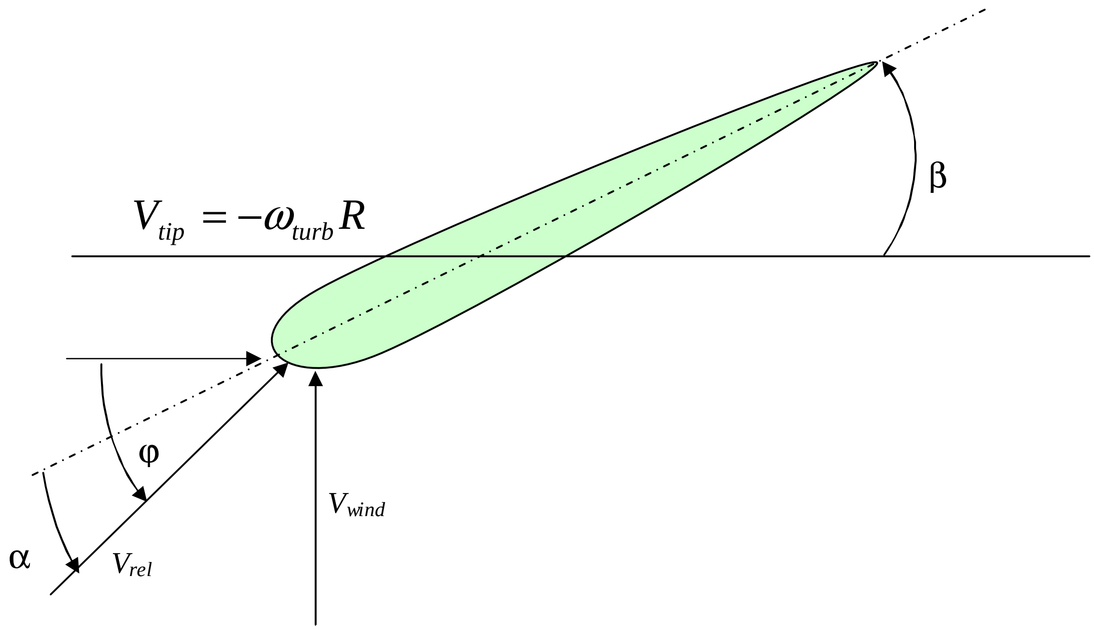


Fig.-6.4 Described the wind conditions around the moving turbine blade.

In the figure-6.4, the pitch angle, β of the entire blade can be adjusted through servo mechanism. If the blade is turned on, the angle of attack, α between the blade and the relative wind, V_{rel} will be changed accordingly. So, the energy extraction from wind is depend on the angle of attack, α between the moving rotor blades and the relative wind speed, V_{WIND}.

The power efficiency coefficient, C_p value of the blades is depend on the blade angle, β and tip speed ratio, λ . So, C_p is the function of λ and β and can be expressed in the following way:

$$C_P = f_{C_P}(\lambda, \beta) \tag{6.8}$$

Therefore, equation (6.4) and (6.8),

Mechanical power, P_{MECH} can be described in the following way:

$$P_{mech} = \frac{1}{2} * \rho * \pi * R^2 * C_P(\lambda, \beta) * V_{WIND}^3 \tag{6.9}$$

The performance coefficient, C_p dictating the operational performance of the wind turbine and follow the non-linear power function of λ and β. If the C_p - λ curve is known for a specific wind turbine with a turbine rotor radius, R it is easy to construct the curve of Cp against rotational speed for any wind speed, V_{WIND}. The following figure-6.5 shows C_p - λ curve for different pitch angle.

For specific wind speed, V_{WIND} the optimal operational point of the wind turbine can be determined by tracking the rotor speed to the optimal tip speed ratio, λ_{OPT}. so, equation (6.6) can rewrite for optimal turbine rotor speed, $w_{turb,OPT}$.

$$\omega_{turb,OPT} = \frac{\lambda_{OPT} * V_{WIND}}{R} \tag{6.10}$$

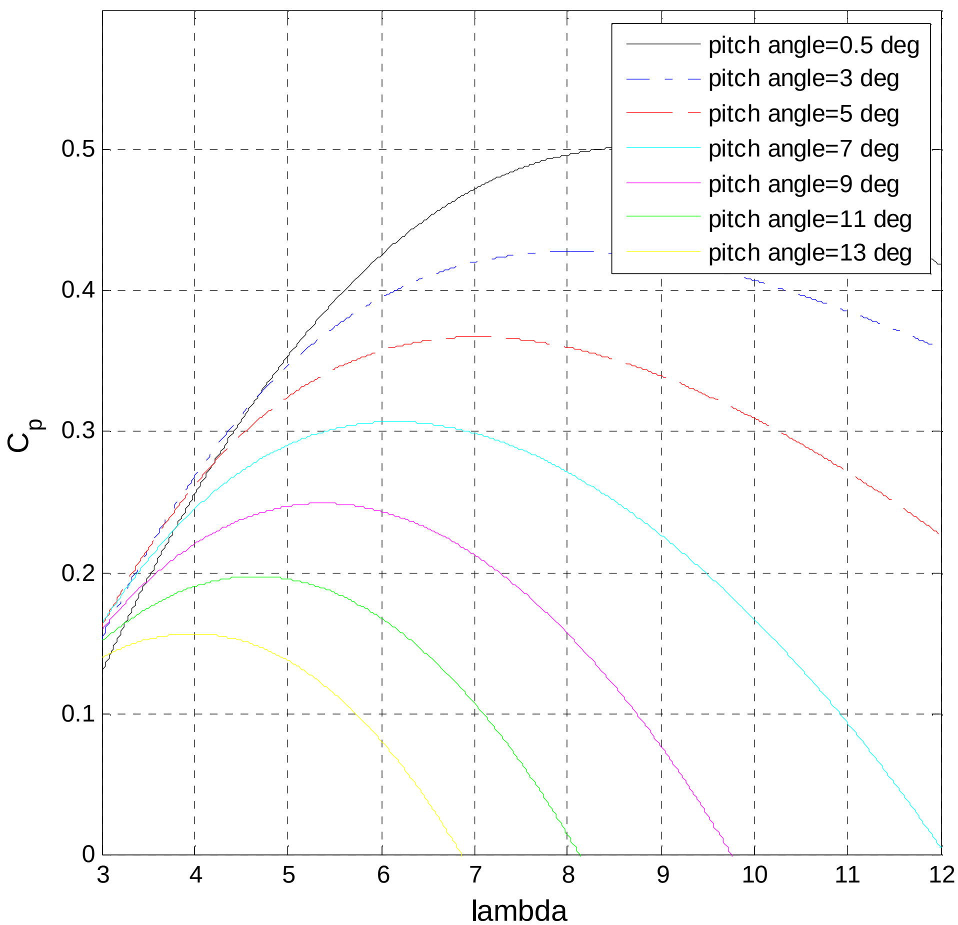


Fig.-6.5 showed the C_P-λ curve for different pitch angle.

From equation (6.10), for the specific wind speed, the optimal rotational speed depends on the turbine radius, R which increases with the rated power of the turbine. So, the larger the rated power of the wind turbine (equation-(6.9)) the lower the optimal rotational speed.

For fixed speed wind turbines it have to designed in order for the rotational speed to match the most likely wind speed in the area of installation. And for variable-speed wind turbines, the rotational speed of the wind turbine is adjusted over a wide range of wind speeds so that the tip speed ratio; λ is maintained at optimal tip speed ration, λ_{POT}. Thereby, the power efficiency coefficient, C_P reaches its maximum value and as a result, mechanical power, P_{MECH} output of a variable-speed wind turbine will be higher than that of a similar fixed-speed wind turbine over a wider range of wind speeds. At higher wind speeds, the mechanical power is kept at the rated level of the wind turbine by controlling the pitch of the turbine blades.

6.6 Power control of wind turbines:

Wind energy has reached a level of maturity regarding its value as an alternative energy generation technology. Wind turbines are designed to produce electrical energy as cheaply as possible. Wind turbines are designed in such way to provide the maximum output at wind speed. In case of strong wind, some portion of energy will be lost for avoiding damage the wind turbine blades and its surrounding. So, all wind turbines are designed with some sort of power control. There are two main different control systems are available to safe run the modern wind turbine. [1] [2] [5] [6]

Pitch controlled wind turbines:

In case of variable-speed wind turbine the optimum power can be produced by appropriate controlling of pitch system that adjusts the effective rotor blade angle, β. Where the blades can be turned out or into the wind as the power output becomes too high or too low. Practically, blade pitch control are used to reduce the overloading the wind turbine when wind speed are available. Some drawback of the pitch control to need of pitch mechanism and higher power fluctuation at high wind speeds.

In modern wind turbine, high efficient turbine’s electronic controller is used to check the power output of the turbine in several times per second and when power output becomes too high, it sends an order to pitch the blade mechanism to turns the rotor blades slightly out of the wind. When the wind is going to droop the controller gives an order to the blades of the turbine to turn back into the wind.

Pitch control techniques are classified into two controls area are passive and active control.

In passive control system to keep the power constant at rated value, the turbine blades are stalled at a certain wind speed higher than the rated wind speed. For each blade, some systems use the hydraulic actuators or separate electric actuators. Most of the case, hydraulic pitch mechanism is usually operated.

In active pitch control, for generating the required power output; the blade pitch angle is continuously adjusted based on the measured parameters. In some cases, the active pitch regulation sometimes can make the system unstable during highly variable wind conditions. In figure- 6.6 represents the pitch control system of wind turbine.

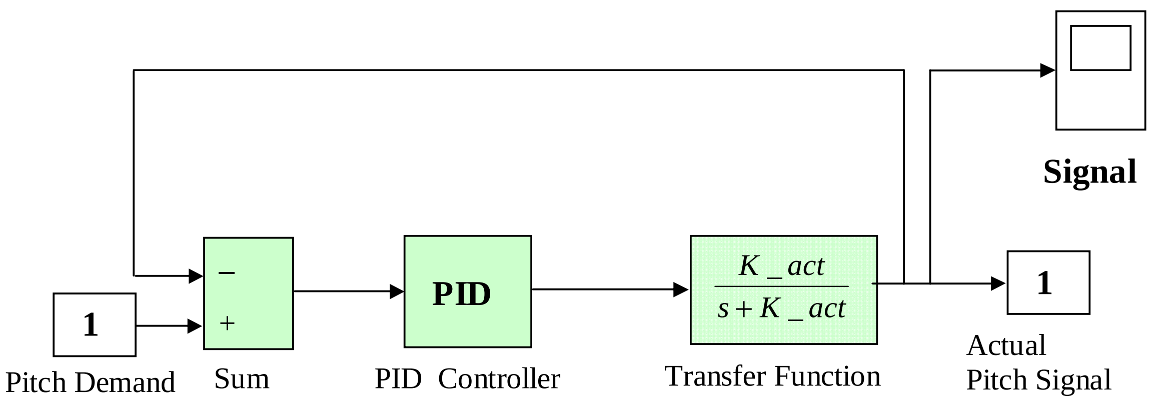


Fig.-6.6 Block diagram of pitch control system.

Stall Controlled Wind Turbines:

Practically, stall control system was for large wind turbines   Stall control wind turbines are designed in simplest way, most robust and also cheapest control method compare to other. Rotor blades in this type of wind turbine are bolted onto the hub at a fixed angle.

When wind speed exceeds a certain level, the design of rotor aerodynamics cause the rotor to stall. As a result, power extraction on the blades is limited. Such slow aerodynamic power regulation causes less power fluctuations than a fast-pitch power regulation. For stall controlled wind turbine the blade is twisted slightly its longitudinal axis. This is partly done in order to ensure that the rotor blade stall gradually rather than abruptly when the wind speed reaches its critical value. The main advantage of this type of turbine is that one avoids moving parts in the rotor itself. The drawbacks are complex aerodynamic design and lower efficiency at low wind speeds.

Active Stall Controlled Wind Turbines:

Nowadays most of wind turbine are being developed with active stall in larger type (1 MW and up) by the Manufacturer. In this type of control the stall of the blade is actively controlled by pitching the blades. To achieve the maximum efficiency at low wind speed, the blades are pitched like to a pitch-controlled wind turbine. At high wind speeds the blades are forwarded into a deeper stall by being pitched slightly into the direction opposite to that of a pitch-controlled turbine. In this type of control system, the advantages are the power output is more accurate than the passive stall control and system can be run almost exactly at rated power at all high wind speeds. Another advantage is that it is easier to stop in emergency and start up the turbine at any circumstances. Normally, pitch mechanism is usually operated using hydraulic or electric stepper motors.

6.7 Wind turbine topology

Wind turbine is operated in fixed speed or variable speed.

Fixed –speed wind turbines:

In this type of wind turbine is designed with induction generator (squirrel case or wound rotor) and directly connected to grid where the rotor speed of the wind turbine is fixed and same to the grid frequency. In fixed speed systems, the wind turbines are coupled to the system bus through a gearbox and induction generator. Compensating capacitor bank for reducing reactive power compensation (because induction generator consumes a significant amount of reactive power which increases along with the active power output) with soft-starter is equipped when connected to the grid. In figure- 6.7 shows the systems structure of the wind turbine with direct connected squirrel cage induction generator.

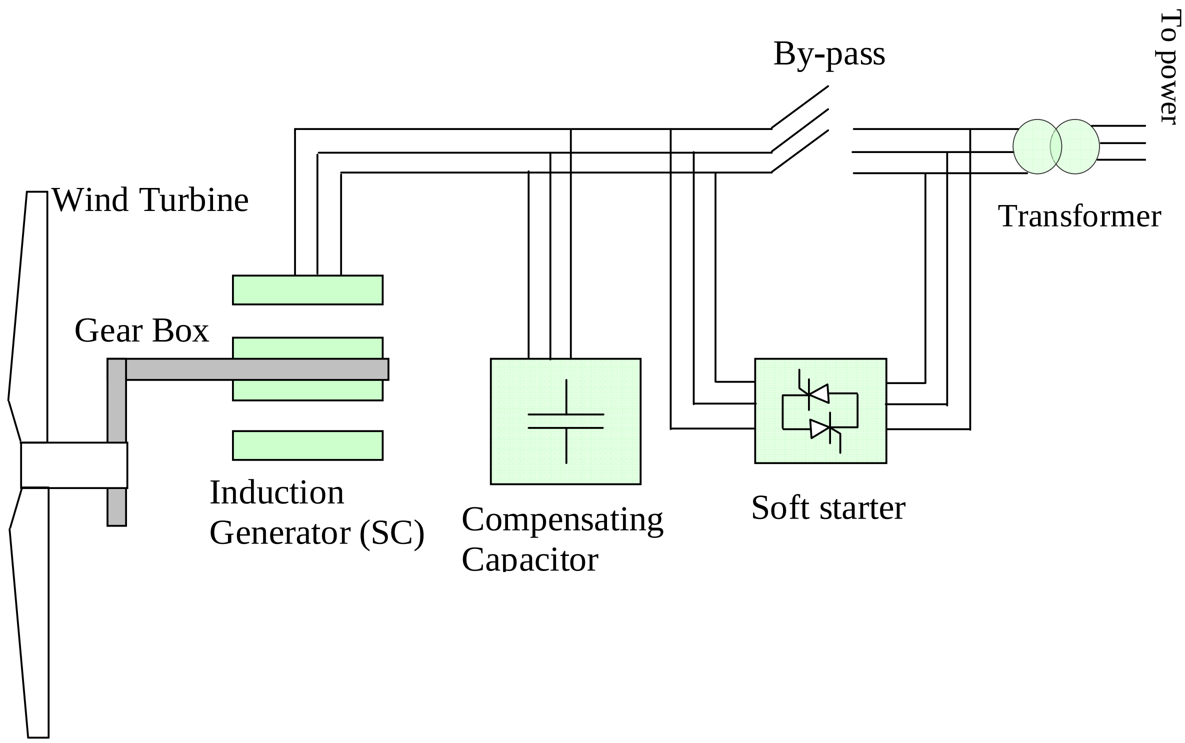


Fig.-6.7 Wind turbine with direct connected squirrel cage induction generator

In fixed-speed wind turbine the mechanical power is converted directly to a three-phase electrical system through induction generator and no complex controller is needed in the electrical part. For an active stall fixed-speed wind turbine, a pitch controller is needed to regulate the pitch angle of the turbine. This type of wind turbine is designed in such way to achieve maximum efficiency in certain wind speed. To increase power production in low wind speed the winding of the generator is designed by 8 poles and for medium & high wind speed the generator is designed by 4-6 poles.

Some advantages of this type of turbine are low cost, simple, robust and reliable and drawbacks are uncontrollable reactive power consumption, mechanical stress and less power quality control.

Variable- speed wind turbines:

To attain maximum aerodynamic efficiency, the variable-speed wind turbines are designed over a wide speed range. In this type of turbine, the possibility to rotational speed of the turbine can be increased or decreased with variable wind speed and consequently, creates the maximum power coefficient by keeping constant the tip speed ratio at predefined value.

Increased power capture, power quality, reduced mechanical stress are advantageous of variable-speed wind turbine compare to fixed-speed wind turbine. Complicated electrical system, loss of power electronics, increased cost, more components are the drawbacks of the variable-speed wind turbine. The following section introduced the combination of different types of generators as well as power converters are used in variable-speed wind turbine.

The following figure-6.8 described the general layout of a variable-speed wind turbine.

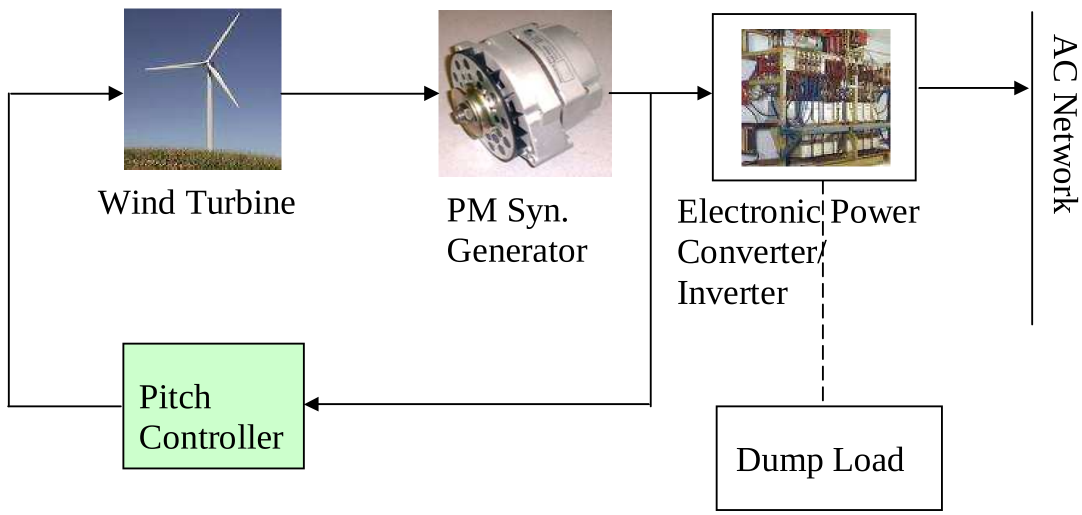


Fig.-6.8 Block diagram of variable speed wind generator based system

Limited variable-speed wind turbine:

Wound rotor induction generator (WRIG) with variable generator rotor resistance is used in this type of wind turbine that connected directly to the grid. In order to smooth grid connection and compensating the reactive power consumption soft-starter and capacitor bank is used respectively. The power output in this system is controlled by changing additional rotor resistance which can be changed by an optically controlled converter mounted on the rotor shaft. The following figure-6.9 represents a Limited variable-speed wind turbine system.

