JIMMA UNIVERSITY

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY OF ELECTRICAL AND COMPUTER ENGINEERING

GRADUATE PROGRAM IN ELECTRICAL POWER ENGINEERING

Comparative Analysis of Intelligent Control Systems for Frequency and Power Control of Gilgel Gibe 2 Hydroelectric Power Plant

By

Biniam Mebrat Kebede

A thesis submitted to Jimma Institute of Technology, School of graduate studies, Jimma University in Partial Fulfillment of the requirements for the degree of Master of Science in Power Engineering

JANUARY 2023

Jimma, Ethiopia

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JANUARY 2023

Jimma, Ethiopia

DECLARATION

I, the undersigned person, state that this Thesis is my original work and has not been presented for a degree award in any other university.

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Candidate Signature Date

The undersigned certify that the thesis entitled: **Comparative Analysis of Intelligent Control Systems for Frequency and Power Control of Gilgel Gibe 2 Hydroelectric Power Plant,** and hereby recommend for acceptance by Jimma Institute of Technology in Partial Fulfillment of the Requirements for the Degree of Master of Science in Power Engineering. This thesis was approved by Jimma University advisors

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APPROVAL

As members of the Examining Board of the final MSc. Open Defense, We certify that we have read and evaluated the thesis prepared by: Mr. Biniam Mebrat Kebede entitled: **Comparative Analysis of Intelligent Control Systems for Frequency and Power Control of Gilgel Gibe 2 Hydroelectric Power Plant** in South Nation National Regional State. We recommend that it be accepted as fulfilling the Thesis requirement for the Degree of Master of Science in Power Engineering.

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Final approval and acceptance of the Thesis is contingent upon the submission of the final copy of the Thesis to the Council of Graduate Studies (CGS) through the Departmental Graduate Committee (DGC) of the candidate's major Department.

DEDICATION

This work is dedicated to my family, my beloved friends who had lost their lives in the horrific car accident that occurred in Gilgel Gibe 2 Mountains on Friday, July 28, 2017, and special dedication to my beloved wife**.**

ACKNOWLEDGEMENTS

First, I would like to thank the merciful and almighty GOD who made it possible for me to begin and finish this work successfully.

Second, I take great pleasure and am deeply indebted to acknowledge my advisor Dr. Kinde Anlay (Ph.D.), Associate Professor, and my Co-advisor Mr. Birhanu Belete (MSc) Electrical and Computer Engineering faculty dean for the significant contribution they made to the realization of the thesis. I thank them for the time they spent in the close follow-up of the progress of the thesis in correcting and improving the manuscript through helpful discussions.

Third, I am grateful to Jimma University and especially to Jimma Institute of Technology Faculty of Electrical and Computer Engineering staff members Mr. Kifle Godana, Mr. Tefera Mekonen and Mr. Abera Jotie for supporting me to conduct this thesis work as much as possible. I thank them also for the relevant technical material they supplied me with and for their much-needed encouragement.

Fourth, I am grateful to Ethiopian Electric Power Gilgel Gibe II hydroelectric power plant manager Mr. Getenet Bekele, Maintenance Manager Mr. Gebeyehu Belay and staff members Mr. Ayenew Gizaw and Ashenafi Tesfa for their unforgettable cooperation in this work to achieve my objectives.

Last but not least I would like to thank my lovely wife Engr. Danawit Kedir, and all my family and friends expressly Mr. Getenet Bekele, for their blessing, guidance, advice, encouragement, and caring support during my thesis work.

ABSTRACT

Power plants have particular control systems to ensure stable operation. The satisfactory operation of a power system requires a frequency control that keeps it within acceptable limits when the system is subjected to significant load variation. With the concept of that the recent developments in the power sector, conventional controllers are designed considering linear power system models; therefore the performance of these controllers may not suffice if a controlled system is of high order and nonlinear for the requirements of power and frequency control. New strategies and controllers for controlling and monitoring hydro power generation are developed to upgrade the conventional controllers. To address these complex problems systematically, several methods have been developed in recent years that are collectively known as “intelligent control” methodologies.

The main goal of this thesis is on analyzing and comparing an intelligent control system for frequency and power control of the Gilgel Gibe 2 HEPP in the networked and isolated mode of operation that has been investigated during operational set point changes. A particle swarm optimization which is robust in solving continuous non-linear optimization problems and fuzzy logic controller for compare and contrast the conventional proportional integral derivative governor control in which active power can be designed with Frequency and Power control of GG2 HEPP. The simulation has been performed for different operating conditions using a dynamic model of the power plant on MATLAB Simulink software to analyze and select the best controller response comparatively.

The simulation result shows that the overall system output performance is improved 97.5% of its settling time using the proposed particle swarm optimization by tuning the existing PID controller comparatively from fuzzy logic and the existing PID controller. When one percent in frequency is increased, the load is drooped from the system network, and the control response shows that PID Tuned by particle swarm optimization resulted in less than 1.243% overshoot, fewer settling times at 0.4052sec, and fewer rising times at 0.0034sec as compared to the fuzzy logic controller and existing PID controller. This controller helps to enhance the power quality of the power plants.

Keywords: **Fuzzy Logic Controller, Particle Swarm Optimization, Governor, Power Control, Frequency Control, Hydro Power Plant**

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LIST OF SYMBOL

a	Wave speed (m/s)
A_1	Cross-sectional area of the tunnel (m2)
A_2	Penstock cross-sectional area (m2)
a_g	Gravitational acceleration constant(m/s2)
a_{ij}	Moment transfer coefficients of turbine
A_s	Cross-sectional area of surge tank (m2)
e	error
e_g	Load self-regulation factor
F_c	Set-point frequency (Hz)
F_g	Actual system frequency
f_n	Rated frequency (1pu)
Δf	Frequency deviation(Hz)
H	High
H	Head of turbine (m) HR = head of turbine (m)
HS	Hydraulic System
K_d	Derivative gain
K_i	Integral gain
K_p	Proportional gain
L	Large
L_1	Length of the tunnel (m)
L_2	Penstock length (m)
M_{go}	Load torque (per unit)
m_t	Momentum of turbine
N	Negative

P_g Generator electric power (W)

P_m Mechanical power of turbine (W)

P_r Generator-rated power output (MW)

P_{ref} Reference power (W)

q Per unit flow rate deviation (Pu)

Q Rate of turbine

t Time(s)

T_a Generator unit mechanical time (second)

T_e Wave reflection (s)

T_s Filling time of surge tank(s)T_w= water starting time(s)

ω Speed

X Rated speed (m/s)

y Per unit gate deviation (Pu)

Ƞ Efficiency of a turbine

ρ Drop in turbine governor characteristics

ABBREVIATIONS

AGC	Automatic Generation Control
ANFIS	Adaptive-Neuro-Fuzzy Inference system
e.g.	For example
EH	Extremely High
EL	Extremely Large
FLC	Fuzzy Logic Controller
GG2	Gilgel Gibe 2
HPP	Hydro power plant
LFC	Load Frequency Control
NLDC	National Load Dispatch Center
PC	Power Control
PFC	Primary Frequency Control
PID	Proportional Integral Derivative
PSO	Particle Swarm Optimization
Pu	per Unit
SC	Speed Control
SNNP	Southern Nation, Nationalities, and Peoples
VH	Very High
VL	Very Large

CHAPTER ONE

1. INTRODUCTION

1.1. Background

Hydroelectricity plays an important role in the safe, stable, and efficient operation of electric power systems to provide an electrical energy. Frequency stability of power systems refers to the ability to maintain steady frequency following a severe system upset resulting in a significant imbalance between generation and load. To suppress power grid frequency fluctuations, generating units change their power output automatically according to the change of grid frequency, to make the active power balanced again. This is the function of primary frequency control (PFC). PFC of electrical power grids is commonly implemented by units in hydropower plants (HPPs), because of the great rapidity and amplitude of their power regulation [1]

A hydropower generation system is a complex nonlinear power system including hydraulic, mechanical, electrical, and magnetic subsystems. Nowadays, the size of HPPs and the structural complexity of systems have been increasing, in Ethiopia. The proportion of electricity generated by intermittent renewable energy sources has also been growing. Therefore, the performance of HPPs in terms of frequency control is more and more important. The research on control strategies and dynamic processes of HPPs is of great importance. The frequency stability of hydropower units is a critical factor in power system security and power quality. The power response time for evaluating the frequency regulation quality is also a key indicator. [1]

In water or hydropower generation "Water-the white coal" is used non-destructively by the force of gravity, which is a carbon-free and inexhaustible resource to generate power. Naturally flowing rivers and streams, flow towards lesser elevations and thus provide a suitable site for hydropower generation. The falling water of waterfalls can be used directly to drive turbines due to its sharp elevation in the hilly area. If the natural fall is not steep, a head is created artificially by damming the river or stream, making a reservoir, and diverting its water to a nearby location with a penstock where the water is made to fall under gravity, driving a turbine for power generation.

Hydro power became increasingly popular as an advantageous clean – green – friendly renewable energy resource. Unlike thermal power plants, there is no pollution of gaseous or fly-ash emissions in the case of hydropower.

Hydropower uses hydraulic turbines to convert energy in flowing water into electricity. Such a source is one way of electrical generation from renewable potential sources. Usually, a hydropower plant comprises a reservoir, water tunnel, surge tank, penstock, hydraulic turbine, speed governor, generator, and grid [3].

In a hydroelectric power plant, stored water flows from a high elevation to the hydro turbine; gravitational potential energy is converted into kinetic energy. Then, the turbine shaft, getting mechanical energy from the conversion, drives the machine to generate electricity [4]. In a turbine, the power is controlled by regulating the flow into the turbine using the position of the wicket gates or nozzles. This regulation is achieved by the turbine governor, which is also called the speed-governing system or turbine-governing system [5].

To suppress the power grid frequency fluctuation generating units change their power output automatically according to the change of grid frequency, to make the active power balanced again. For this frequency regulation, generation stations exhibit a significant contribution to system frequency. From Ethiopian hydro power generation, Gilgel Gibe II hydro power plant is one, and the units have two operating modes controlled by frequency and power control.

Frequency control is used for start-up in island operations and grid-connected operations. Power control mode is used for primary frequency control while the unit is supplying power to 400KV voltage networks [8]. Controllers are used to contributing to the safe operation of the power system by maintaining system voltages, frequency, and other system variables within acceptable limits. Regulation of frequency is closely related to active power control while voltage regulation is closely related to reactive power control [8].

Basic Requirements for all Generating Units

Active power imbalances in the power system are reflected throughout the system by a change in frequency. Therefore, generating units have to be equipped with speed governors providing speed control action. The relationship between speed and load can be adjusted by changing the load reference set-point of the speed controller or through a power controller [2]. The controller is equipped with a hydraulic turbine governor and excitation control.

A controller is a mechanism that seeks to minimize the difference between the actual value of a system (i.e. the process variable) and the desired value of the system (i.e. the set point). When one or more output variables of a system need to follow a certain reference over time, a controller manipulates the inputs to a system to obtain the desired effect on the output of the system. The existing controller which manipulates the above task is proportional integral derivative (PID) for all operating conditions in Gilgel Gibe 2 HEPP. The PID controller first compares the systems output with a user defined set point and generates an error signal. It then tries to minimize this error signal by adjusting its output. This in turn drives the system.

This thesis identified which best controller is capable of the system after it replaced the existing PID in a steady state to control the Frequency and power. The controller reads the speed of the turbine after every sampling period.