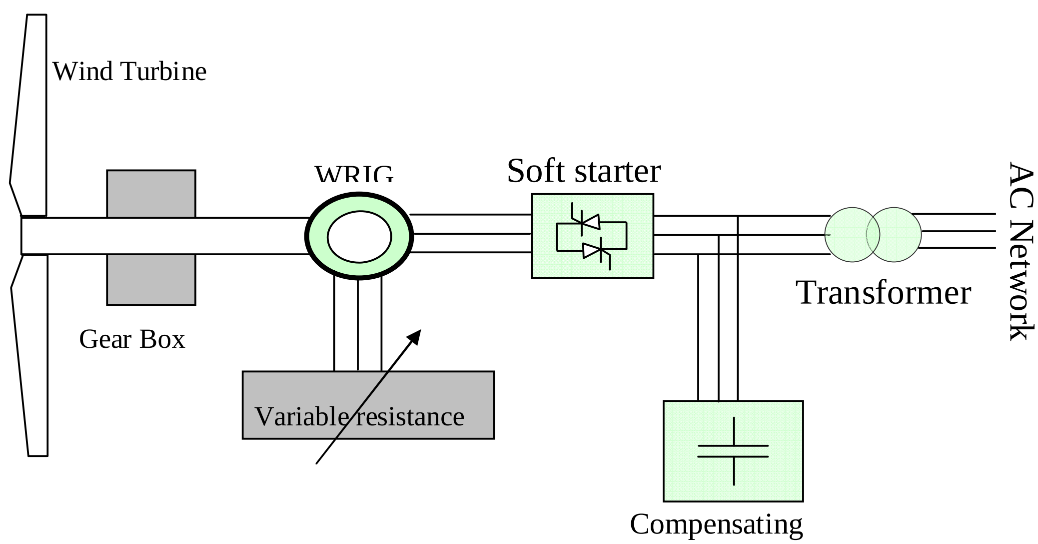


Fig.-6.9 Block diagram of Limited variable-speed wind turbine

Variable-speed with partial scale frequency converter:

Double fed induction generator (DFIG) with partial scale frequency converter is used in this type of Variable-speed wind turbine that connected to rotor circuit where stator circuit is connected to the grid and rotor circuit to the converter through slip rings. Here, in order to smooth grid connection and compensating the reactive power consumption; partial scale frequency converter is used. It has wide dynamic speed range from -40% to +30% compare to limited variable speed wind turbine. The following figure-6.10 represents a variable-speed with partial scale frequency converter wind turbine system.

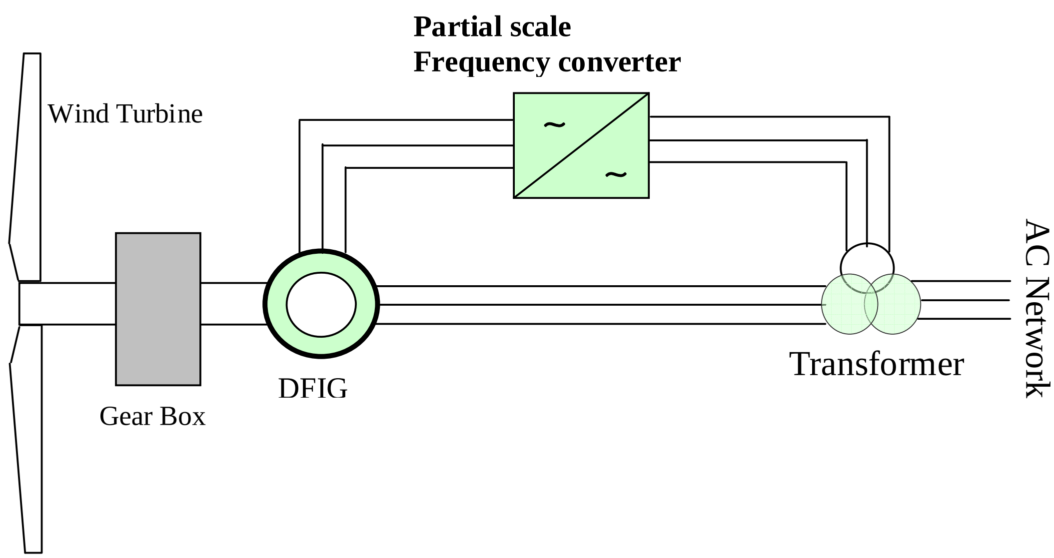


Fig.-6.10 Block diagram of Variable-speed with partial scale frequency converter system

Variable-speed with full- scale frequency converter:

Figure-6.11 represents the full variable speed wind turbine with electrically excited WRSG (wound rotor synchronous generator) or WRIG or PMSG (permanent magnet synchronous generator) connected to the grid through a full- scale frequency converter. Here, in order to smooth grid connection and compensating the reactive power consumption; full- scale frequency converter is used. The advantage to use the full-scale frequency converter compare to partial-scale is no need to gearbox in the turbine system and direct driven multiple generator with large diameter is used.

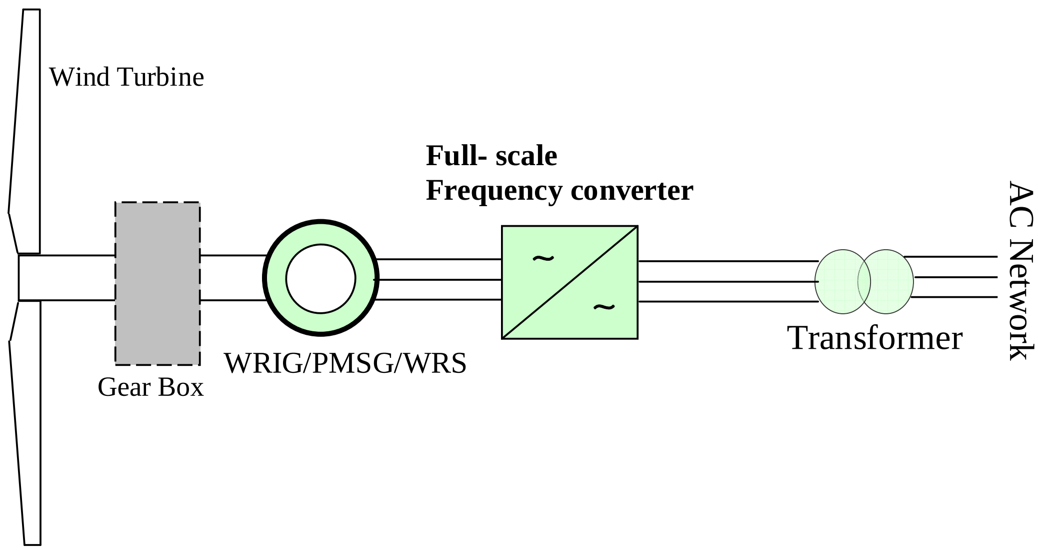


Fig.-6.11 Block diagram of Variable-speed with partial scale frequency converter system

6.8 Model study of GE® Wind turbine:

In this chapter, we studied the computer simulation of GE-3.6 Wind Turbine model.

The following figure-6.12 represents the GE WTG Dynamic models. In this model wind turbine generator is unusual from a system simulation perspective and used the wound rotor induction generator (WRIG). Machine is DFIG type and equipped with a solid-state AC excitation system that supplied through converter.

The main purposes of the turbine control are to maximize power production by maintaining the desired rotor speed and avoiding equipment overloads. Blade pitch control and electrical control are main two controls to satisfy the objective. Being considered load flow phenomena, conventional generator and transformer are used for initialization of the dynamic simulation programme. The following four main device models are considered to construct the WTG model.

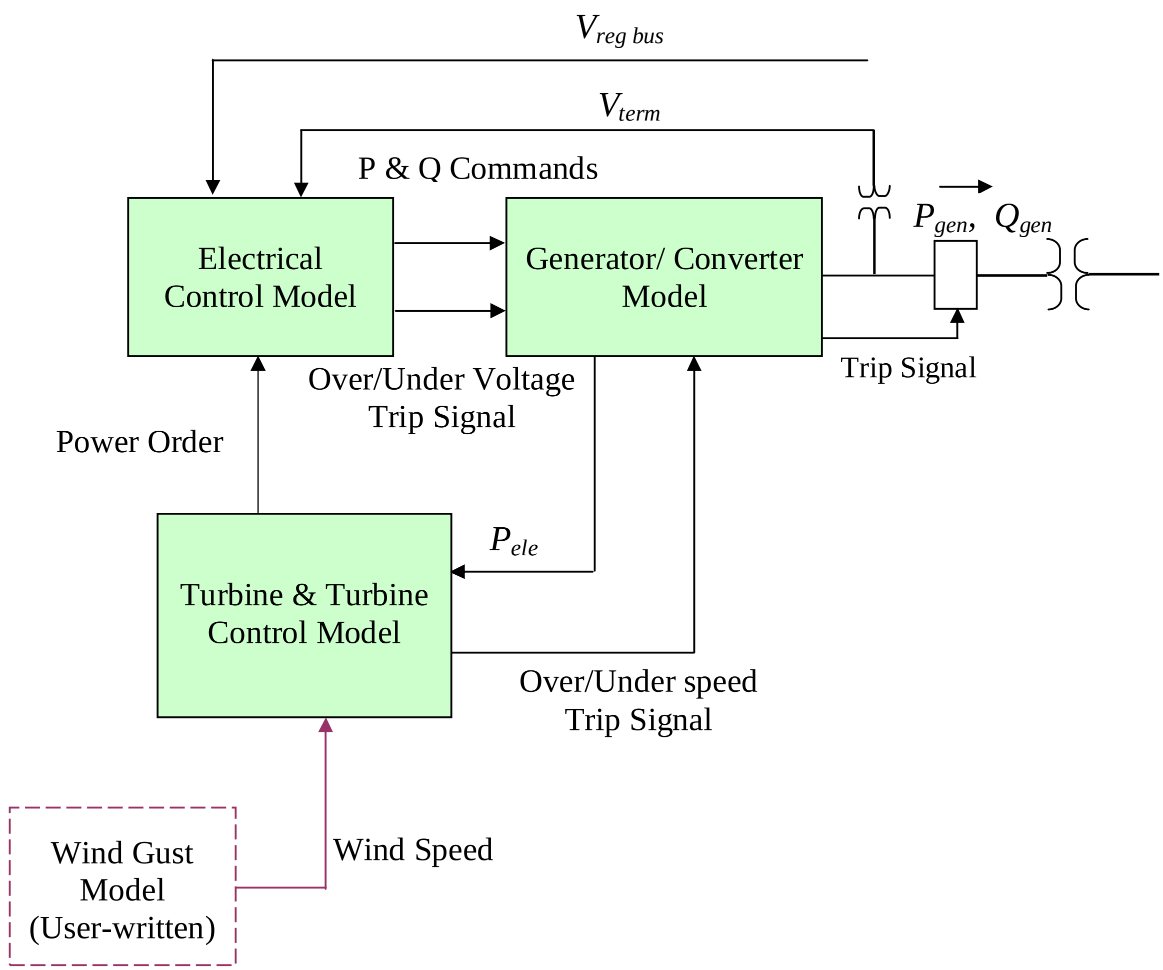


Fig.-6.12 showed the GE WTG Dynamic models and data connectivity.

1. **Generator/converter model:** This model represents the physical equivalent of the generator and converter hardware and provides the interface between the WTG electrical controller & network.

2. **Electrical control model:** This model indicates the active and reactive power to be delivered to the power system based on input from the turbine model and power systems conditions. In this model the control functions are separated into two main categories are closed loop control and open loop control. The closed loop controller contains the voltage regulation and power factor control functions. The open loop

control responds to large disturbance and contains the important protective functions relating to the electrical aspects of the WTG.

3. **Wind Turbine and Turbine control model:** Wind power system is Electro-mechanical system where Electricity is produced from wind turbine by conversion of kinetic energy of wind. So, wind turbine model in figure 6.13 provides a simplified representation of a very complex electro-mechanical system. The model represents the all of the relevant controls and mechanical dynamics of the wind turbine. In this model; the following equations and parameters has assumed to represent the characteristic curves (for GE-3.6 MW WTG). The wind turbine mechanical power (shaft power) from energy contained in the wind is:

$$P_{mech} = \frac{1}{2} * \rho * \pi * R^2 * C_P(\lambda, \beta) * V_{WIND}^3$$

For rigid shaft representation used in this model, the relationship between blade tip speed and generator rotor speed is fixed constant denoted by K_b.

$$\lambda = \frac{K_b \omega}{V_w}$$

The value of K_b for GE-3.6 is 69.5.

The mathematical presentation of C_p

$$C_p(\beta, \lambda) = \sum_{i=0}^{4} \sum_{j=0}^{4} \alpha_{i,j} \beta^i \lambda_j \tag{6.11}$$

The coefficient of $\alpha_{i,j}$ are given in the appendix. The curve fit is a good approximation for values of $2<\lambda<13$. values of λ outside this range represents very high and low wind speeds, respectively, which are outside the continuous rating of the machine.

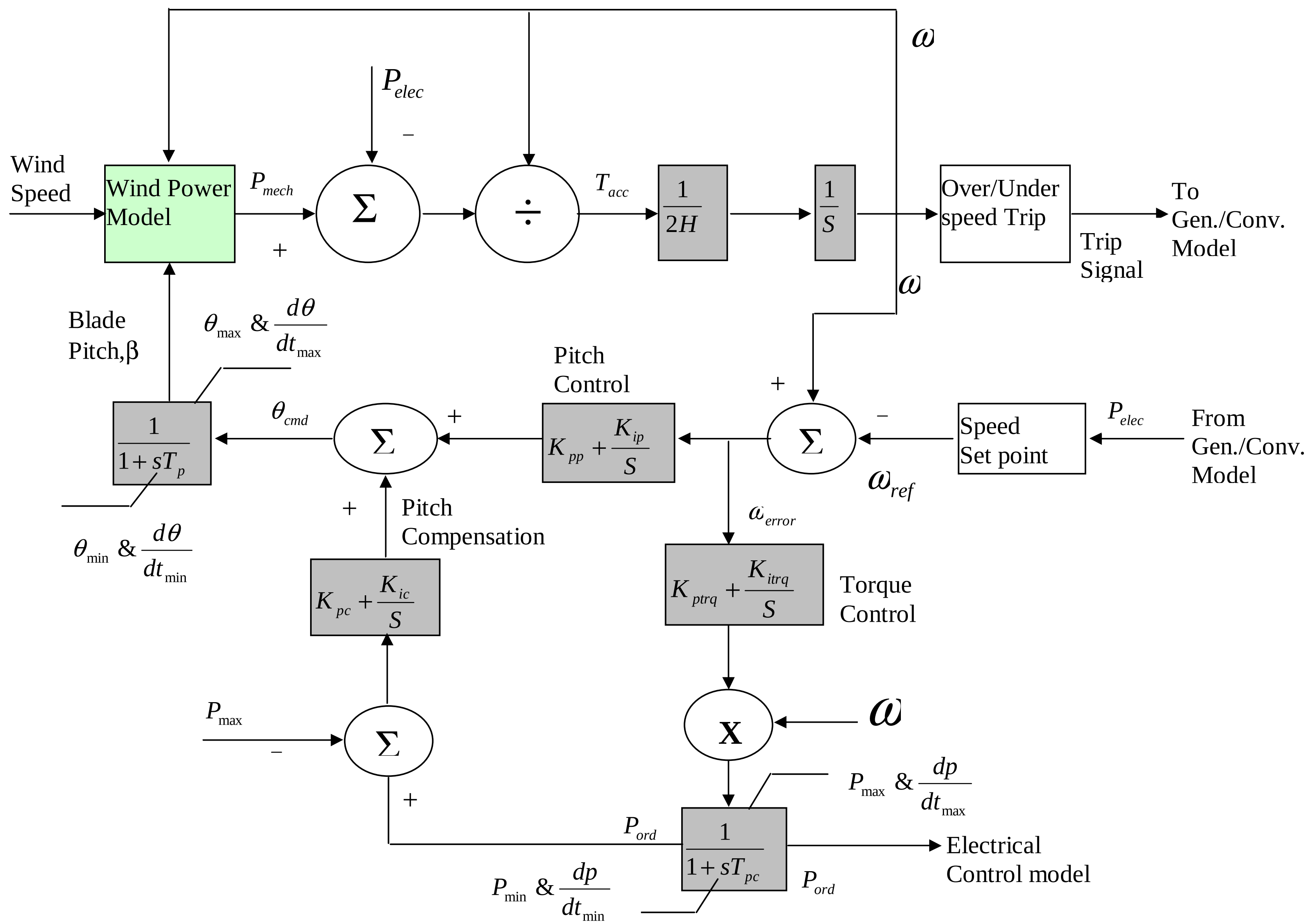


Fig.-6.13 showed the GE WTG Model Block Diagram.

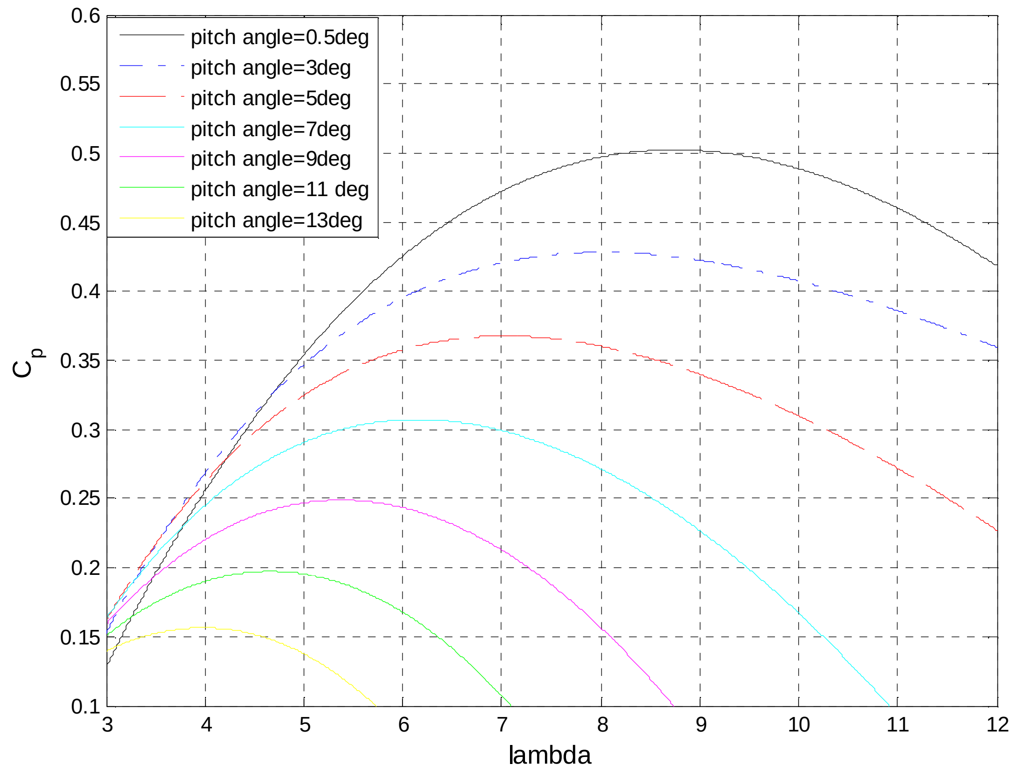
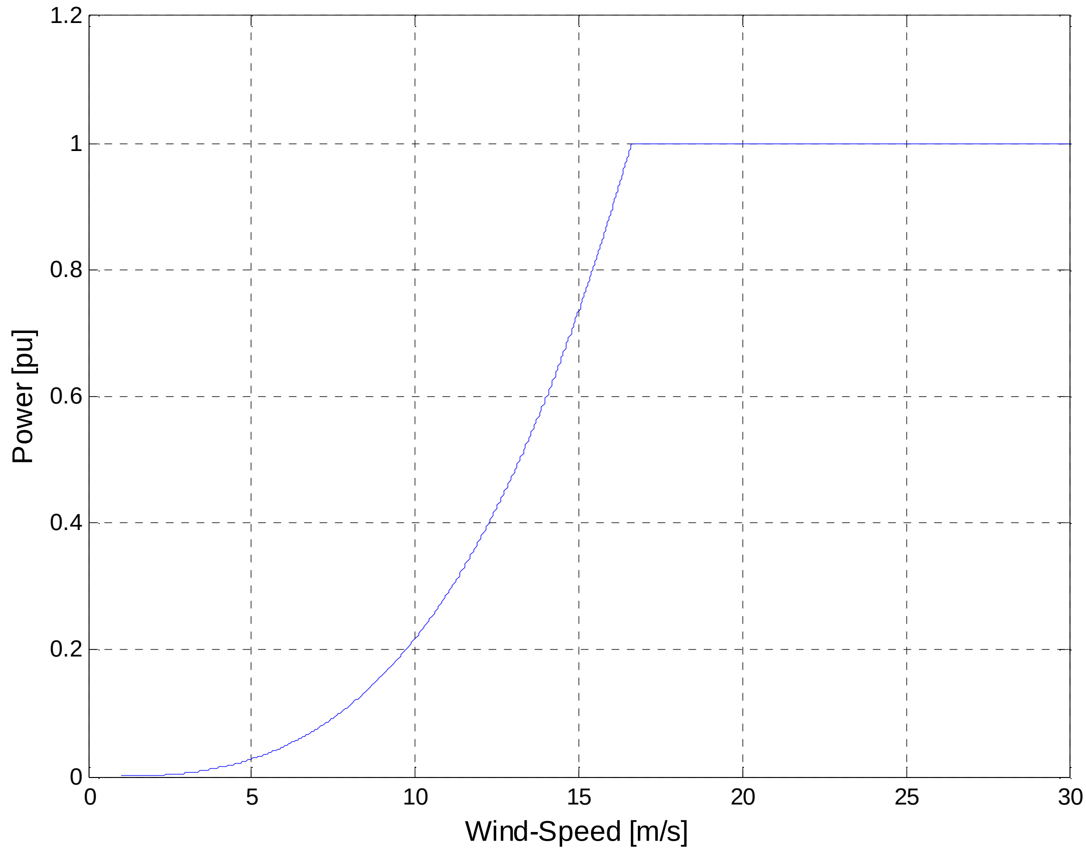