PID controller is applied to the system to control the gate of the running water and thus control the rotor speed of the turbine. The PID controller is eventually replaced by a fuzzy logic controller and particle swarm optimization is used for tuning PID comparatively to select the best response to each signal disturbance due to network and isolated system. Since as much empirical evidence has shown the proposed PSO algorithm approach has superior features, including easy implementation, stable convergence characteristics, and good computational efficiency that is an effective optimization tool, it is expected better robust and transient response than the Fuzzy controller and existing conventional PID controller [10]. Matlab Simulink is used in building system models and simulating their behavior.

1.2. Statement of the Problem

In a hydropower system, there are a lot of utilities that interconnect each other and exchange power with neighboring plants. One of the challenges of interconnected hydropower plants is maintaining their nominal frequency. For a huge hydropower plant, the primary concern is power generation as changes in load cause a steady-state frequency change depending upon the governor's droop characteristics as well as the sensitivity of the load frequency. Frequency errors which occur during power generation are not avoidable; therefore, maintaining a steady generation frequency at the desired range is required stably with efficient controller. The power imbalance allowed by frequency deviation may cause an interruption and miss real time operation.

Unsuitable control structures, short and open circuit, internal and external fault, and unexpected contingency problems may happen in hydro units are cause of varying in the existing frequency and power controls of the grid. So, active power control in individual generating units has a positive contribution to grid frequency stability.

The frequency and power control of the Gilgel Gibe II hydro power plant it is achieved the desired value of power under the PID controller. But, the PID controller has many draws back such as transient response performance, steady state error, a high percentage overshoot, large resetting time, and large peak time when compared to other current intelligent controllers. So, in this thesis, it is designed and compared fuzzy logic controller and particle swarm optimization to control the active power of a unit based on frequency and power control of GG2 HEPP under network-connected operation and isolated operation through the use of MATLAB R2013a Software.

1.3. The Objective of the Study

1.3.1. General Objective

The main goal of this Thesis is a comparative analysis of the Intelligent Control System for frequency and power control to safeguard the operation of the Gilgel Gibe 2 hydroelectric power plant.

1.3.2. Specific Objectives

The specific objectives of the study are:

- Modeling and design of existing Gilgel Gibe II hydroelectric power plant unit of frequency and power control, using appropriate transfer functions.
- Analyze and evaluate the existing PID controller with the two proposed controllers fuzzy logic controller and particle swarm optimization tuned PID for comparative analysis using GG2 HEPP frequency and power

control under the networked and isolated mode of operation.

- Improve transient response performance of a stabilized closed loop system which is limitation of the existing PID controller on disturbance attenuation level.
- Proposing the best and most robust controller to optimize the operation of generating units and secure the overall system for Gilgel Gibe 2 Hydroelectric power plant after compare and contrast.

1.4. Methodology

This thesis's research method involves several different tasks to lead toward completion.

Investigation of conventional PID controller: to study the main causes of frequency and power Control transient response error during conventional control, literature review and data collection are made.

Literature review: several published research works about an assessment of conventional and intelligent controller techniques are extensively reviewed from books, papers, articles, and journals.

Data collection: to obtain detail information about the existing frequency and power control and controller limitation and model of interconnected system, data is collected from GG2 HEPP. The required data for design and analysis like design capacity, installed capacity, parameter setting for modeling are collected from datasheets and the recorded commissioning of Gilgel Gibe 2 Hydroelectric power plant. The Proper hydraulic and governor system data's are obtained through finding drawings, operation and maintenance manuals; interviewing, and direct observation by visiting the GG2 HEPP.

Data Analysis: MATLAB software is applied to assess and simulate the overall behavior of the networked and isolated system operation system by establishing various numerical models of HPPs with different degrees of complexity for different purposes using Laplace transform and transfer function for solving linear ordinary differential equations and theoretical derivation, and time domain numerical simulation is implemented based on MATLAB Simulink tool is executed in the thesis outline.

Modeling and Simulation: the performance of the existing conventional and the proposed intelligent controller time response is examined through simulation by using MATLAB/SIMULINK. Simulation studies are carried out for different active power measurement value constants to show the comparison with simulation results then fuzzy logic and PSO supervisor compared to the conventional PID controller.

- Designing existing proportional Integral Derivative, writing a particle swarm optimization MATLAB code for a closed loop system for three variables, selecting the best membership function for the Fuzzy logic controller, and then verifying with the proposed plant model.
- Simulink model using MATLAB R2013a software for both networked and isolated systems using conventional existing PID and an intelligent controller of fuzzy logic and particle swarm optimization tuned PID is developed
- Simulating, analyzing, and comparing the particle swarm optimization tuned PID, fuzzy logic, and existing PID designed for Gilgel Gibe 2 HEPP output of active power response with the reference set point of frequency and power respectively. Reported graphically by plotting the step response and characteristics of parameters of interest.
- The final stage is the conclusion and recommendation based on the observed and analysis method of research findings.

1.5. Significance of the Study

The significance of this study was to provide an electrical power generation system keeping the operating frequency at the desired and scheduled value. This change in frequency is due to the change in the load level of the system. This frequency variation can be controlled and regulated using a load frequency control. Therefore, modeling and designing an appropriate intelligent controller is significant for frequency and active power control for Gilgel Gibe 2 as well as power system stability of the country also merged with in concept. The main contribution of this theses work is to propose the appropriate intelligent controller after analysis and comparing the active power output response for the Gilgel Gibe 2 hydroelectric power plant unit.

1.6. Scope and Limitations of the Study

A power system is designed to operate at certain nominal frequencies and terminal voltages. A few deviations from this may consequence in dynamic instability within the system which may cause loss of connected equipment and leads to overall system failure. Change in reactive power is sensitive to the system voltage while the change in real power mainly affects the system frequency. Therefore, real and reactive powers are controlled separately with the use of control equipment in the overall power system.

The load frequency control (LFC) loop controls the real power and frequency and the automatic voltage regulator (AVR) loop regulates the reactive power and voltage magnitude. The scope of the study stands for the Gilgel Gibe 2 hydroelectric power plant maintaining the conventional controller of frequency and power by an intelligent controller tuning the PID parameters using MATLAB Simulink software. The limitation stands for the dynamic modeling of this hydroelectric power plant and for controlling the active power of the Gilgel Gibe 2 Hydroelectric power plant only.

1.7. Thesis Outline

In chapter two, the theory of hydroelectric power, an overview of the Gilgel Gibe 2 hydroelectric power plant, control system, and, previous work related to the modeling and control system of the hydropower plant is presented.

In chapter three, the detailed mathematical model of the Gilgel Gibe 2 hydroelectric power plant of the hydraulic system, head race tunnel, surge tank, turbine, penstock, and servomotor are designed in this chapter. Power and frequency active power control options and the proposed governing control system are also discussed as required.

Chapter four, presents the existing PID data input model, the Fuzzy logic controller design for a selection of membership functions, and the construction of rule tables for both power error and change in power error the PSO algorithm established and determining parameters are presented accordingly. And also, in chapter five, the simulation results are displayed using MATLAB-Simulink. Discussions and a comparative analysis of the results are presented. Finally, the conclusions of this thesis and recommendations are presented in chapter six.

CHAPTER TWO

2. HYDROELECTRIC POWER PLANT AND CONTROL MECHANISM

2.1. Literature Review

Research has been conducted on the dynamic modeling of a hydropower plant unit and control of power and frequency in different scenarios using different control mechanisms. Works reviewed in this section are categorized into two methods of study.

2.1.1. Conventional Control Method

Mathematical model of hydropower units, especially the governor system model for different operating conditions, based on software TOPSYS, case studies are conducted based on one Swedish hydropower plant (HPP) and three Chinese plants. The simulation is for start-up, no-load operation, normal operation, and load rejection in different control modes (frequency, opening, and power feedback). As a result, the model application is simulating different physical quantities of the unit such as guide vane opening, active power, rotation speed, and pressures at volute and draft tube for all by using a PID controller, in case the conventional controller is a major drawback [1]. A modification of the transient droop setting on the speed governor to improve response time conflicts with the stable operation of units in the Turkish power system. The modification, which is common in most HPPs, has essentially a negative effect on the Turkish frequency stability. The simulation results are compared with the real measurements after utilizing MATLAB- Simulink isolated and grid-connected using a conventional PID controller [26]. Modeling result of island interconnected and step response of unit 1 Ataturk hydropower plant MATLAB Simulink using conventional PID controller [19].

2.1.2. Intelligent Control Method

Modeling, design, and experimental analysis of an Automatic Generation Control (AGC) for a hydropower plant using the Adaptive-Neuro-Fuzzy Inference system (ANFIS). This was aimed at reducing the frequency deviations which occur during power generation. The proposed ANFIS was trained with input-output data of the fuzzy logic controller (FLC). The ANFIS model is used as a hybrid learning model which includes the Least Square Estimate (LSE) and back propagation algorithm (BPA). The conventional PID, FLC, and ANFIS controllers were investigated using MATLAB. The simulation results show that the ANFIS controller performs better compared to the PID as well as the FLC. Further results indicate that the proposed ANFIS controller helps to speed up the performance of the AGC of the hydropower plant. The ANFIS controller not only improved the performance but also made the fuzzy inference system (FIS) less dependent on the expert system. [11].

Modeling of the dynamic behavior of the Adiguzel, in Turkey hydroelectric power plant was made by using the power generation model in MATLAB/Simulink program synchronous generator and other components in the system in a manner reflecting its behavior in the real system performance of the classical controller and self-adjusting fuzzy logic controller in electro-hydraulic governor circuit is examined according to different load statuses. The conventional PID without tuning by an intelligent optimization and fuzzy logic controller which inputs signal as a membership function, output variable consists of 27 much narrowed real numbers and a range of 27 rules to control island power system with different load variations is used [13]

A governor design by reduced-order sliding mode for a hydropower plant with an upstream surge tank is investigated using an all-waterway system and a grid. From the view of state space in modern control theory, the governing system is partially observed, which challenges the governor's design. By introducing an additional state variable, the control method of reduced-order sliding mode is proposed, where the governor design is based on a reduced-order governing system. Since the governor is applied to the original governing system, the system stability is analyzed using the small gain theorem. A genetic algorithm that is slow to search for the best solution than PSO optimization to tune the PID and Fuzzy that this thesis proposed is employed to search a group of parameters of the predefined sliding surface, and a fuzzy interference system is utilized to decrease the chattering problem in an isolated mode of operation only [21].

2.2. Hydroelectric Power

Hydroelectric power is the power generated by using the potential energy stored in flowing water. Technological advancement has resulted in most power utilities being interconnected into a single power grid to maximize the efficiency of the generating stations. Due to increased load demands from consumers which may cause the power system network to be in highly stressed conditions, the need for increasing the efficiency of the generation station is arising. The possible means of increasing this efficiency is to model and simulate the generating stations, which aid in describing the static and dynamic behavior of the whole network. These evaluations aim to assess the behavior of the power system in isolated, reserve capabilities, and stability analyses in the whole power system through modeling and simulating the hydropower plant.

Hydropower plants convert the potential energy of the water head to mechanical energy by using a hydraulic turbine. [1]. Hydro turbines are in turn connected to a generator that converts mechanical energy to electrical energy. The main components of a hydropower plant are illustrated in this Figure 2.1.

The hydropower plant is made of a generator, a turbine, a penstock, and a jet valve. The water drives the turbine-generator set and the rotating generator electricity. At the initial stage, the stored water with a clear hydraulic head possesses potential energy as it flows through the head race tunnel, surge tank, and penstock it gradually loses potential energy and gains kinetic energy before reaching the turbine. A critical look at the process of energy generation by hydropower plants shows that hydropower plant models are highly influenced by the penstock-turbine system, the electric generator, and numerous control systems [6].