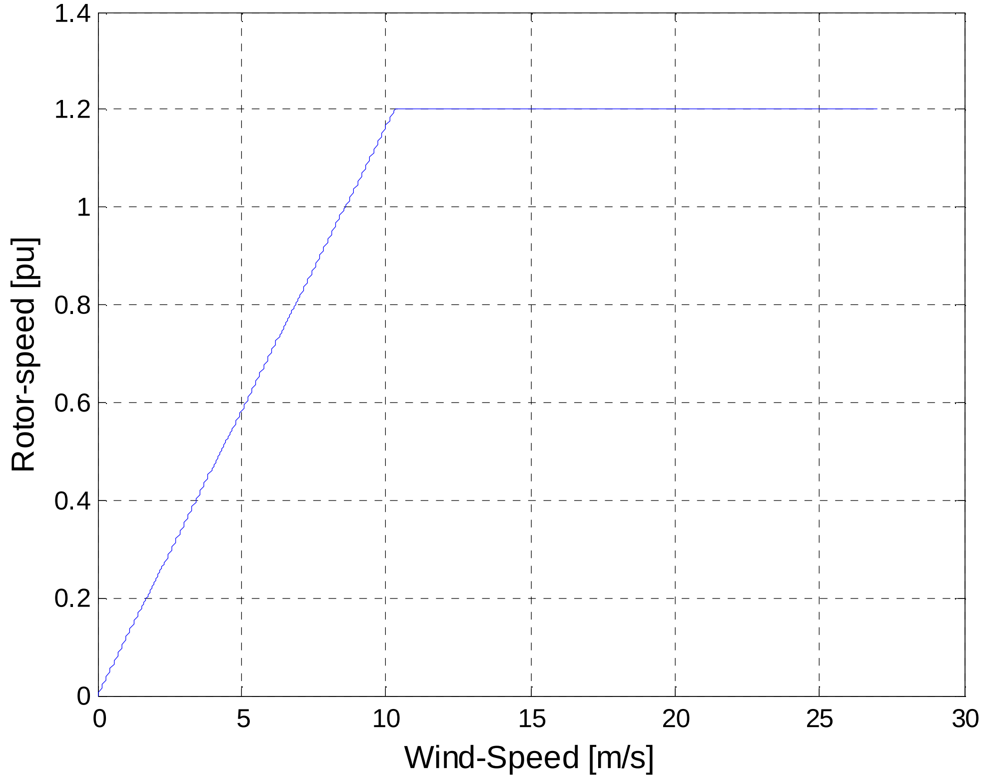
Fig.-6.14 showed the C_P-λ curve of GE-3.6 MW WT for different pitch angle from 0.5 deg to 13 deg.

In this figure it showed that C_P is optimal at 0.5 deg when λ_{opt}=8.25 and C_P is minimum at 13 deg when λ_{min}=4. so, when the pitch angle is increase the C_P is decreases from its optimal.



<u>Fig.-6.15</u> showed the Power- wind speed curve of GE-3.6 MW WT.

In this figure, by keeping the pitch angle to nearly zero (0.5), the turbine output power-wind speed is hold at maximum level. From this figure we can also describe the cut-in speed of the GE-3.6 MW wind turbine is nearly 3.5 m/s, average wind speed is 8.5 m/s, rated wind speed is 11.25 m/s and cut-off wind speed is 27 m/s.



<u>Fig.-6.16</u> showed the Rotor speed- wind speed curve of GE-3.6 MW WT.

In this figure, the rotor reached the maximum value i.e. rated value at 1.2 pu when wind speed is 10.2 m/s that is a little bit lower than the rated wind speed of the power curve in figure 6.15 at rated speed. It should be noted that the minimum rotor speed of this model is 0.7 pu.

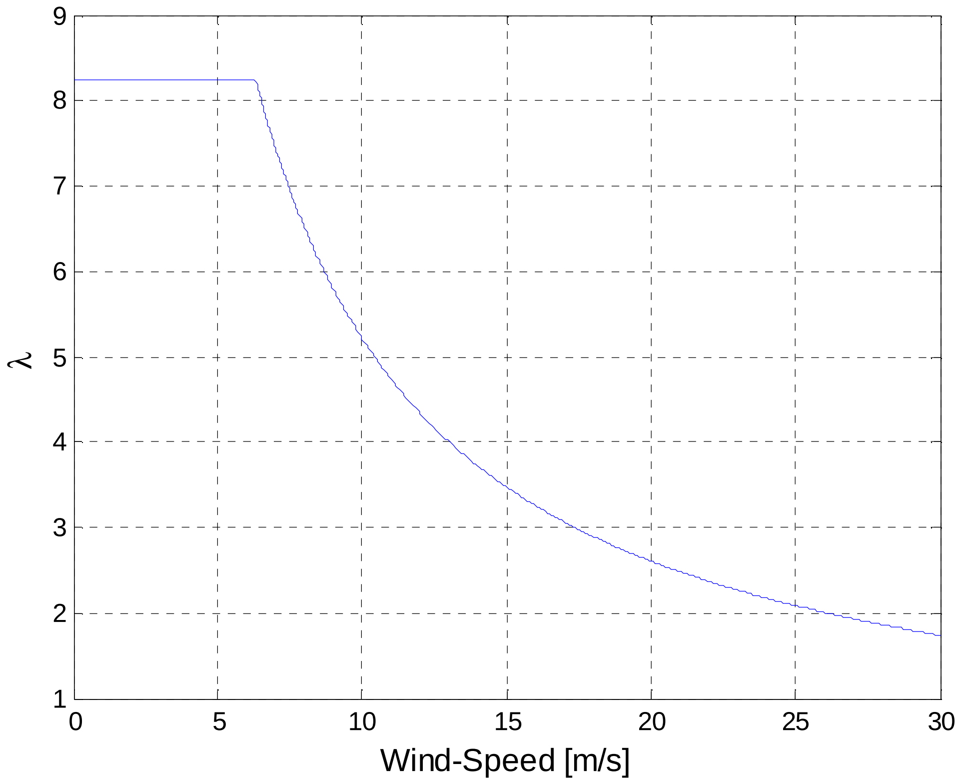


Fig.-6.17 showed the Tip speed ratio - wind speed curve of GE-3.6 MW WT.

In this figure, it showed that the Tip speed ratio is maximum at 8.25 when the wind speed is increased the Tip speed ratio is decreased by maintaining relation with equation (6.6).

4. Wind flow/speed model: Wind power fluctuations are relatively complex and stochastic in nature. The wind speed variable is accessible to a user-written model that can be designed to apply various wind fluctuations

Chapter-7

Comparison

Contents overview

7.1 Operation of GE-3.6 MW Wind Turbine:

Electricity is produced from wind turbine by conversion of kinetic energy of wind. But, turbine blade can't extract all kinetic energy from wind. The kinetic energy of a cylindrical air of radius, R traveling with wind speed V_{wind} and corresponding total wind power will be:[3] [4]

$$P_{mech} = \frac{1}{2} * \rho * \pi * R^2 * C_P(\lambda, \beta) * V_{WIND}^3$$

Where:
ρ_{AIR} = Air density (kg/m^3) =1.225 kg/m^3
R = Rotor Radius (m)
V_{WIND} = Wind speed (m/s)

At high wind speeds, the mechanical power with optimal power efficiency coefficient, C_p, will exceed the nominal power for which the wind turbine is designed. So, it is essential to reduce the mechanical power by turning the blades away from the optimal pitch angle. It is possible to do either out of the wind or up against the wind.

By pitch control: If the blades are turned out of the wind, the lift on the blades is gradually reduced. This control requires a relatively large change in pitch angle which in turn it reduce power significantly.

By active stall control: If the blades are turned up against the wind, the turbine blades will stall and thus automatically reduce the lift on the turbine blades. This effect is obtained with a relatively small change in pitch angle. This control requires a more accurate control of the pitch angle because of the high angular sensitivity.

GE-3.6 MW WTG Model *(Appendix-Model-W-01 fig.-7.0),* here two models are described in two different categories (1) Pitch controller inactive (***(Appendix, model-W-03, fig.-7.1.2)***) and (2) Pitch controller active (***(Appendix, model-W-02, fig.-7.1.1)***). Both model is run in de-rated power by applying 5 to 7 deg pitching the blades virtually in simulation (Note- generally, electrical power as well as rotor speed will be disturbed due to pitching the blade) and then applied the desired step input (by adding step function in the model-Appendix-7.2) to increase the power. Here, a clear picture between using Pitch controller and without pitch controller is shown.

7.1.1 With Pitch Control:

The following figure-7.1 represents the Aerodynamic power, Electrical Power and corresponding rotor speed in pu at 0.5 (≅0) pitch angle and using high wind speed (12 m/s) and no wind step applied in this model. ***(Appendix, model-W-02, fig.-7.1.1)***

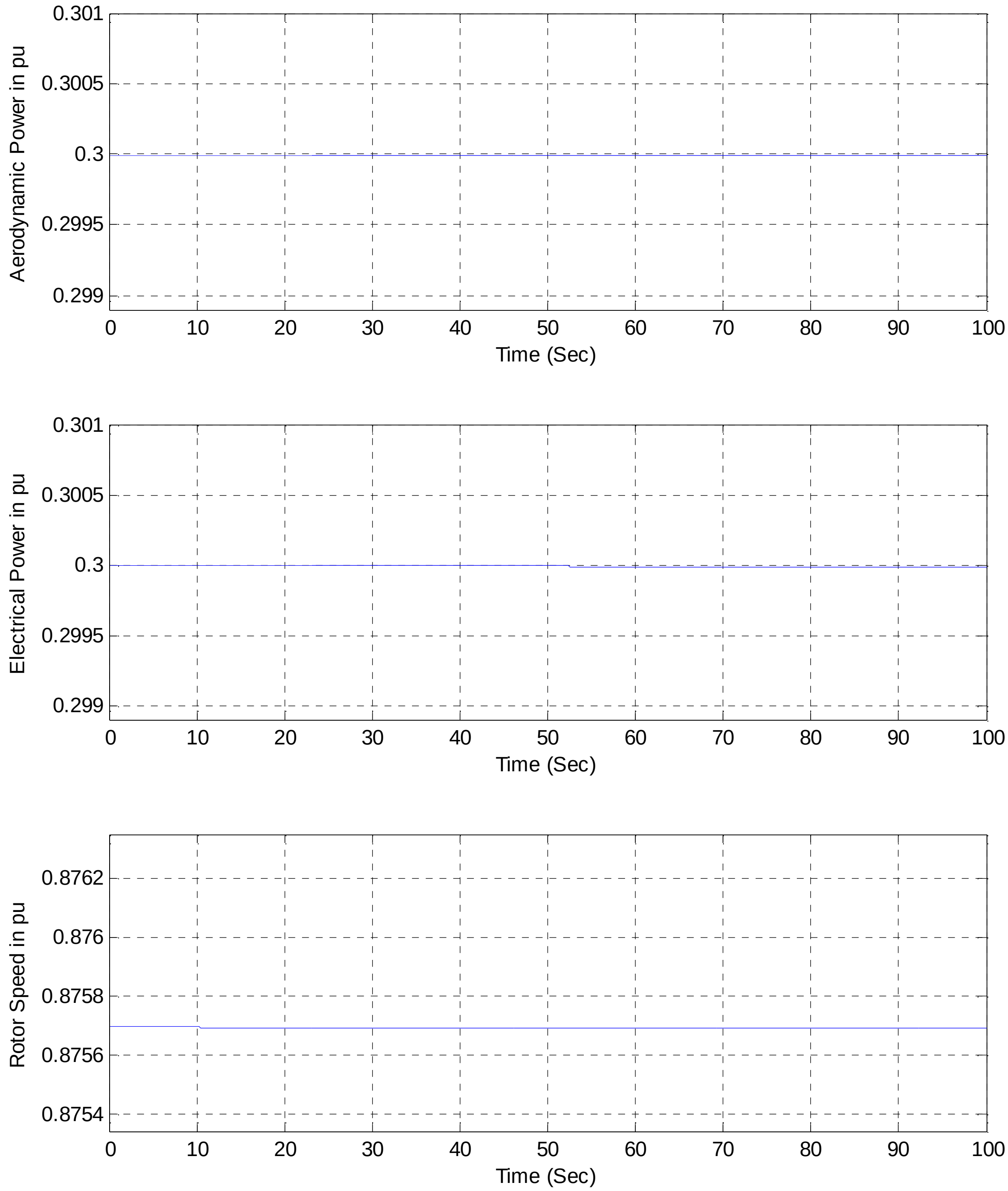
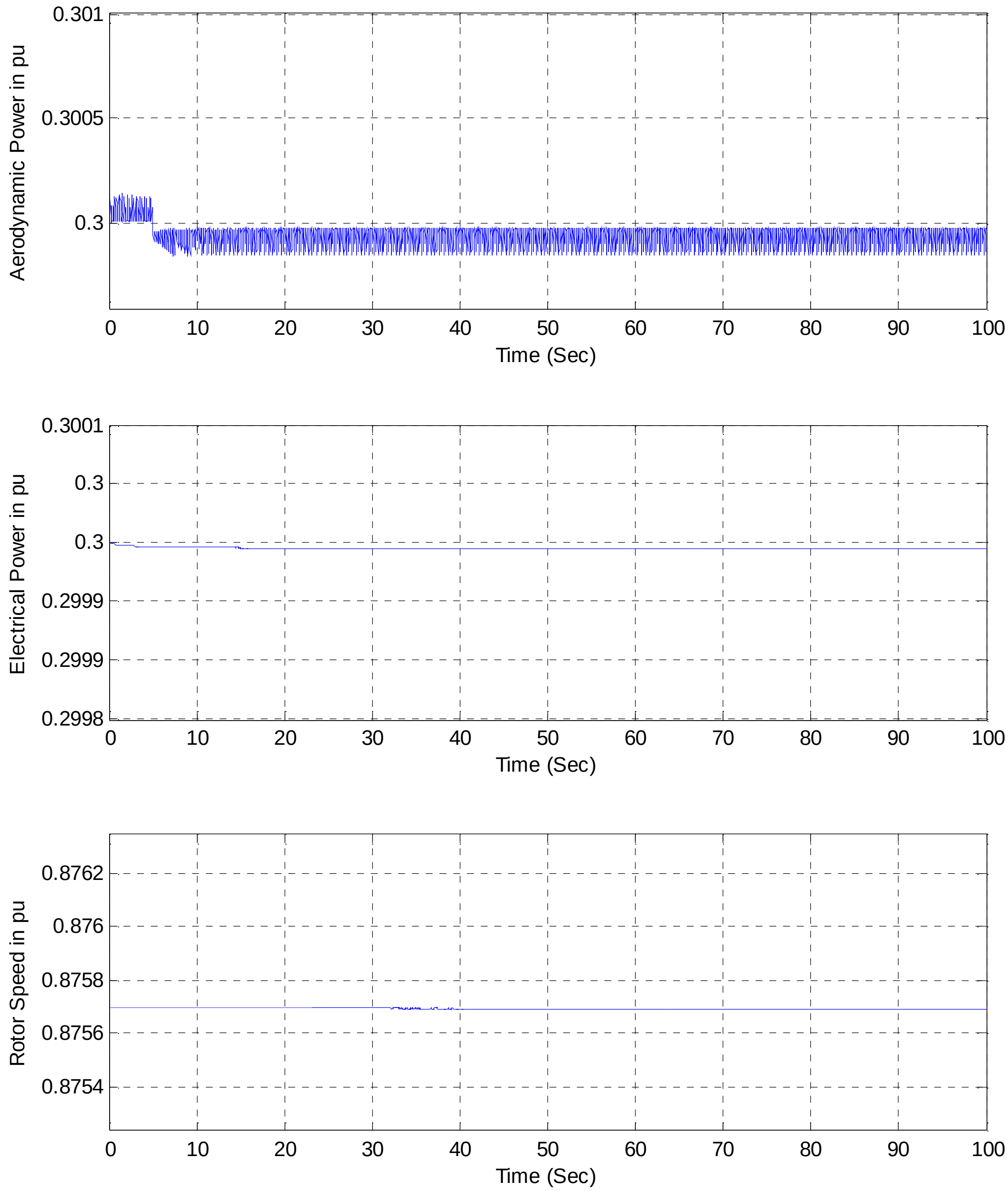


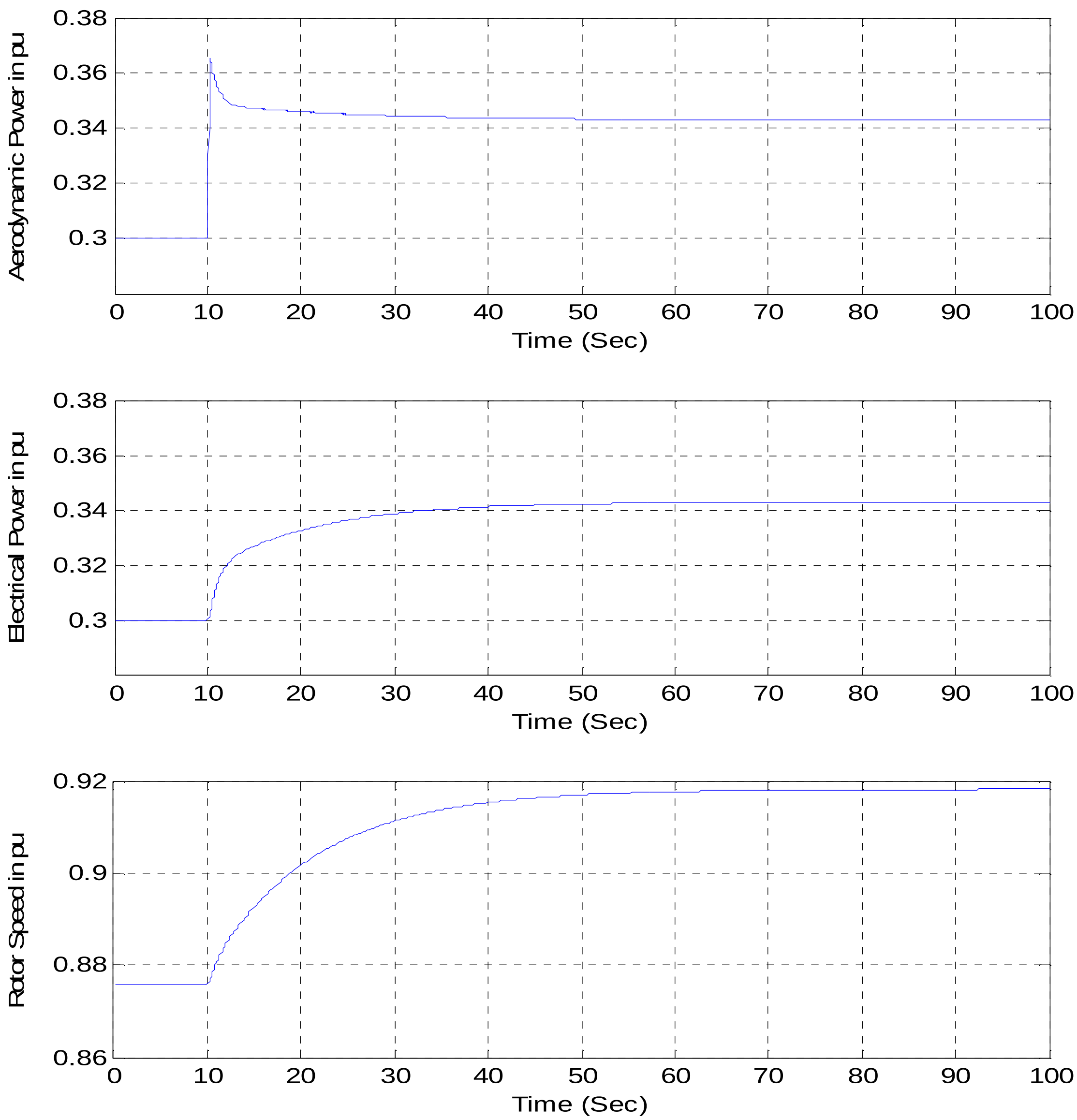
Fig.-7.1 represents the Aerodynamic power, Electrical Power and corresponding rotor speed respectively.

The following figure-7.2 represents the Aerodynamic power, Electrical Power and corresponding rotor speed in pu at 05 pitch angle and using high wind speed (12 m/s) and no wind step applied in this model.



<u>Fig.-7.2</u> represents the Aerodynamic power, Electrical Power and corresponding rotor speed respectively.

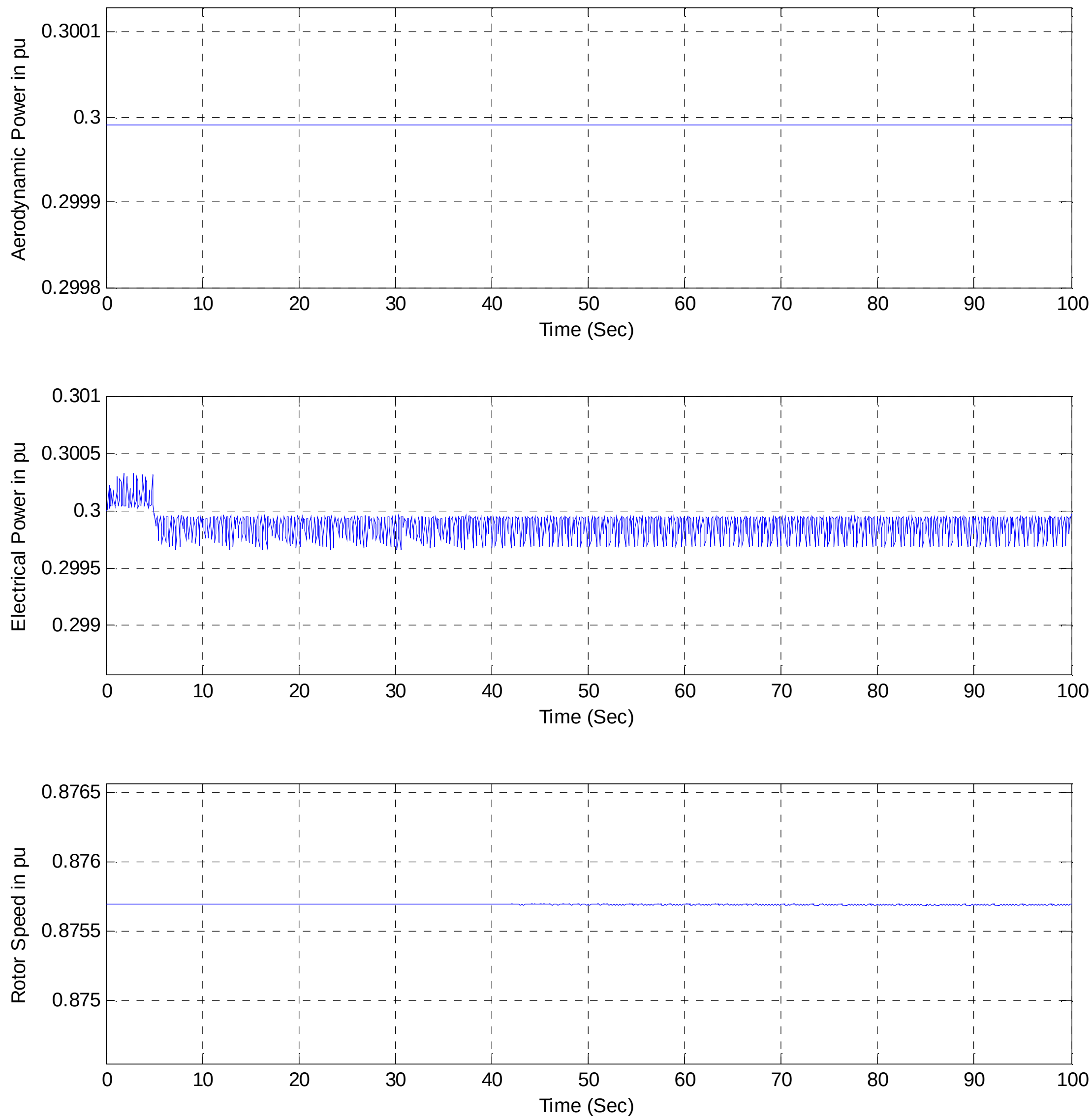
<u>Step Input</u>: In this model ***(Appendix, model-W-02, fig.-7.1.1)*** we applied the step input (3) in the step function to increase the Aerodynamic power, Electrical Power and corresponding rotor speed**.** The following figure-7.3 represents the Aerodynamic power, Electrical Power and corresponding rotor speed.



<u>Fig.7.3</u> represents the Aerodynamic power has increased 0.3 to 0.342 i.e. the Aerodynamic power increased 14% and it reached the steady state level within 30 sec, Electrical Power from 0.3 to 0.342 i.e. the Electrical Power increased 14% and it reached the steady state level within 43 sec and corresponding rotor speed from 0.873 to 0.92 i.e. rotor speed increased 6% and it reached the steady state level within 52 sec respectively.

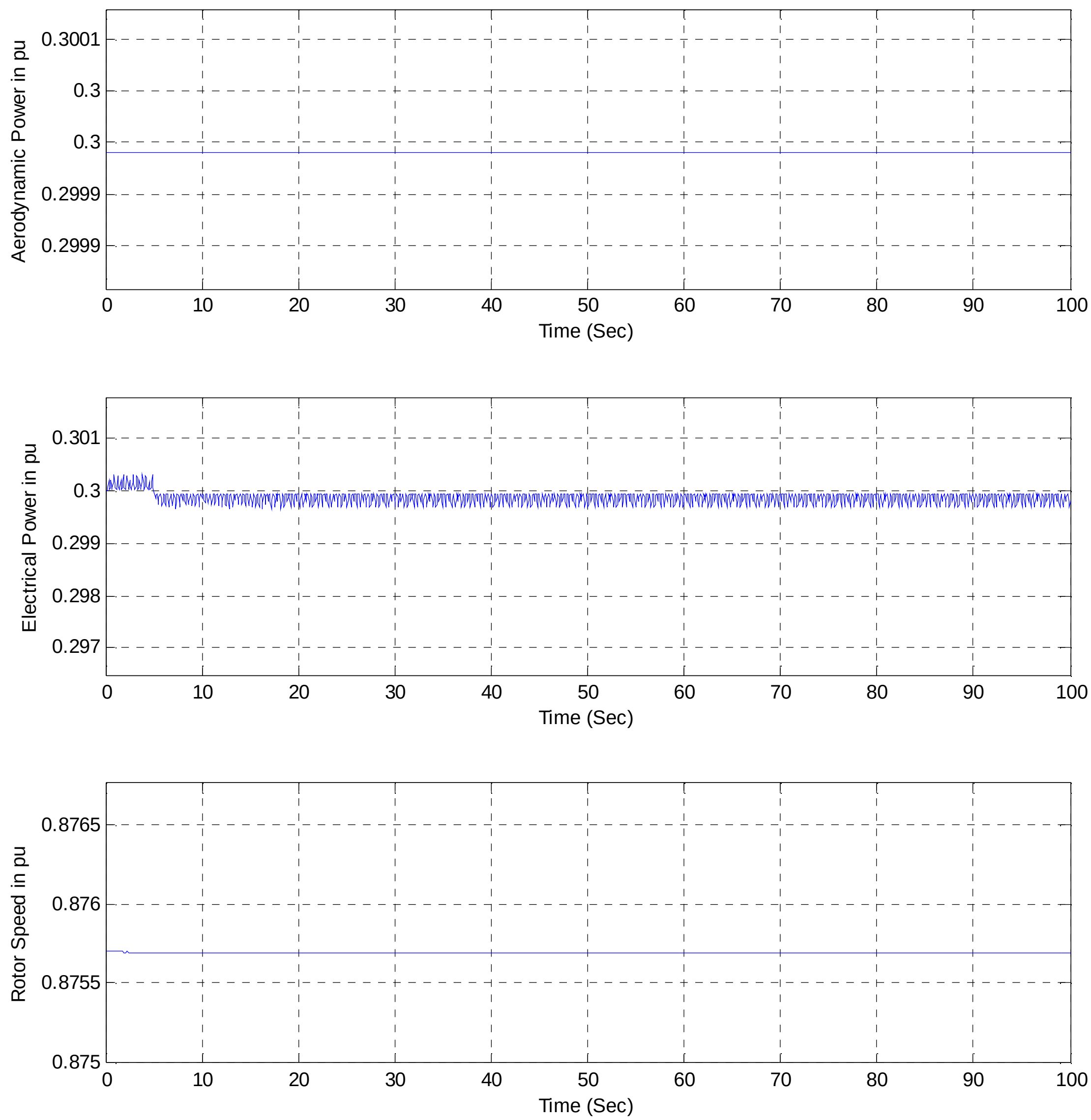
7.1.2 Without Pitch Control:

The following figure-7.4 represents the Aerodynamic power, Electrical Power and corresponding rotor speed in pu at 0.5 (≅0) pitch angle and using high wind speed (12 m/s) and no wind step applied in this model. ***(Appendix, model-W-03, fig.-7.1.2)***



<u>Fig.-7.4</u> represents the Aerodynamic power, Electrical Power and corresponding rotor speed respectively.

The following figure-7.5 represents the Aerodynamic power, Electrical Power and corresponding rotor speed in pu at 05 pitch angle and using high wind speed (12 m/s) and no wind step applied in this model.



<u>Fig.-7.5</u> represents the Aerodynamic power, Electrical Power and corresponding rotor speed respectively.

<u>Step Input</u>: In this model, we applied the step input (3 decimal values) in the step function to increase up the Aerodynamic power, Electrical Power and corresponding rotor speed**.** The following figure-7.6 represents the Aerodynamic power, Electrical Power and corresponding rotor speed. ***(Appendix, model-W-03, fig.-7.1.2)***

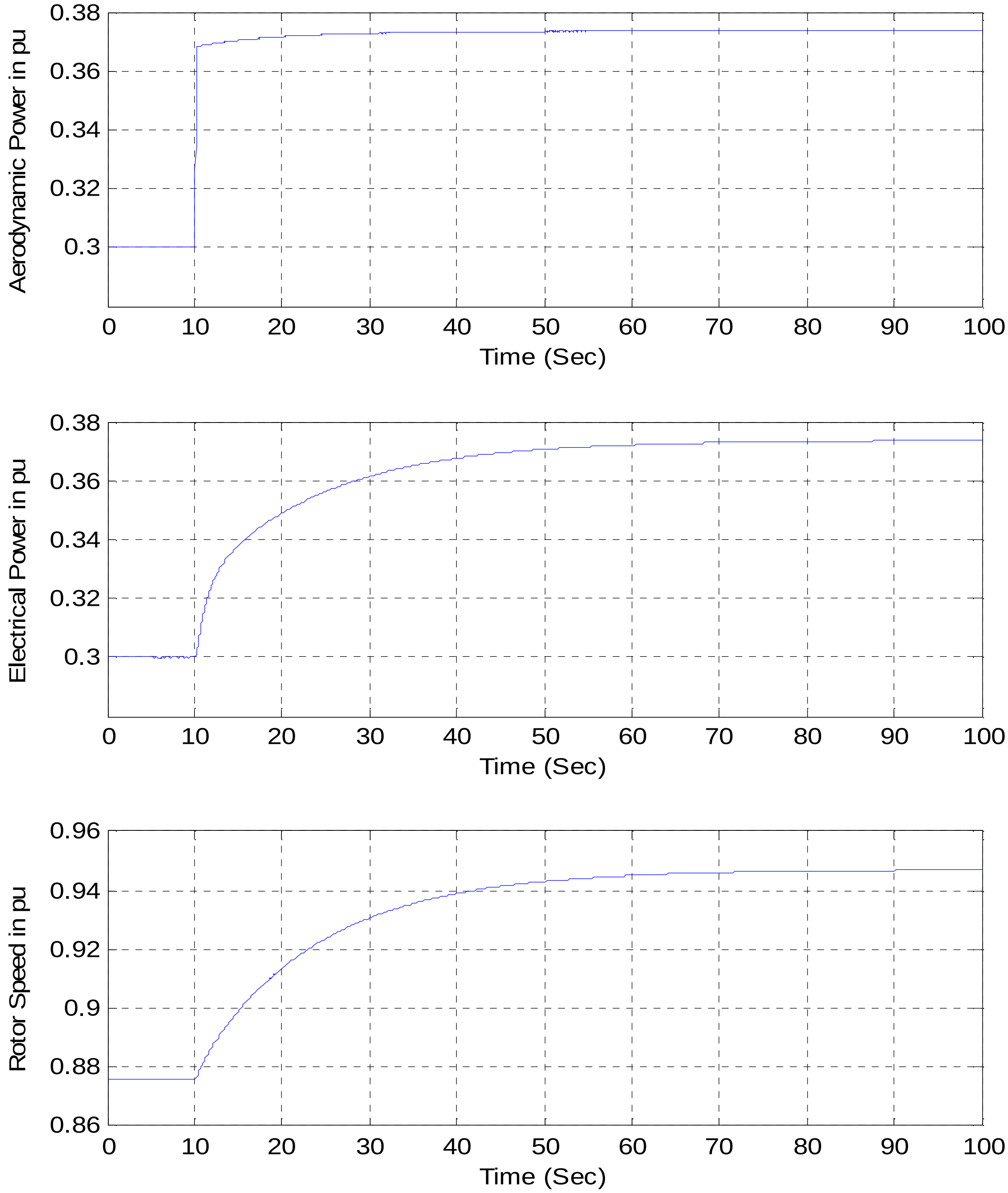


Fig.7.6 represents the Aerodynamic power has increased 0.3 to 0.375 i.e. the Aerodynamic power increased 25% and it reached the steady state level within 20 sec which 10 sec. less than with pitch controller system, Electrical Power from 0.3 to 0.375 i.e. the Electrical Power increased 25% and it reached the steady state level within 55 sec that 12 sec more than with pitch controller system and corresponding rotor speed from 0.876 to 0.947 i.e. rotor speed increased 8% and it reached the steady state level within 62 sec respectively.

In "without Pitch Control system" the Aerodynamic power and Electrical Power is 11% and rotor speed is 2% more than the "with Pitch Control system".

The following figure-7.7 described the comparison of Aerodynamic power and Electrical Power of GE-3.6 WT model with pitch control and without pitch control:

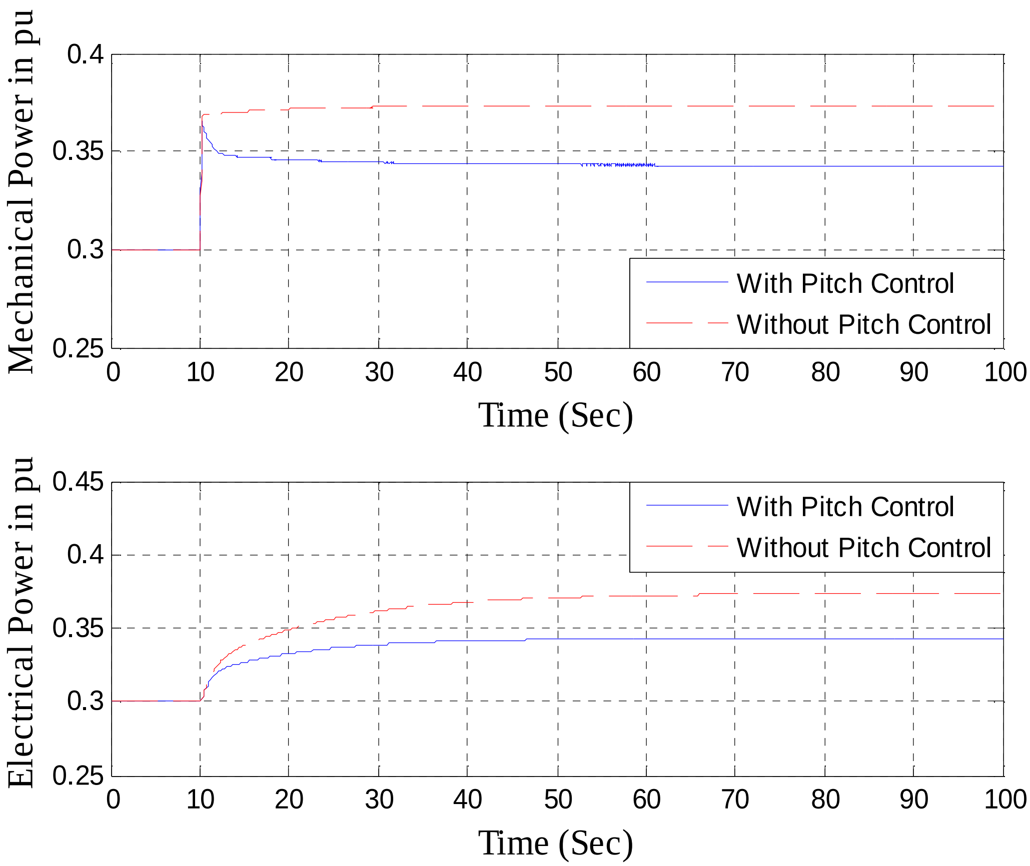


Fig.7.7 represents that the Aerodynamic Power "without pitch control system" in this model more power and taken less time to reach steady state position than "with pitch control system" and corresponding Electrical power "without pitch control system" in this model more power and taken more time to reach steady state position than "with pitch control system".