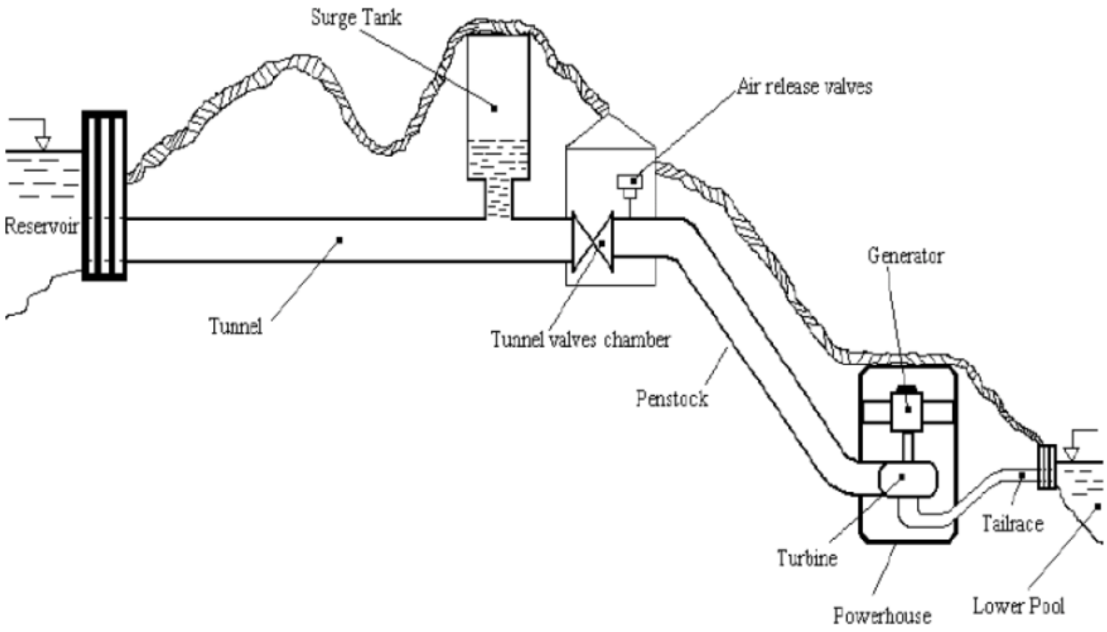

Figure 2.1 General layout of a hydro power plant

Nowadays, the size of HPPs and the structural complexity of systems have been increasing, in Ethiopia. Ethiopian Electric Power has the authority of constructing and administration of power generation plants, high voltage transmission lines, substations, whole sale of electricity, conduct feasibility studies, design, and surveys which were given by the council of ministers with proclamation number 302/2006 as of 2006 E.C.

Regarding power generation plants, currently, Ethiopian Electric Power administers 18 power plants there generate a total of 4244MW of electricity nationwide. Among the 18 power plants, 14 are from hydro with a total installed capacity of 3814MW electricity. 4 wind power plants have generated electricity in Ethiopia which amount to 324MW in aggregate. The remaining 104MW of electricity is generated from a diesel generator and (7.3MW) from geothermal [14]. The location, type of dam, installed capacity, and how many units are mounted on the power plant are listed in Table 2.1. Gilgel Gibe 2 hydroelectric power plant should be the focus of this thesis to model and study for obtaining a robust control system.

Table 2.1 Ethiopian Electric Power plant list

No	Name of the power plant	Installed capacity in MW	Number of Units	Type of Dam	Location
1	Gilgel Gibe III HEPP	1870	10	Concrete gravity dam	SNNP State
2	Beles HEPP	460	4	Natural Dam (Lake Tana)	Regional State of Amhara
3	Gilgel Gibe II HEPP	420	4	Diversion dam	SNNP regional state
4	Takeze HEPP	300	4	Concrete gravity dam	Regional State of Tigray
5	Gilgel Gibe I HEPP	184	3	Concrete gravity dam	Regional State of Oromia
6	Melka Wakena HEPP	153	4	Concrete gravity dam	Regional State of Oromia
7	Fincha HEPP	134	4	Gravel dam	Regional State of Oromia
8	Amerti Neshi HEPP	95	2	Concrete gravity dam	Regional State of Oromia
9	Tis Abay II HEPP	73	2	Natural Dam (Lake Tana)	Regional State of Amhara

10	Awash II HEPP	32	2	Concrete gravity dam	Regional State of Oromia
11	Awash III HEPP	32	2	Concrete gravity dam	Regional State of Oromia
12	Koka HEPP	43	3	Concrete gravity dam	Regional State of Oromia
13	Tis Abay I HEPP	11.4	3	Natural Dam (Lake Tana)	Regional State of Amhara
14	Aba Samuel HEPP	6.6	4	Concrete gravity dam	Regional State of Oromia
15	Adama II WPP	153	Wind turbine	-	Regional State of Oromia
16	Ashegoda WPP	120	Wind turbine	-	Regional State of Tigray
17	Adama I WPP	51	Wind turbine	-	Regional State of Oromia
18	Aluto Geothermal PP	7.3	Steam Turbine	-	Regional State of Oromia
Total Energy including Diesel		4244 MW			

2.3. Overview of Gilgel Gibe II Hydro Power Plant

Hydropower is a key tool for sustainable development. In line with this several hydroelectric power plants are being developed and operated in the country in an economically viable, environmentally sound, and socially responsible manner. Gilgel Gibe 2 Hydroelectric power plant was among these and is now fully operational, generating 420 MW. [15]

This plant is born as a cascade of the Gilgel Gibe I hydroelectric power plant and its construction work commenced in June 2004. The water that generates 184 MW at the Gilgel Gibe I power plant is diverted via a 26 km-long tunnel and generates an additional 420 MW of electric power at the Gilgel Gibe II power plant. The difference in elevation between the intake and the powerhouse is about 500m. It is this head that allows the generation of 420 MW of electric power with four Pelton Turbines driven by Gilgel Gibe II generators. Figure 2.2 shows the site view of Gilgel Gibe 2 Hydroelectric power plant.