The following figure-7.8 described the comparison of Speed Deviation and Pitch Angle of GE-3.6 WT model with pitch control and without pitch control:

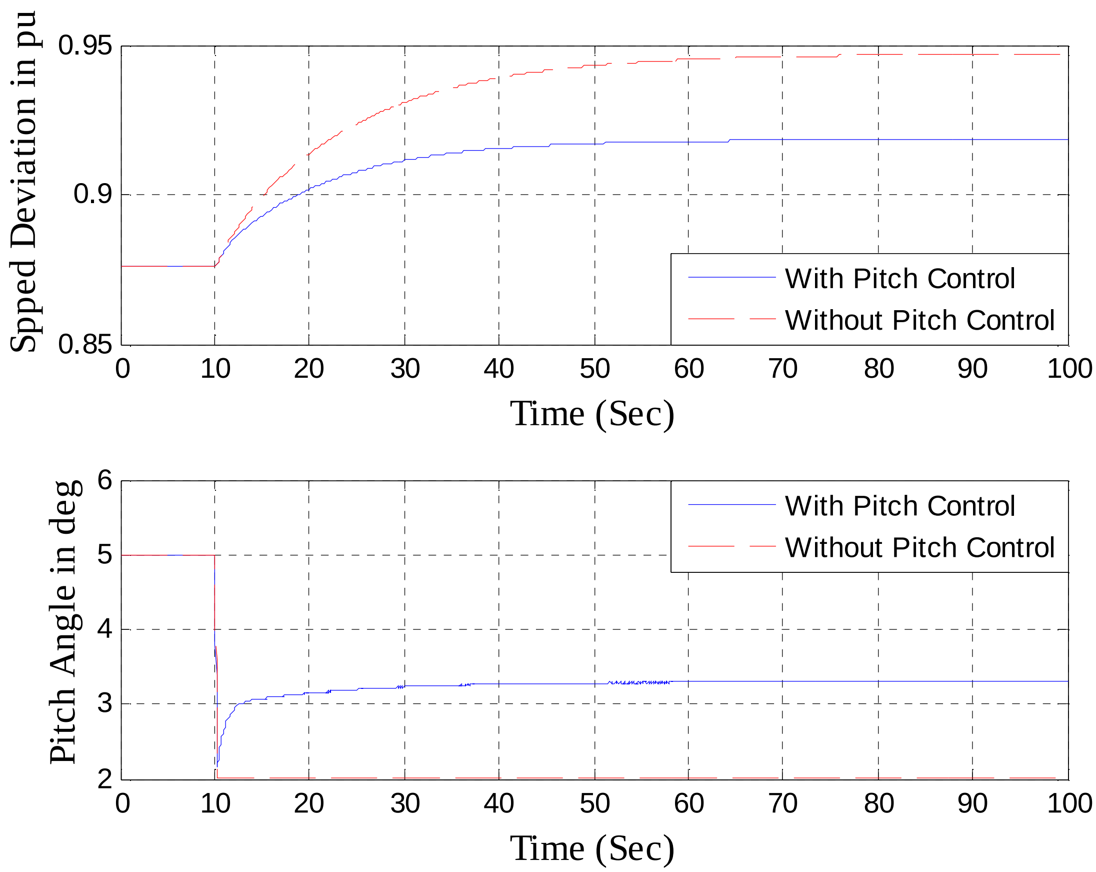


Fig.-7.8 represents that the Speed Deviation in "without pitch control system" in this model taken longer time to reach steady state position than "with pitch control system" and Pitch angle in "with pitch control system" should be same as "without pitch control system" but 60% more.

7.2 Turbine responses of the conventional Power plant

7.2.1 Turbine response of Hydro power unit:

The following 7.10 figure shows the Turbine response of Hydro Power Plant against the step change in Gate position. [7] [8]

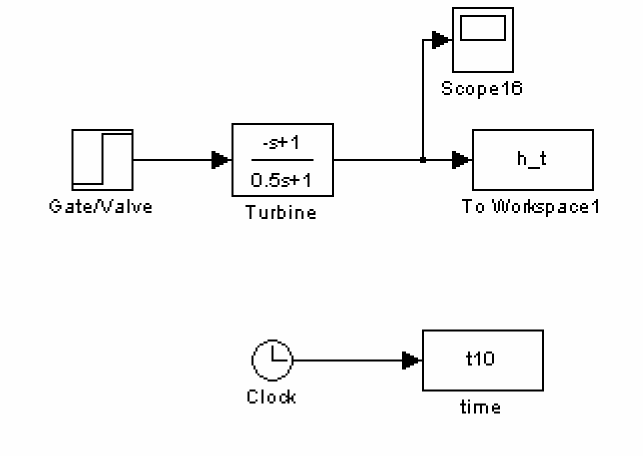


Fig.-7.9 represents the Turbine unit of Hydro Power plant.

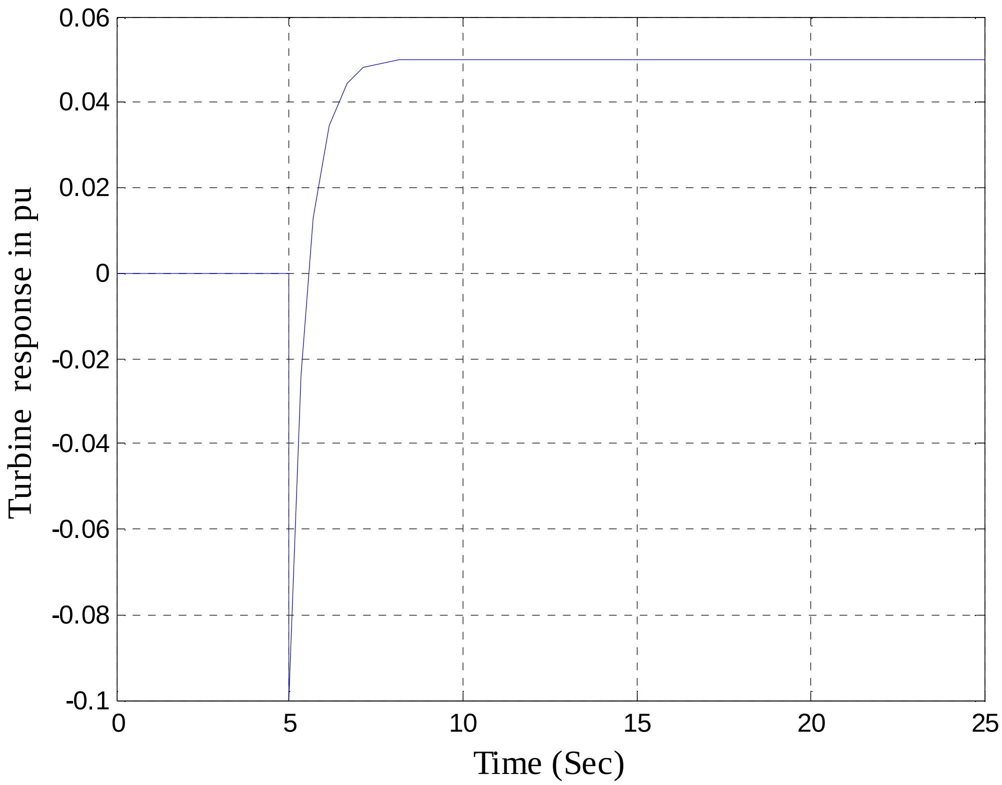


Fig.-7.10 represents Turbine response of Hydro Power Plant against the step change in Gate position.

7.2.2 Turbine response of Steam power unit:

The following 7.12 figure shows the Turbine response of Steam Power Plant against the step change in Gate position.

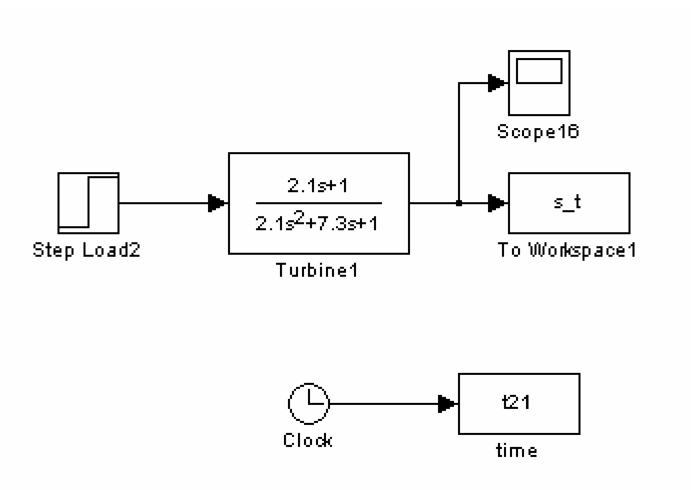


Fig.-7.11 represents the Turbine unit of steam Power plant.

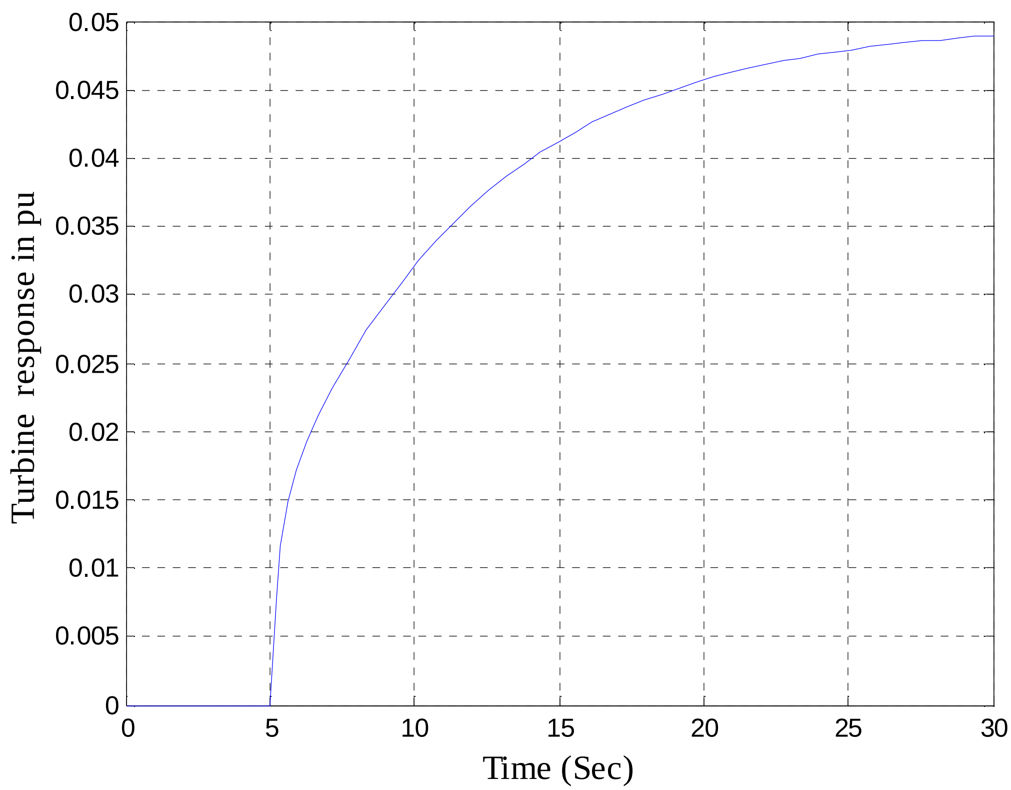


Fig.-7.12 represents Turbine response of Steam Power Plant against the step change in Gate position.

7.2.3 Turbine response of Thermal power unit:

The following 7.14 figure shows the Turbine response of Thermal Power Plant against the step change in Gate position.

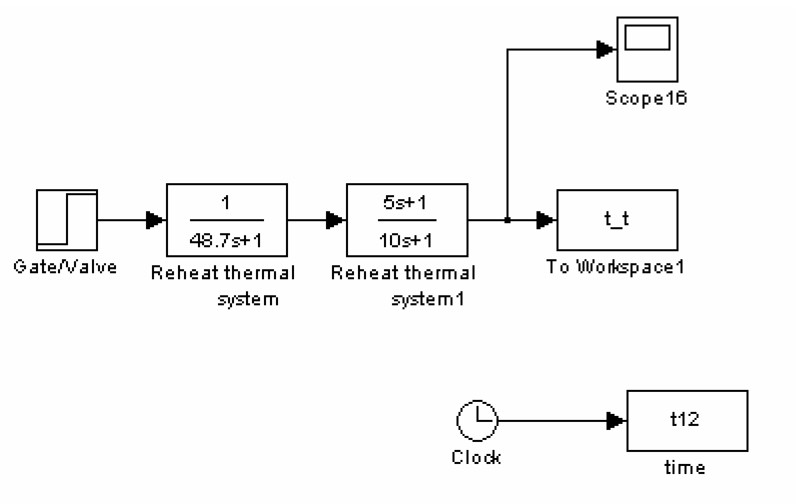


Fig.-7.13 represents the Turbine unit of Thermal Power plant.

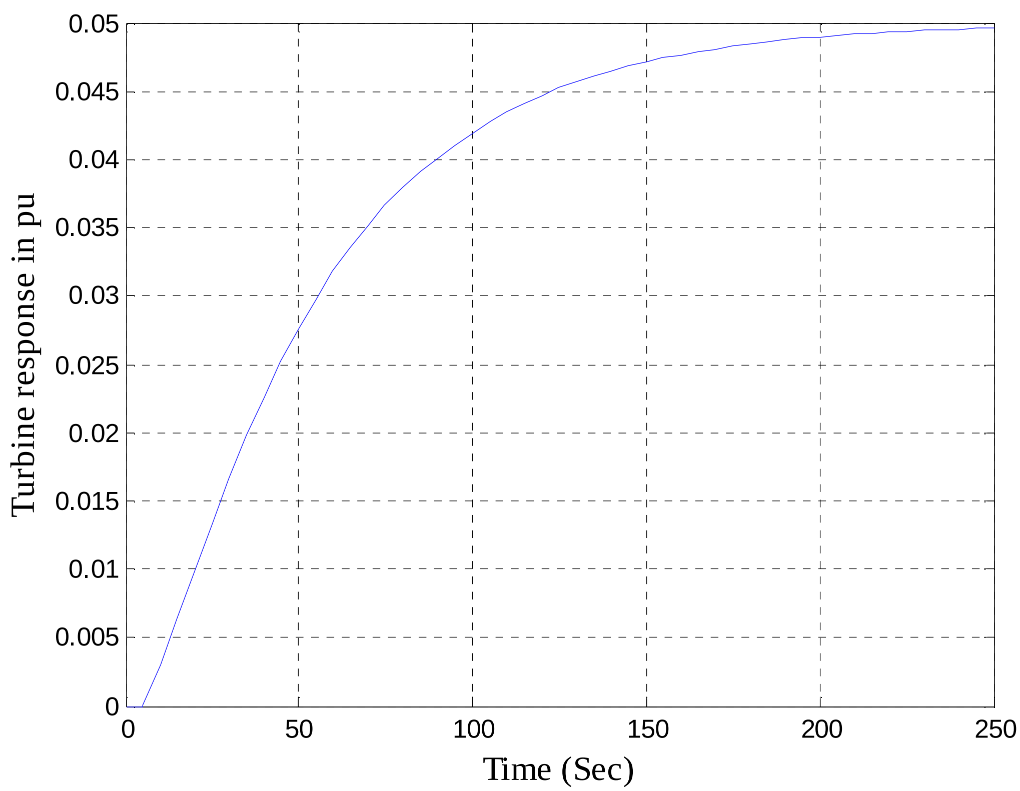


Fig.-7.14 represents Turbine response of Thermal Power Plant against the step change in Gate position.

7.3 Comparison of Turbine responses of Conventional Power unit with Wind Energy

The following 7.15 figure shows the Turbine response as a Mechanical Power of Conventional Power unit with wind energy against 5% Gate position disturbance.

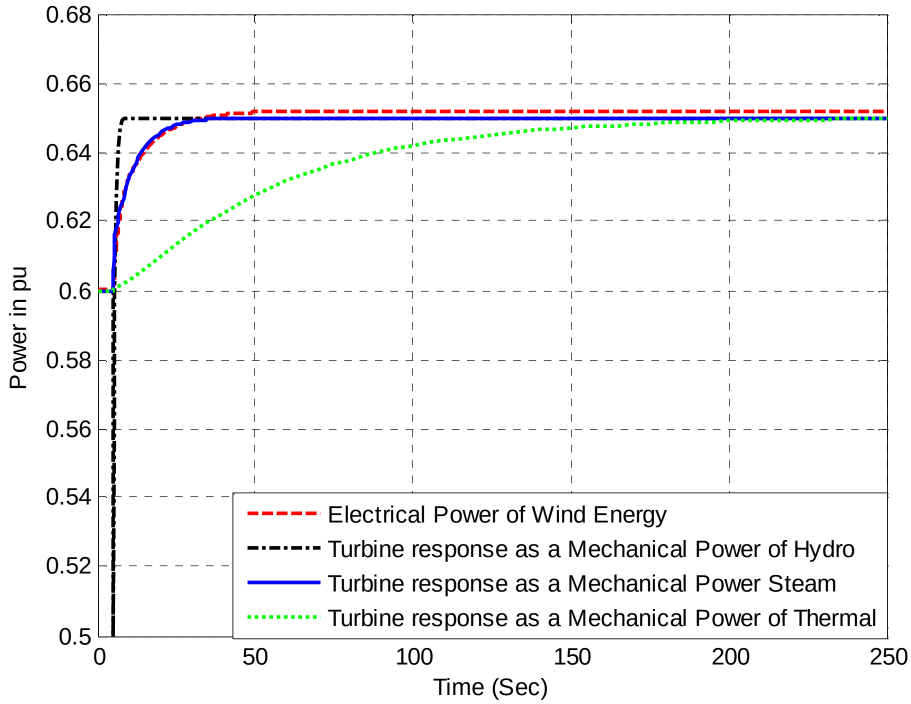
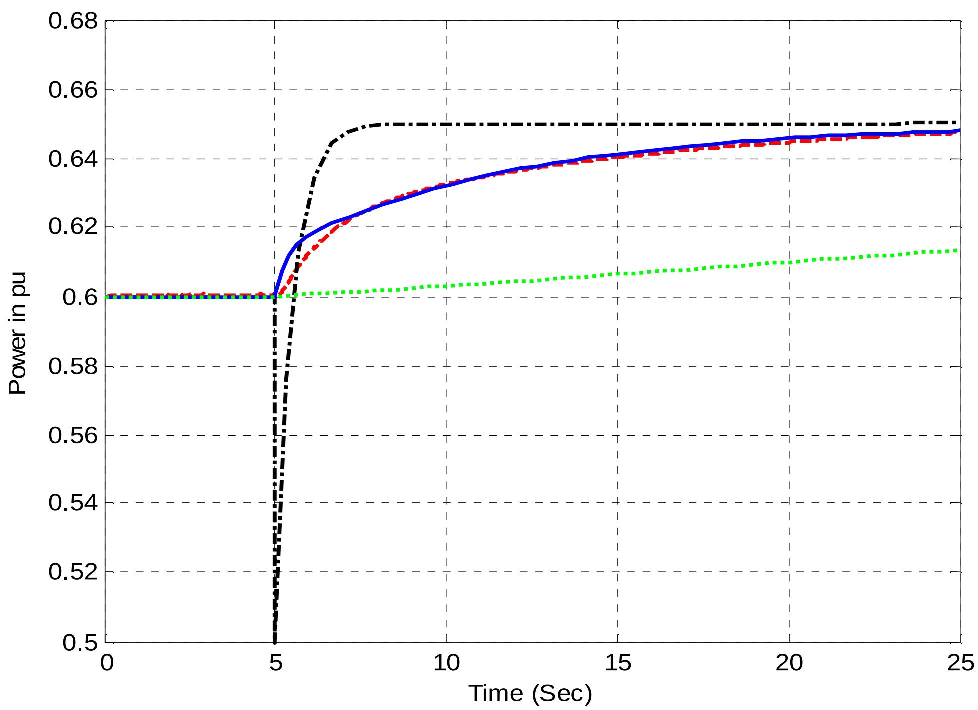


Fig.-7.15 represents the Turbine responses of Conventional Power plant with Wind energy.

Zoom Position to visualize the Turbine response of Hydro power.



7.4 Statement of the comparison

Here, it was compared the combined operation with Wind Energy (Electrical power) to Conventional power plant- Hydro, Thermal & Steam (Mechanical power) by increasing the load of the power system in such way, when the system load is increased (5% load disturbance); power of the entire system goes unbalanced and corresponding system frequency also decreases from its nominal value. According to primary frequency control (Local automatic control which delivers reserve power in opposition to any frequency change), the conventional power plant acquire time (Response and Settling time of Mechanical power of Hydro, Thermal & Steam unit take 04-25 sec and 20-68 sec respectively to stabilize the system) to supply the demand power in order to balance the entire system which in turn will balance the system frequency. During this transition time power to the system can be supplied from the wind turbine to meet the raised power and to stabilize the frequency. Thus wind turbines can be used as a source for limited ancillary service to the system where the Response and Settling time of Electrical Power of the wind turbine are 03 sec – 09 sec and 08 sec –38 sec respectively.