Figure 2.2 Site view of Gilgel Gibe 2 HEPP

The project was financed by the Italian Government, the European Investment Bank, and the Government of Ethiopia. Gilgel Gibe II hydroelectric power plant is situated in two regional states, Oromia and the Southern Nation, Nationalities, and Peoples (SNNP) the Intake is located some 250 km southwest of Addis Ababa, 80 km northeast of Jima town, and the Outlet and the Powerhouse in Yem Special Woreda of SNNP Regional State. The power plant is accessed by two newly constructed roads; from Fofa town to GGII Power Plant 35 km long gravel road and from Kose town to GGII Power Plant 38 km long asphalt road.

2.3.1. Elements of Gilgel Gibe 2 Hydroelectric Power Plant

A. Intake

The main features of the Intake area works are the de-silting weir, intake tower, and storage weir. De-silting structure is located on the Gilgel Gibe river 1 km upstream of Gilgel Gibe I power house; it has a 16m height and 201m long structure made of steel reinforced rock fill that acts as a filter preventing part of the suspended silt and mud that could be deposited into Gilgel Gibe Il reservoir (Weir). While the water from Gilgel Gibe [turbine(s) is low in silt contents, the water from the spillway and the gallery carried by the river upstream of the tailrace is not. For this reason, the de-silting Weir structure has been built to trap the silt.

Intake Tower consists of a traditional concrete structure equipped with roller gates and stop logs. It is a 35m tall, 27m wide, and 42m long structure. The water can reach the turbines, through the 26 km headrace tunnel, by controlling the gates installed at the Intake tower where the Headrace Tunnel starts.

B. Storage Weir

The Storage Weir (Small Reservoir) is a 56m high mass concrete weir located downstream of the Intake and has a capacity of impounding 2.26 million m^3 of water. At full reservoir level, the water stretches up to 2.5 km upstream on the valley floor. The reservoir regulates the water flow into the tunnel and guarantees sufficient water to produce buffer entry at Gilgel Gibe II & whenever the Gilgel Gibe I power plant stops temporarily for any reason.

C. Headrace Tunnel

Before the start of the boring operation, 150m and 317m long Adits were excavated (by drill and blast technique) at the inlet and outlet respectively to launch the excavation of the Headrace Tunnel with TBMs. A 378m long lateral adit was also constructed at the outlet to serve as an access for the rails to load and unload excavated material. Then the headrace tunnel construction started with two TBMs, one at the Inlet and the other at the Outlet heading. It is used to convey water potential across the mountain that generates electricity at Gilgel Gibe 2 power plant. The internal diameter of the lined tunnel is 6.3 m and 26 km in length.

D. Penstock

Penstock is a surface-mounted high-pressure pipe structure that delivers water from the tunnel to the hydraulic turbines. It includes part of the penstock that stretches from the bottom of the surge shaft to the outlet portal (horizontal penstock) and continues down to the powerhouse (inclined penstock). The penstock bifurcates at the valve chamber located just after the Tunnel Outlet. Near the powerhouse each penstock again bifurcates, making 4 in total, and delivers water into the four-Pelton turbines. The total length of the penstocks is 2,280m (each with 1,140m) with a diameter varying between 3.6m and 2.8m. The inclined penstock rests on special concrete saddles and is anchored by 11 concrete blocks placed along the penstock alignment.

Number of penstock	2
Thickness	16mm to 40mm
Internal Diameter	3.6m down to 2.8m
Nominal flow each	51 m3/ s
Length	1.2 km each having an expansion joint

E. Powerhouse

The powerhouse is a surface concrete structure 36m high, 44m wide, and 139m long. Foundation elevation is 916m.a.s.l, transformer elevation is 937m.a.s.l, normal river elevation is 920m.a.s.l, and turbine elevation is 926m.a.s.l. It consists of four Pelton turbines each having a rated power of 105MW for a total of 420MW. The water is sprayed through six nozzles on the paddle wheel of the turbine and then it is released into the Omo River. Inside the Power house, there are two gantry cranes, each having 120 tons and 16 tons with a maximum of 272 tons lifting capacity.

The main features of the electromechanical works are Main Inlet Valves, Pelton Turbines, Hydraulic, and digital Governors, Generator, Excitation systems, Protection systems, Main Power Transformer, Auxiliary Service systems, Switchyard Control, and SCADA system.

F. Main Inlet Valve

The Main Inlet valves (MIV) are spherical in type and operated utilizing oil pressure on two double-actuating Servomotors. Valves are for opening and closing under balanced pressure, as well as for emergency closing under maximum flow and maximum head.

No of valves	4
Valve type	Spherical
Diameter:	1.9m
Rated flow	24.531 M^3/s
Max. Static pressure:	5.5MPa
Max. Design pressure:	6MPa
Operating oil pressure:	60 bar

G. Pelton Turbines

The 6 nozzles' Vertical Pelton Turbine converts all available head/water pressure into velocity (kinetic energy) through water jets formed by the nozzles. Jets of water from nozzles act on the runner buckets to rotate the shaft. All Turbines comprise distributor pipes, nozzles, deflectors, runners, and shafts which are directly coupled to the generator rotor shaft.

Table 2.2 Pelton Turbine Specifications

Pelton Turbine	Minimum	Rated	Maximum
Head (m)	462	485	495
Power (MW)	102.0	107.0	108.6
Discharge (m^3/s)		24.531	
Nominal speed	333.33 rpm		
Runaway speed	rpm		
Direction of	clockwise (viewed from the Top)		

Figure 2.3 Gilgel Gibe 2 Turbine Runner and its Coupling Shaft

H. Hydraulic and Digital Governors

The hydraulic governor supplies pressurized oil for the operation of nozzles and deflector Servomotors under designed pressure. The Digital governor is an electronic type turbine speed controller.

The Digital Governor has the following 3 control modes

- Speed Control
- Flow Control
- Load Control / Load-Frequency Control/

I. Generator

The power plant is equipped with four generators and each has the capability of delivering 125MVA-rated output continuously at nominal voltage and frequency. The generators produce electrical energy proportionally to the amount of water the hydraulic turbine (prime mover) receives and depends on the power system load requirement.

Generator’s Features

- Type synch. of the machine		- Rated Voltage	15kv
- Rated frequency	50Hz	- No poles	18
- Number of phases	3	- Rated current	4811A
- Rated speed	333.33 RPM	- Rated torque	3044 KN
- Rated output	125 MVA	- Rated power factor	0.85
- Class of insulation	F	- Stator winding connection	Y

J. Power Transformer

The main power transformer transforms low voltage and high current into high voltage and low current power and makes it economical to transport the generated power through a very comparatively thin conductor called the transmission line. Four such transformers are working at Gilgel Gibe II Power Plant.

Transformer's Features:

- Type: Three-phase, outdoor - Rated power: 125MVA
- Number of steps: 4 up - Rated voltages 15/ 400 KV

K. Switchyard

The 212 km transmission line is a single circuit 400kV transmission line and includes 184 km and 28 km from the Gilgel Gibe II power house switchyard to Sebetta II 400/230/33 kV substation and from the Gilgel Gibe II power house switchyard to New Gilgel Gibe I 400/230/ 132/33 kV Socoru substation, respectively. And included also about 15 km and 4 km double circuit 230 kV from the Sebetta II substation to Existing Sebetta (Kara Kore) substation and from cutting points on the existing Gilgel Gibe II - Ghedo and Gilgel Gibe I Wolkite 230 kV lines to the Gilgel Gibe I.

L. Power generation

The amount of electricity that can be generated by a hydropower plant depends on two factors

- Flow rate: the quantity of water flow in a given time
- Head: the height from which the water falls

The greater the flow and head, the more electricity is produced [12] as per (2.1)

$$P = \eta Q H g \tag{2.1}$$

The generation set point and capacity of Gilgel Gibe 2 hydroelectric power plant in one specific day is as shown in Figure 2.4, It was produced as power given manually by the operator because to balance the demand and supply power, when the demand and generated is equally no frequency fluctuation happens, frequency is constant means generation is synchronized, this frequency is always related with active power as the reactive power is related with a voltage of power system.

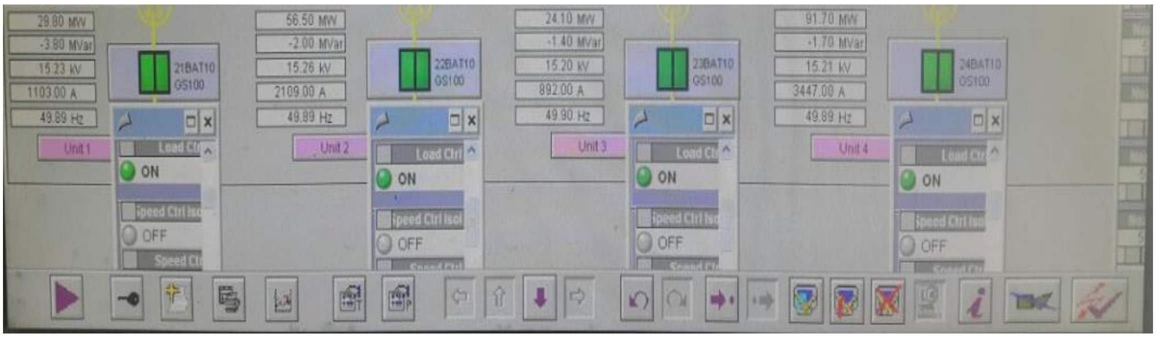

Figure 2.4 GG2 SCADA system displayed the power generated for each unit

2.3.2. Control System used in Gilgel Gibe 2 Hydroelectric Power Plant

Control mechanism in Gilgel Gibe II hydro power plant during my survey about the governor. Governor and accompanying equipment enable turbine control at turbine start and stop, operation of turbine unit in parallel with network and an isolated system [10].

2.3.2.1. Digital Governor

A function of the Digital Governor Control modes maintains the same turbine speed at any unit load when the unit is operating in an isolated system and when operating in parallel with a common system network. the governor keeps the governor power constant, the turbine starts to nominal speed, double regulation, needle-deflector control, multi-needle control, turbine stop function by predefined stop ram, self-monitoring, and supervision, parameter adjustment via operator panel, remote operation by VSHyCon 400 unit control, remote operation by VSHyCon Manual Control Panel “MCP”, Local Operation by Governor LCD Operator Panel OP177 B, Local Maintenance Operation by VCA3 Amplifier. Governor output operates all the time on nozzle injectors and deflector servomotor to determine the right flow through the turbine [15]. The hydraulic turbine governor controls the frequency intern speed of the turbine according to load variation.

The turbine starts with 6 nozzles (symmetrical forces), synchronizing with two nozzles (1-4). Depending on the requested flow (respectively load) automating starting, and opening of further nozzles, and also automatic closing of unnecessary nozzles by keeping the priority sequence of the nozzles.