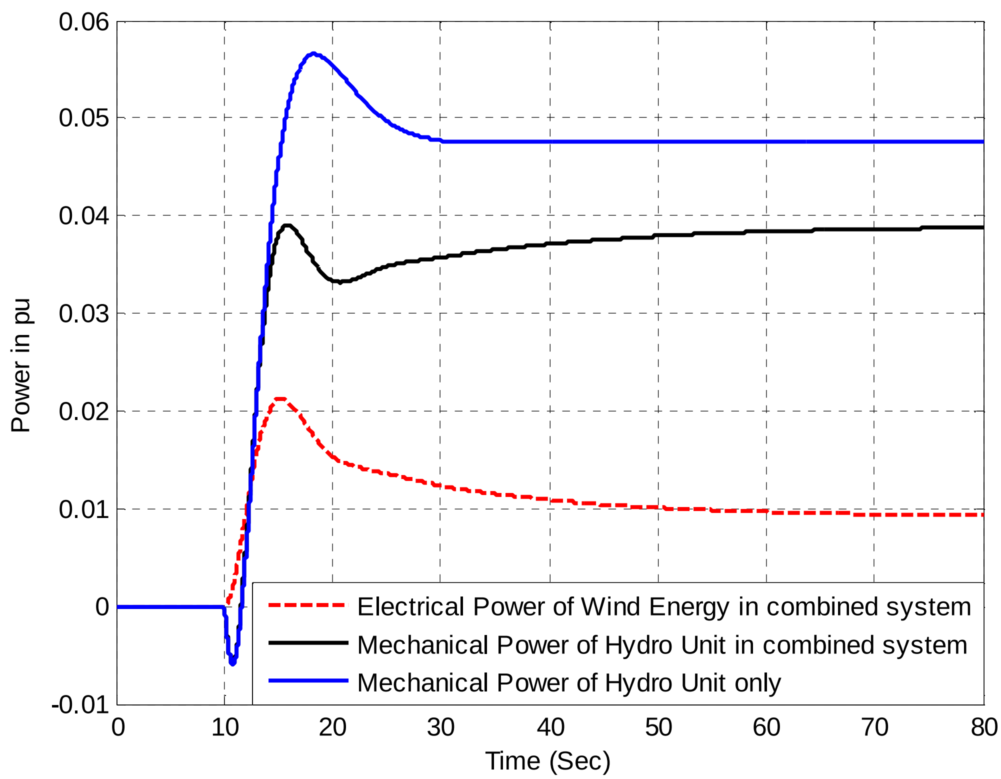
Normally Wind Energy is connected to the power system like other power plants. We propose to run the wind turbines at a de-rated power (i.e. a condition where the wind turbine is run below its actual rated capacity using pitching the blades) during normal operation to the grid. When the demand in the grid increases a transition occurs, where the conventional power plant takes time to meet the increased demand, at this moment wind turbine comes in provide to meet the demand and keep the system frequency stable.

7.5 Comparing the output power of Hydro Power with GE-3.6 MW Wind Turbine:

Combined operation of Hydro power unit by 5% load disturbance with GE-3.6 MW Wind Turbine.

The wind Energy (**GE-3.6 MW WT**) is run without pitch control system (Appendix, Model-WH-02, fig.-7.1.1) at 5 deg angle pitching blades. The step input is applied into GW model from the Hydro power as speed deviation.

Applied 5% step load in Hydro power and corresponding Turbine mechanical power from Hydro and Electrical power from Wind Energy are described in the figure-7.16.



Electrical Power penetration of Wind=20%
Mechanical Power penetration of Hydro=80%

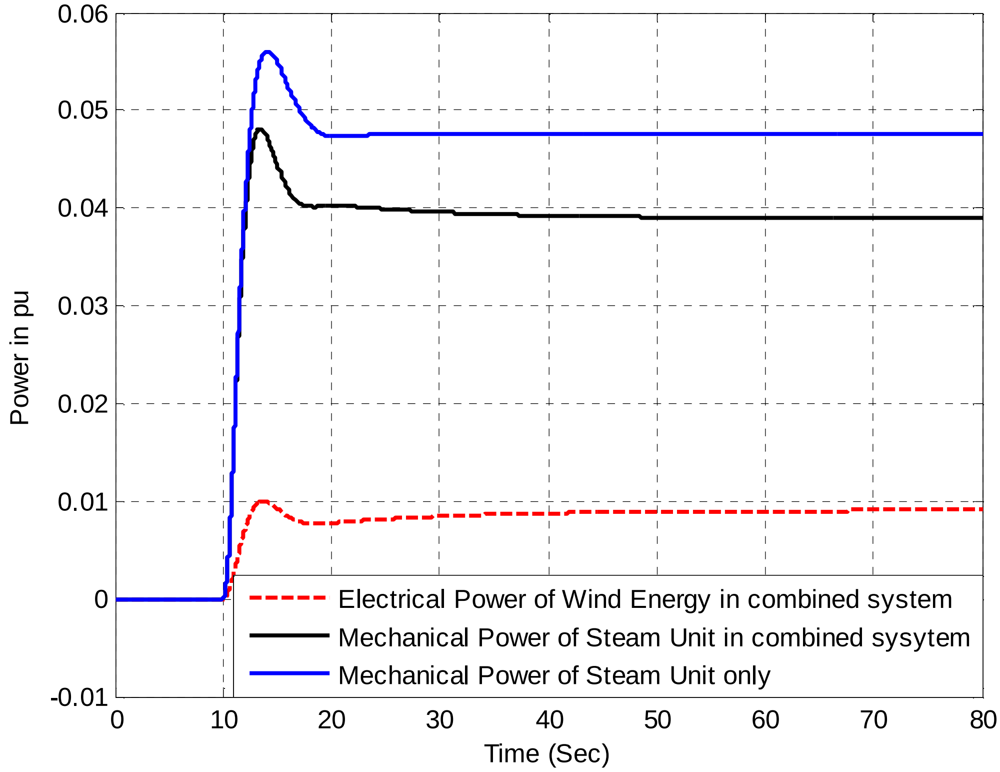
Fig.-7.16 showed the contribution of power- Electrical Power of Wind (red) and Mechanical Power of Hydro (black) for 5% load disturbance and corresponding rise time and settling time for both Wind & Hydro power are figured in 8.1 results.

7.6 Comparing the output power of Steam Power with GE-3.6 MW Wind Turbine.

Combined operation of Steam Power unit by 5% load disturbance with GE-3.6 MW Wind Turbine.

The wind Energy (**GE-3.6 MW WT**) is run without pitch control system (Appendix, Model-WS-03, fig.-7.1.2) at 5 deg angle pitching blades. The step input is applied into GW model from the Steam power as speed deviation.

Applied 5% step load in Steam power and corresponding Turbine mechanical power from Steam and Electrical power from Wind Energy are described in the figure-7.17.



Electrical Power penetration of Wind=20%
Mechanical Power penetration of Steam=80%

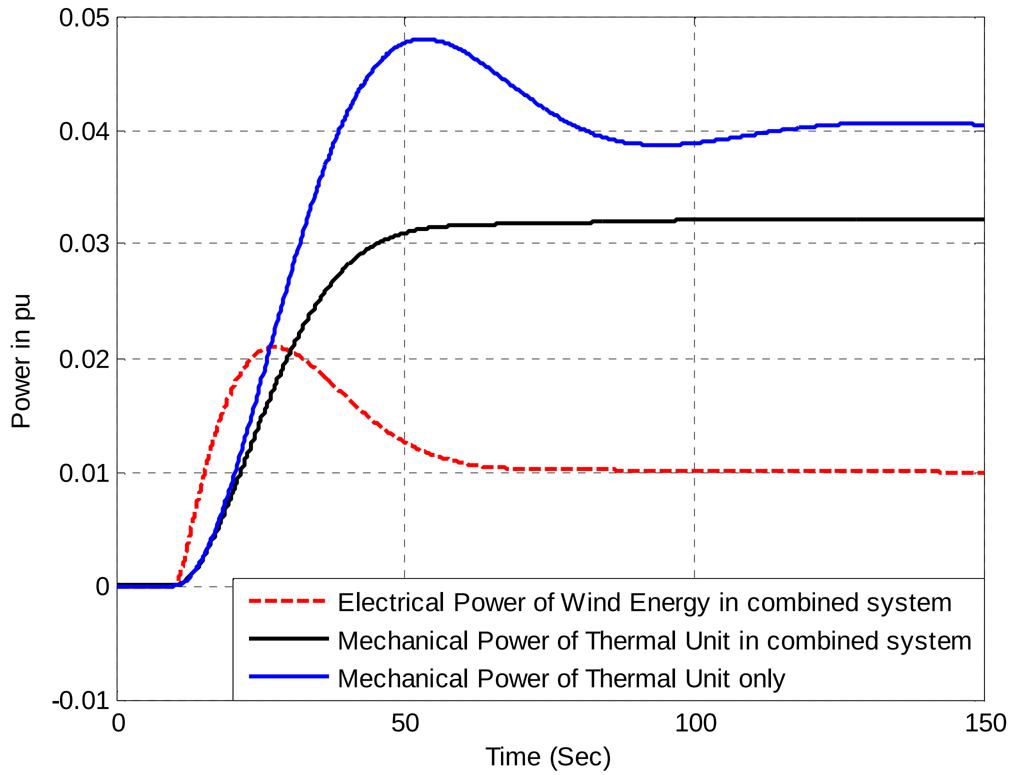
Fig.-7.17 showed the contribution of power- Electrical Power of Wind (red) and Mechanical Power of Steam (black) for 5% load disturbance and corresponding rise time and settling time for both Wind & Steam power are figured in 8.1 results.

7.7 Comparing the output power of Thermal Power with GE-3.6 MW Wind Turbine:

Combined operation of Thermal Power unit by 5% load disturbance with GE-3.6 MW Wind Turbine.

The wind Energy (**GE-3.6 MW WT**) is run without pitch control system (Appendix, Model-WT-04, fig.-7.1.3) at 5 deg angle pitching blades. The step input is applied into GW model from the Thermal Unit as speed deviation.

Applied 5% step load in Thermal power and corresponding Turbine mechanical power from Thermal and Electrical power from Wind Energy are described in the figure-7.18.



Electrical Power penetration of Wind=20%
Mechanical Power penetration of Thermal=80%

Fig.-7.18 showed the contribution of power- Electrical Power of Wind (red) and Mechanical Power of Thermal (black) for 5% load disturbance and corresponding rise time and settling time for both Wind & Thermal power are figured in 8.1 results.

Chapter-8

Results and Conclusion

Contents overview

8.1 Results

For 5% load disturbance of the conventional power plant, we have identified the following Response Time and Settling Time in combined operation with Wind Energy:

1. Power from Hydro -Wind power Unit:

Hydro Power	*Wind Power*
Response time: 5 sec	*Response time:* 3 sec
Settling time: 20 sec	*Settling time:* 25 sec

Where:
Electrical Power penetration of Wind=20%
Mechanical Power penetration of Hydro=80%

2. Power from Steam-Wind power Unit:

Steam Power	*Wind Power*
Response time: 04 sec	*Response time:* 2 sec
Settling time: 7 sec	*Settling time:* 08 sec

Where:
Electrical Power penetration of Wind=20%
Mechanical Power penetration of Steam=80%

3. Power from Thermal-Wind power Unit:

Thermal Power	*Wind Power*
Response time: 25 sec	*Response time:* 9 sec
Settling time: 68 sec	*Settling time:* 38 sec

Where:
Electrical Power penetration of Wind=20%
Mechanical Power penetration of Thermal=80%

The following table shows the operational sequence of the conventional power plant with Wind power at normal operation and at contingency (load disturbance of the conventional power plant) period.

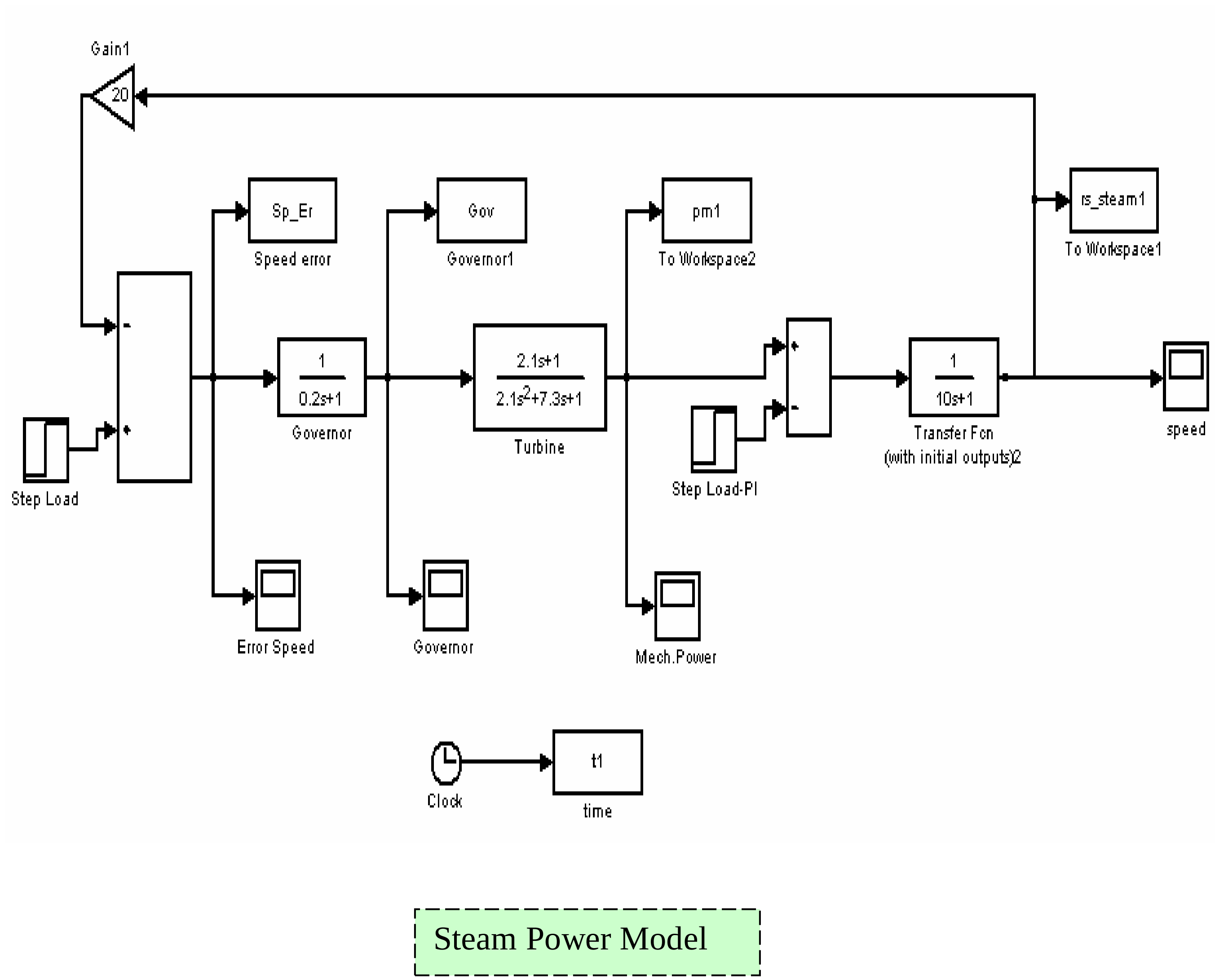
Normal Operation	**At contingency**	**Normal Operation**
❖ Hydro Power	❖ Hydro Power (5% load disturbance) with wind Energy	❖ Hydro Power
❖ Steam Power	❖ Steam Power (5% load disturbance) with wind Energy	❖ Steam Power
❖ Thermal Power	❖ Thermal Power (5% load disturbance) with wind Energy	❖ Thermal Power
❖ Wind Power (De-rated)	❖ Wind Power (power increased at rated level for stabilizing the power of the System)	❖ Wind Power (De-rated)

8.2 Conclusion

- ✓ Thus we have investigated the given wind turbine and response times are compared with other power plants
- ✓ It is found that Wind turbine has a quick response in some case and response equal to that of high capacity power plant
- ✓ It can be used as ‘Limited ancillary’ service
- ✓ In Nordic countries, wind penetration is only 1% and aiming for 20% penetration
- ✓ These results can be used for analyzing Frequency Response of Wind turbines.

Appendix

A. Steam Power Unit
Model-S-01



Open loop transfer function of the system GH(s)=20(1+2.1s)/(1+0.2s)(1+0.2s)(1+7s)(1+10s)

Fig. - 2.1 Model of Steam power unit. [7]

B. Hydro Power model

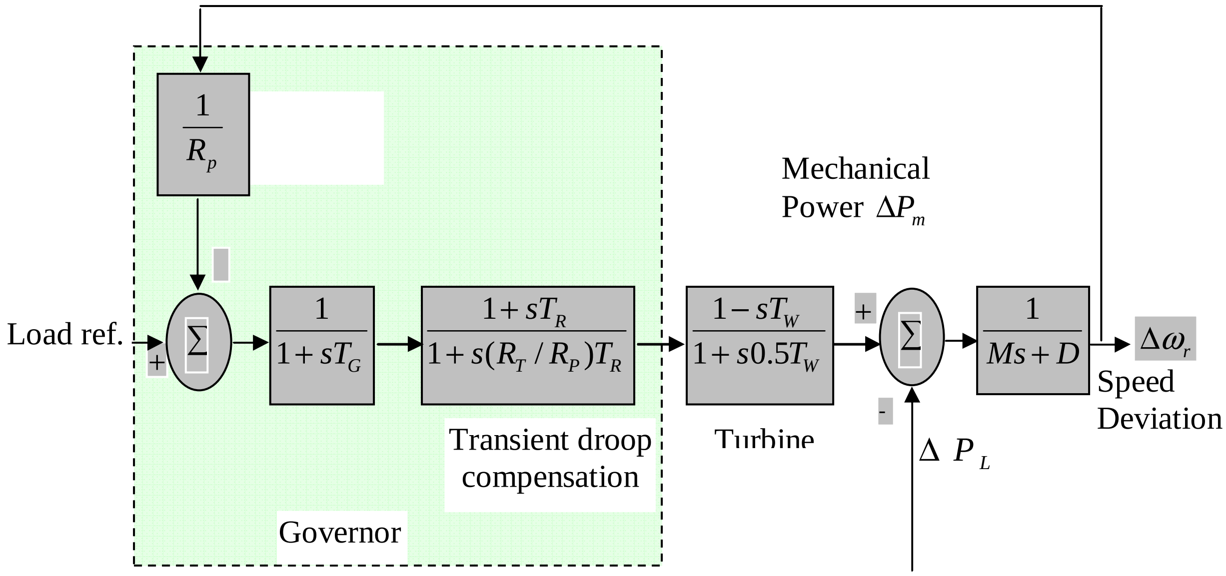
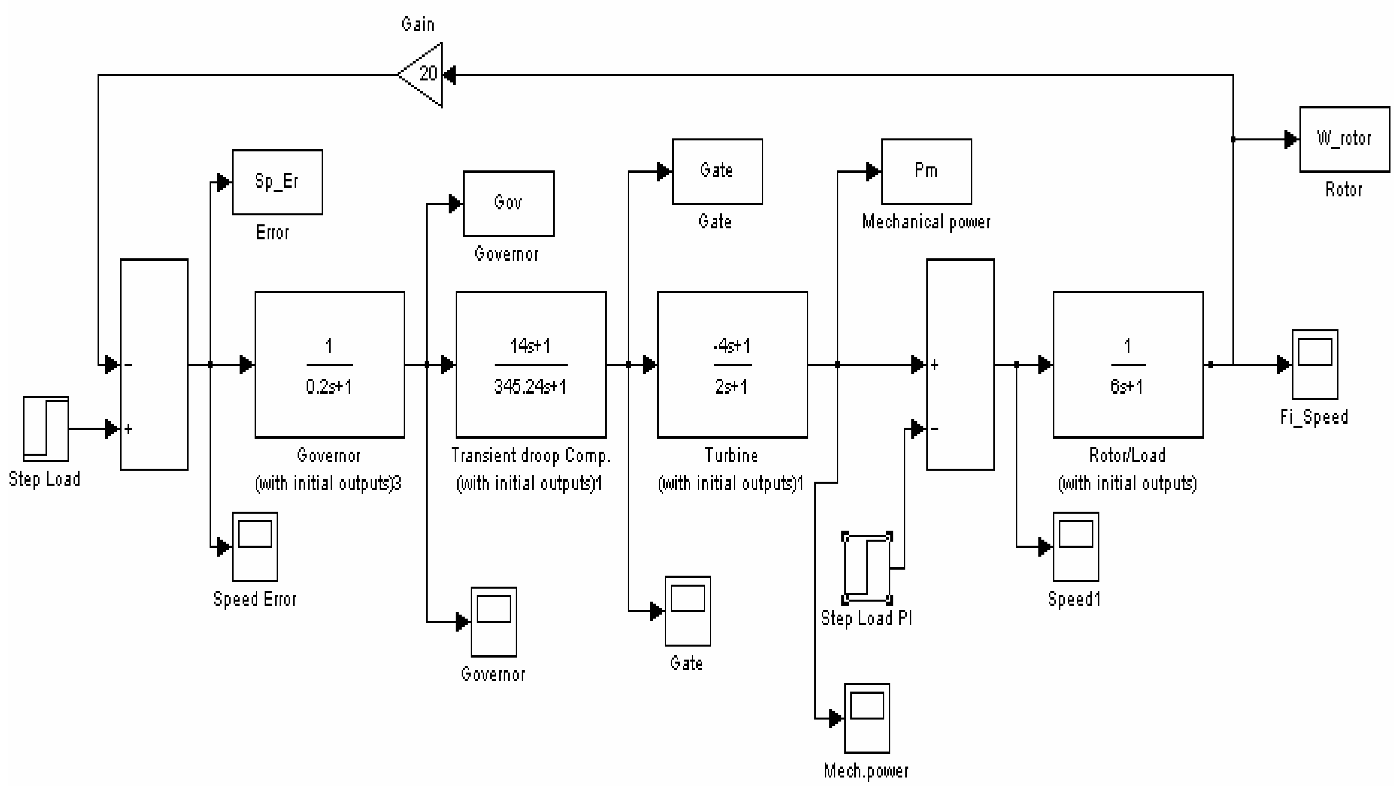


Fig.- 3.1 Simulink Model of Hydroelectric power unit. [7]

Model-H-01



Hydro Power Plant Model

Fig.- 3.1.1 Model of Hydroelectric power unit. [7]

Value of the parameters:

Parameters/ Unit	R_P	R_T	T_W	T_G	T_R	M	D	$\frac{1}{R_P}$
Hydraulic Unit Model	**0.05**	**1.233**	**4.0 s**	**0.20 s**	**14.0 s**	**6.0 s**	**1.0**	**20**

Parameters	
R_P	**Permanent Droop**
R_T	**Temporary Droop**
T_W	**Water Starting Time**
T_G	**Main Servo time constant**
T_R	**Reset time**
M	**Inertia Coefficient**
D	**Damping Constant**
$\frac{1}{R_P}$	**Gain**

Hydro Power unit
Model-H-02

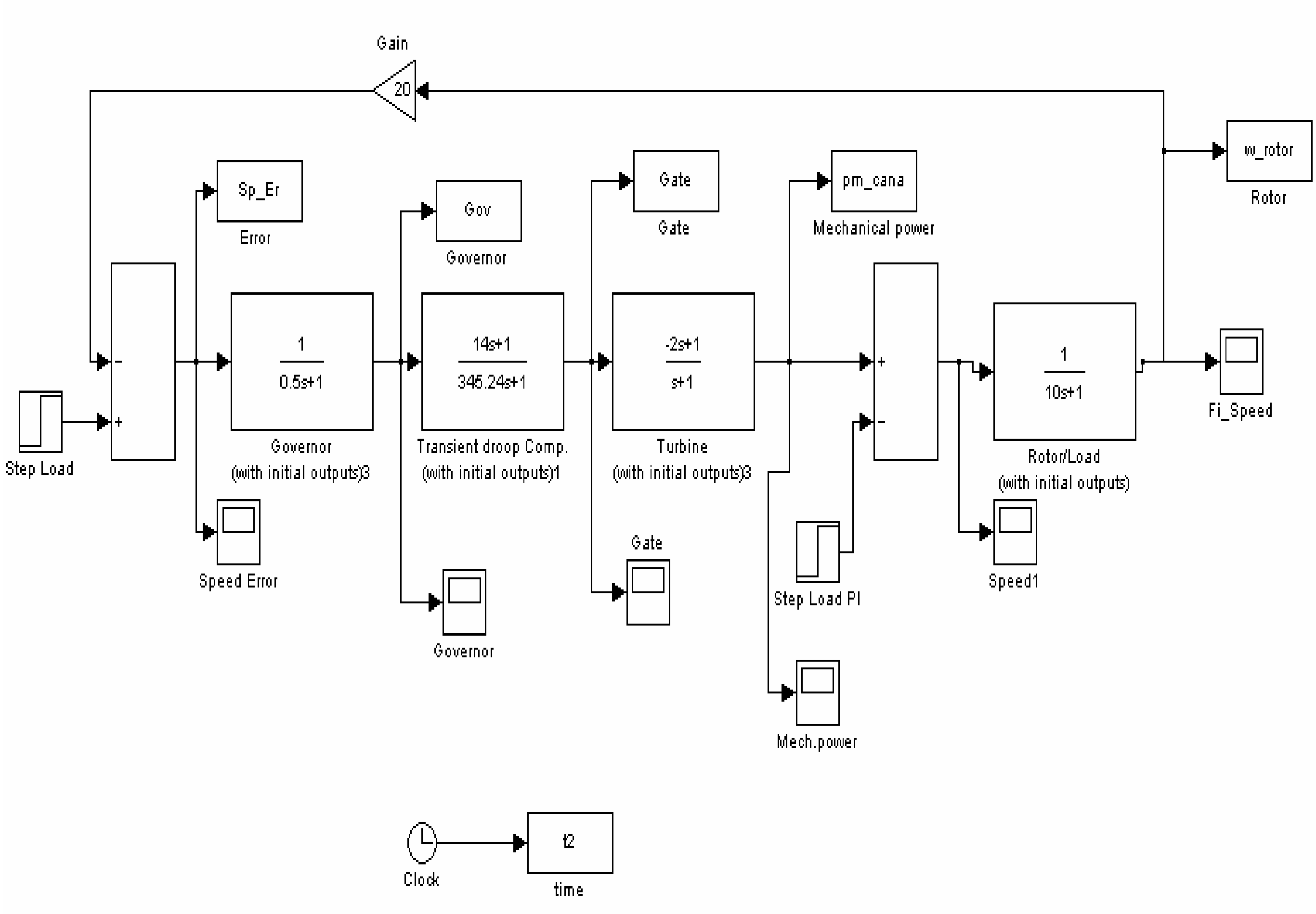


Fig.- 3.1.2 Model of Hydroelectric power unit. [8] [9]

Parameters/ Unit	R_P	R_T	T_W	T_G	T_R	M	D	$\frac{1}{R_P}$
Hydraulic Unit Model	**0.05**	**1.233**	**2.0 s**	**0.50 s**	**14.0 s**	**10.0 s**	**1.0**	**20**

Hydro Power unit

Model-H-03

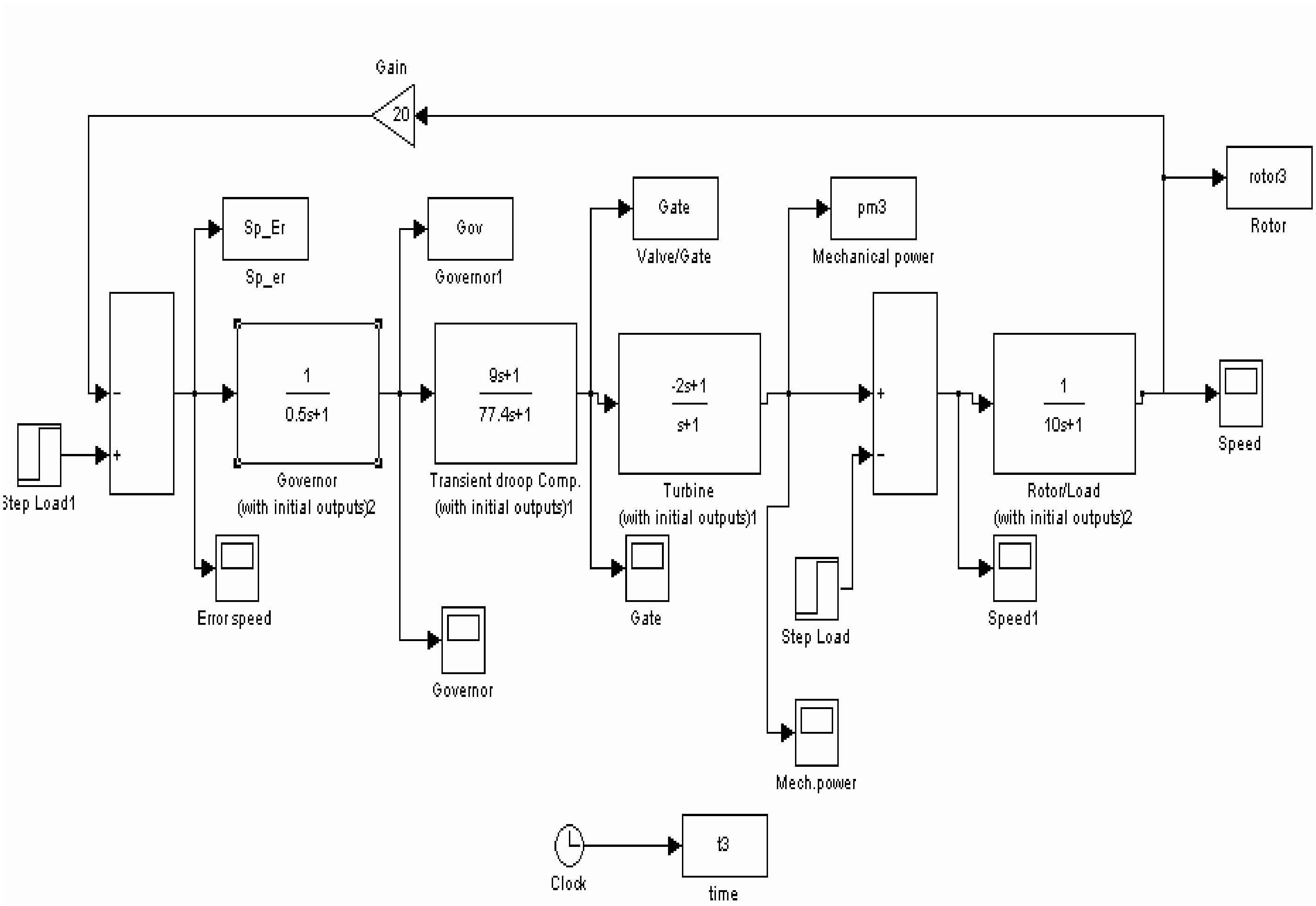
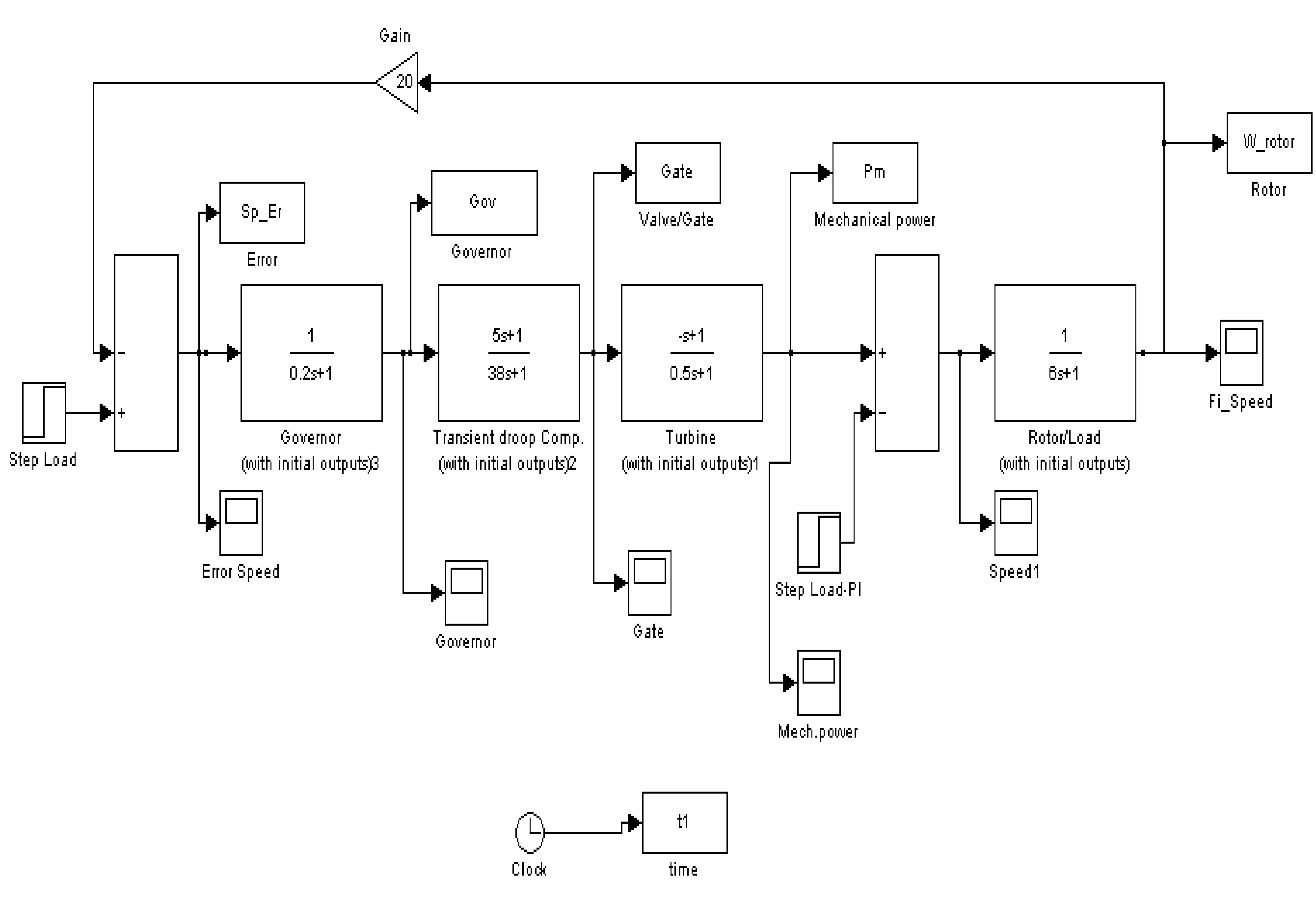


Fig.- 3.1.3 Model of Hydroelectric power unit.

Parameters/ Unit	R_P	R_T	T_W	T_G	T_R	M	D	$\frac{1}{R_P}$
Hydraulic Unit Model	**0.05**	**0.43**	**2.0 s**	**0.50 s**	**9.0 s**	**6.0 s**	**1.0**	**20**

Hydro Power unit

Model-H-04



Transfer Function:

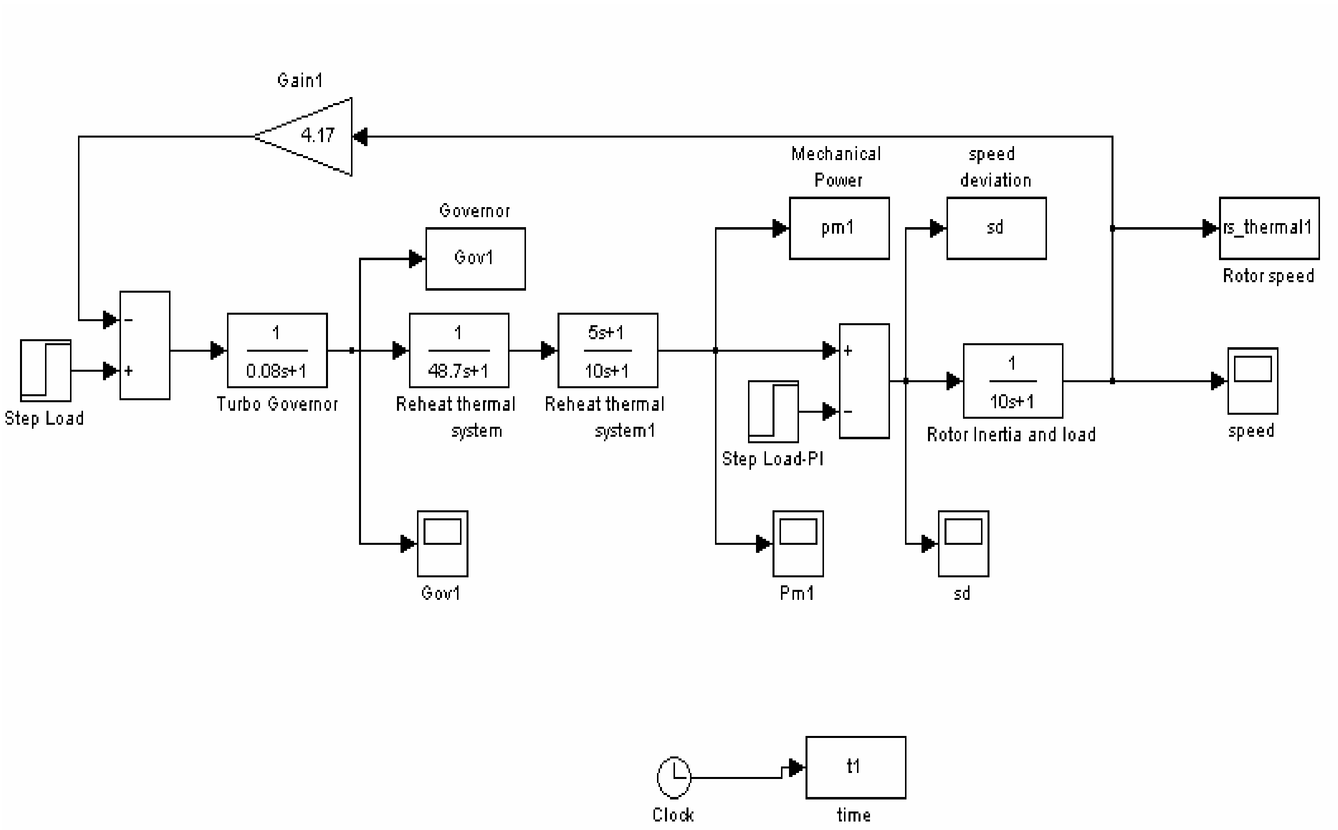
1. Open loop transfer function of the system (**without** transient droop compensation Gc(s) =1.0) is GH(s) =20(1-s)/(1+0.5s)(1+0.2s)(1+6s)

2. Open loop transfer function of the system (**with** transient droop compensation, Gc(S)=(1+5s)/(1+38s)) is GH(s)=20(1-s)(1+5s)/(1+0.5s)(1+0.2s)(1+6s)(1+38s).

Fig.- 3.1.4 Model of Hydroelectric power unit.

C. Thermal Power Unit

Model-T-01



Thermal Power Plant Model

Transfer Function:

Open loop transfer function of the system GH(s) =4.17(1+5s)/ (1+0.08s) (1+48.7s) (1+10s)

Fig. - 4.1 Model of Thermal Power unit.[7][18]

D. GE-3.6 MW WT,
Simulink® Model:
Model-W-01

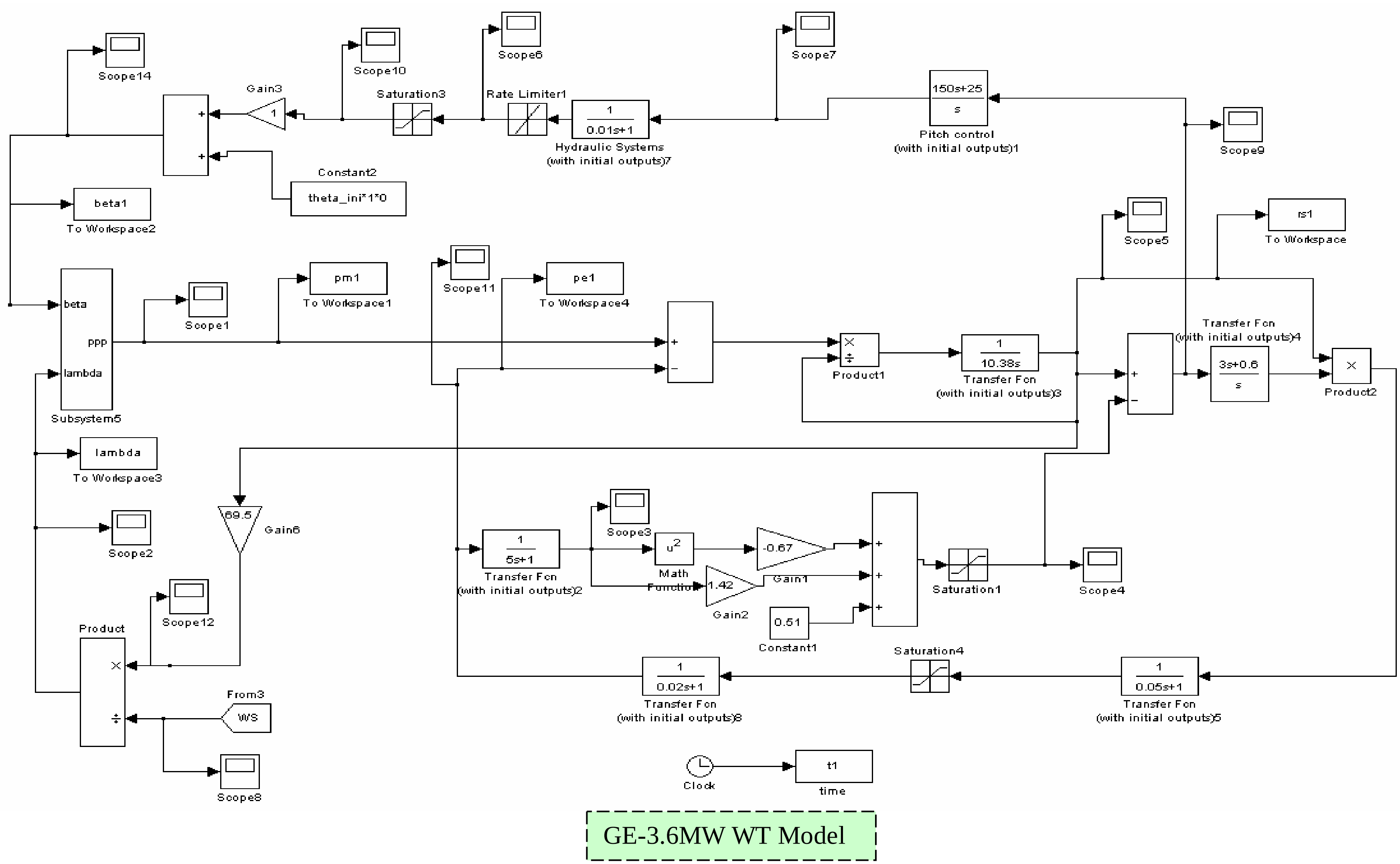
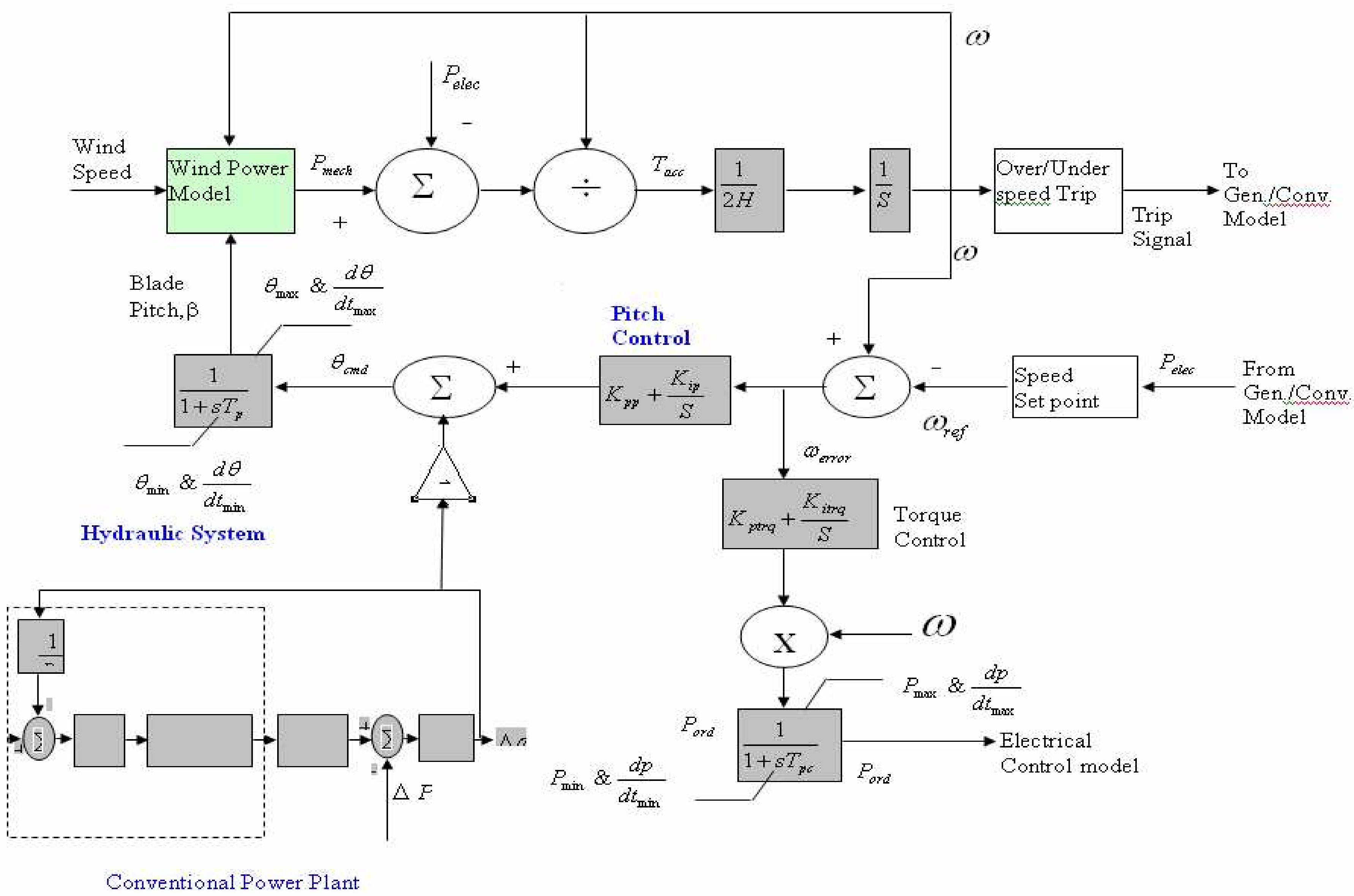


Fig. - 7.0 Model of GE-3.6 MW Wind Turbine. [3] [4]



Wind Speed
Wind Power Model
P_{mech}
+
P_{elec}
-
Σ
$\div$
T_{acc}
$\frac{1}{2H}$
$\frac{1}{S}$
ω
Over/Under speed Trip
Trip Signal
To Gen./Conv. Model
Blade Pitch, β
θ_{max} & $\frac{d\theta}{dt_{max}}$
θ_{cmd}
$\frac{1}{1+sT_p}$
θ_{min} & $\frac{d\theta}{dt_{min}}$
Hydraulic System
Pitch Control
$K_{pp} + \frac{K_{ip}}{S}$
ω_{ref}
Speed Set point
P_{elec}
From Gen./Conv. Model
ω_{error}
$K_{ptrq} + \frac{K_{itrq}}{S}$
Torque Control
X
P_{max} & $\frac{dp}{dt_{max}}$
P_{ord}
$\frac{1}{1+sT_{pc}}$
P_{min} & $\frac{dp}{dt_{min}}$
Electrical Control model
ΔF
Conventional Power Plant

Combined GE-3.6 MW WT with Hydro Unit

Simulink® Model:

Model-WH-02

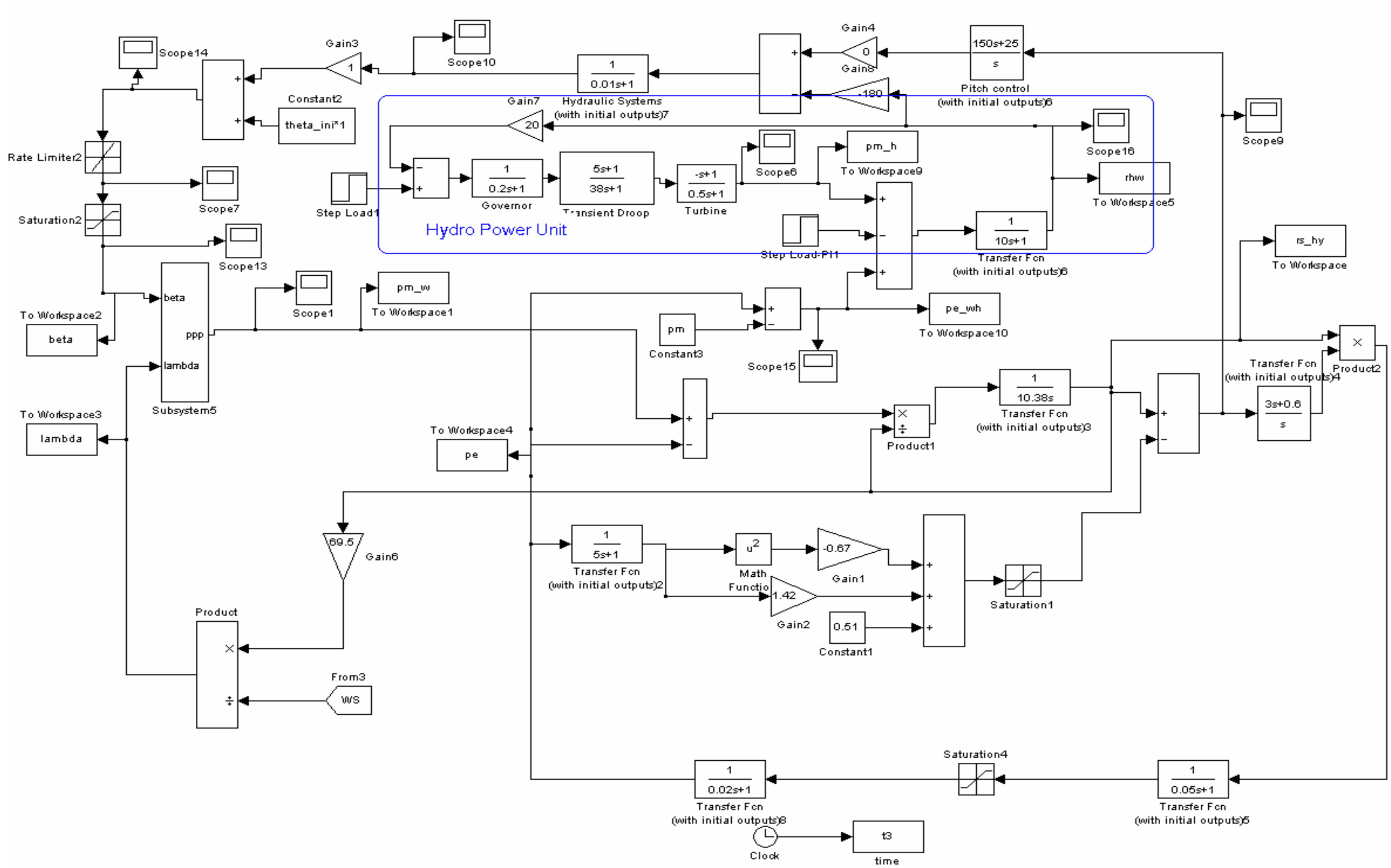


Fig. - 7.1.1 Model of GE-3.6 MW Wind Turbine with Hydro Unit.

Combined GE-3.6 MW WT with Steam Unit

Simulink® Model:

Model-WS-03

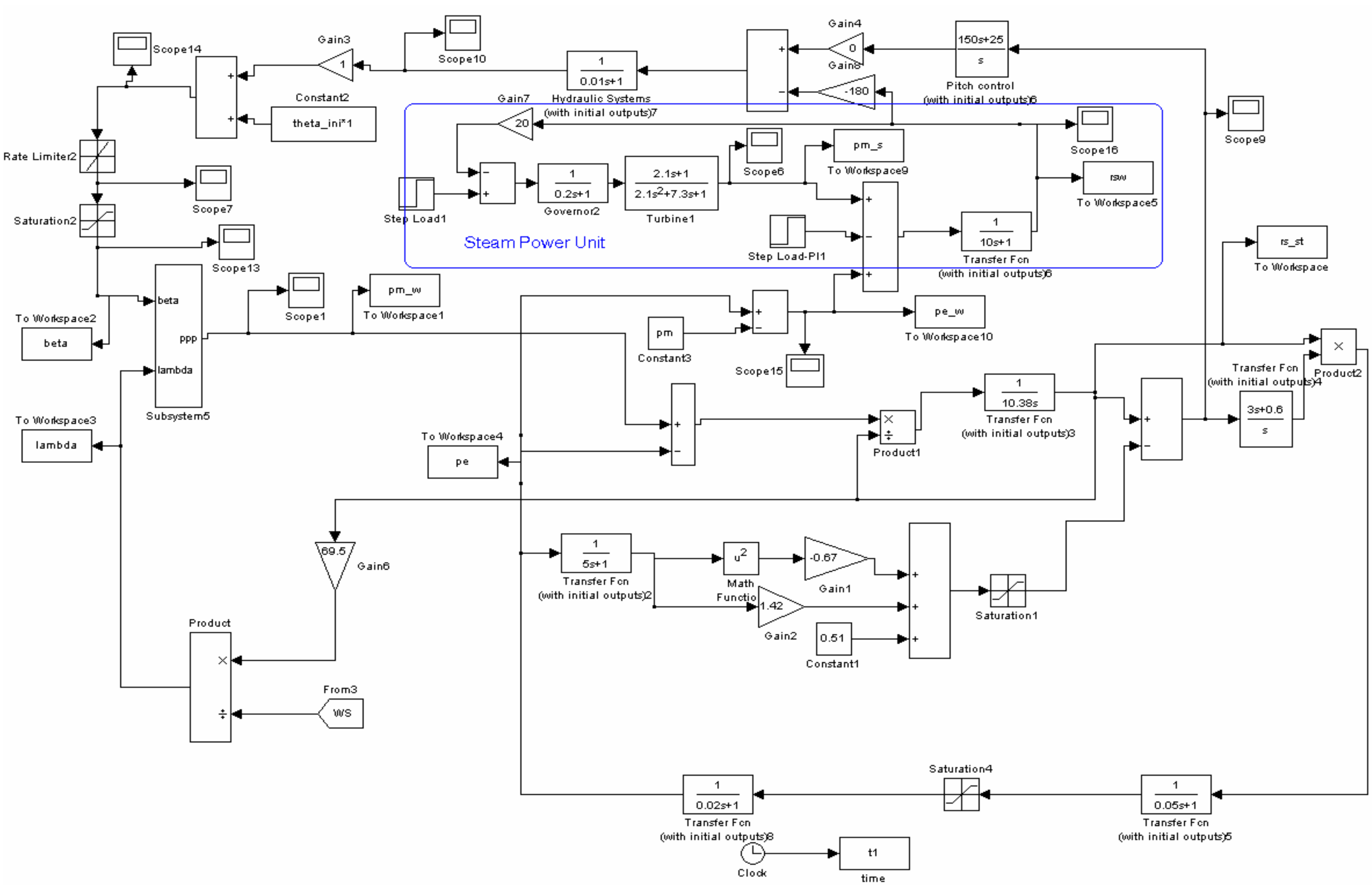


Fig. - 7.1.2 Model of GE-3.6 MW Wind Turbine with Steam Unit.

Combined GE-3.6 MW WT with Thermal Unit

Simulink® Model:

Model-WT-04

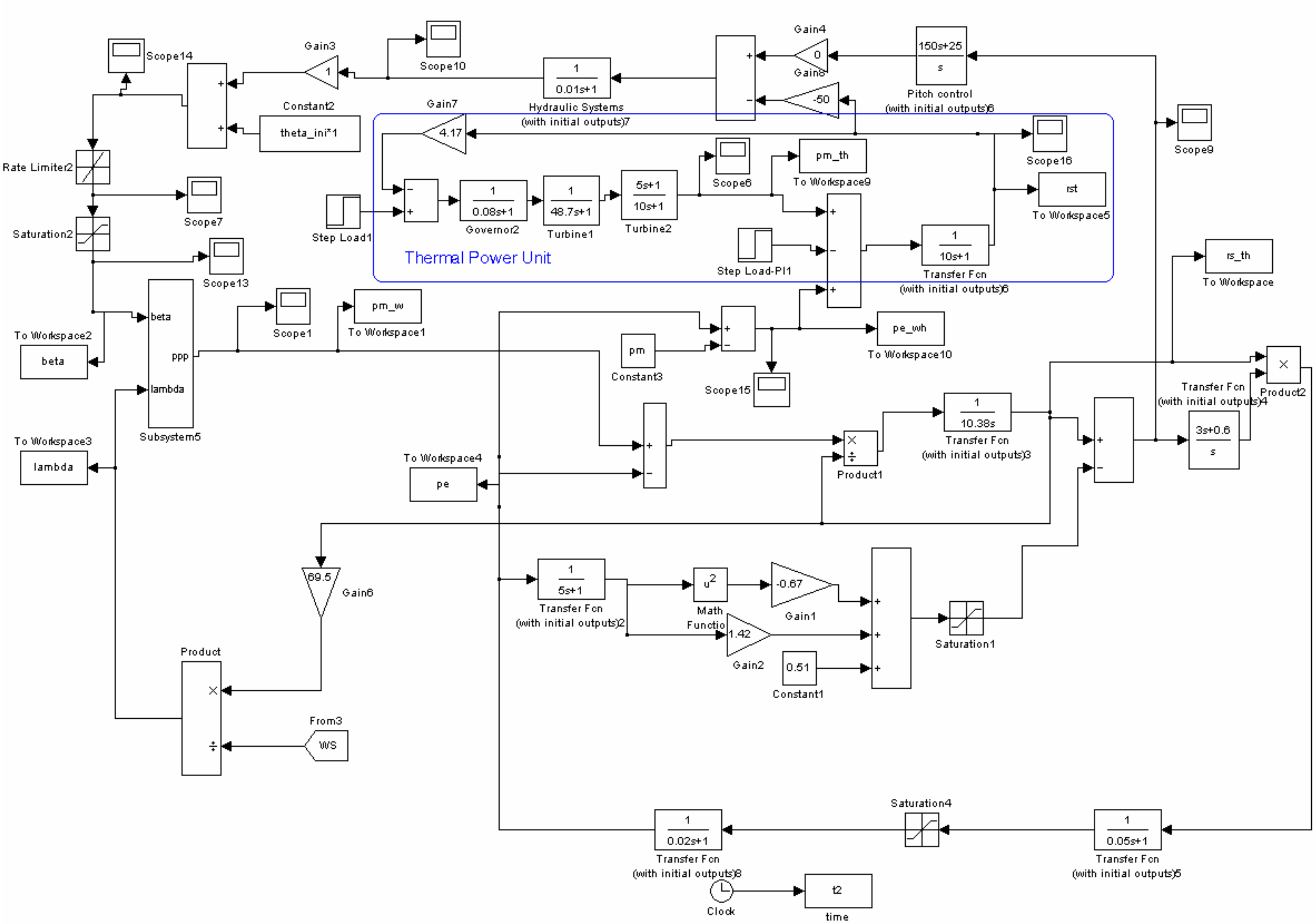


Fig. - 7.1.3 Model of GE-3.6 MW Wind Turbine with Thermal Unit.

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