Priority:	1^{st} 2^{nd} 3^{rd} 4^{th} 5^{th} 6^{th}
Nozzle No:	1 - 4 - 3 - 6 - 2 - 5
Loading of the unit:	⟹
Unloading the unit	⟸

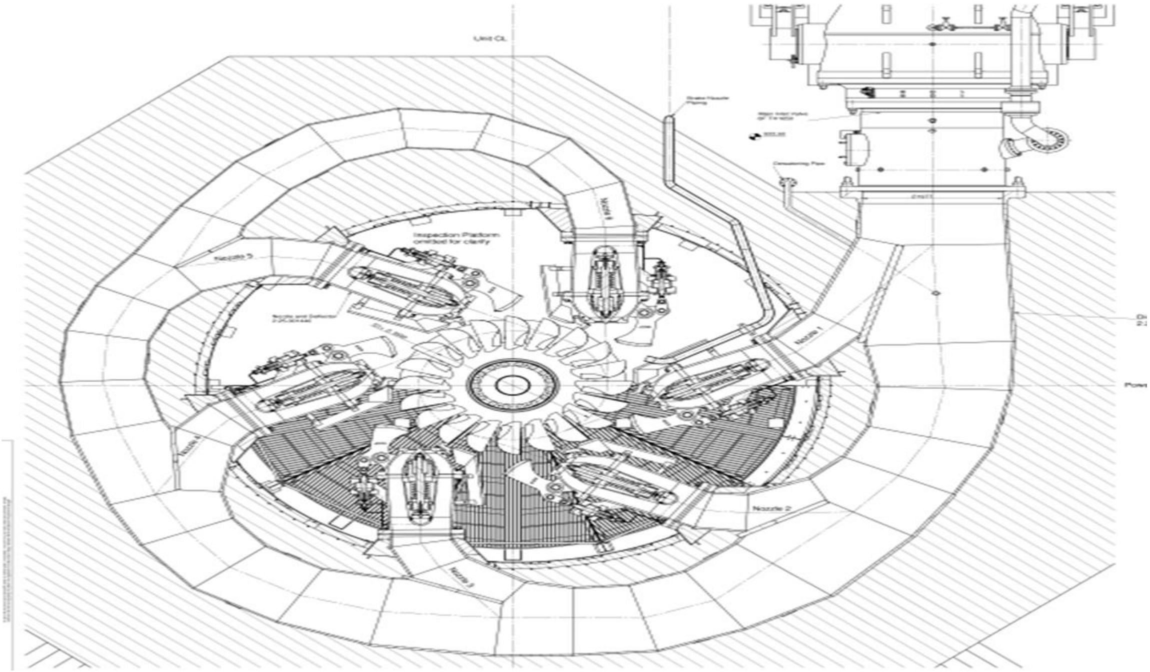

Figure 2.5 GG2 Turbine driven by 6 nozzles (symmetrical forces) [15]

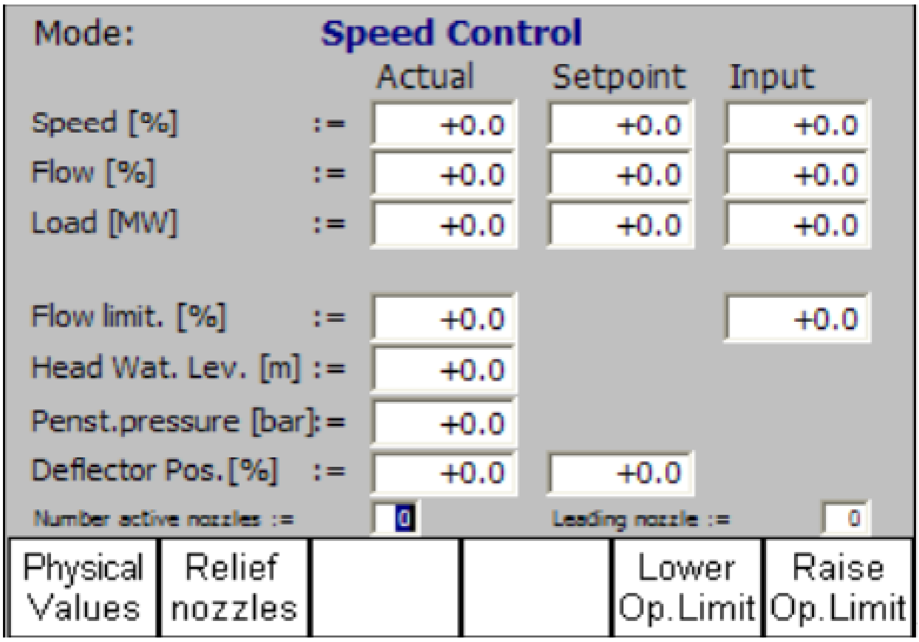

Figure 2.6 GG2 Governor LCD Operator Panel [15]

2.3.2.2. Operating Mode of Governor in Gilgel Gibe Hydro Power Plant

The main frequency governor control modes are:

- Speed Control
- Flow Control
- Load Control / Load-Frequency Control

Speed Control

The speed governor is a PID governor (governor parameters vary according to the operating condition). There are 3 sets of parameters; one for no-load operation (optimized for synchronization), one for isolated operation (high damping), and one for network parallel operation (low damping).

Flow Control

Flow control is possible in network parallel operation only, i.e. the circuit breaker must be closed and the speed has to be within the speed band. The flow controller uses as the actual value the calculated turbine flow which is determined depending on the nozzle opening and the head base. This calculation is performed using the turbine characteristics programmed in the governor. Flow set point and actual value are shown and adjusted utilizing the display. Flow control is activated automatically after a power signal failure occurred if the governor was in load control. The flow controller is a PI-control loop whose calculated value is transferred to the opening control loop. The value of the flow set point is compared with the flow limiter and the lower value is transferred to the position control loop (minimum selection). The nozzle follows the set point considering an appropriate zero offset and the deflector position is calculated using a relationship curve.

Load Control

To achieve a quick response to alterations of the power reference value, a pilot characteristic is included which may be head-dependent if a head signal is available. The output of this characteristic is added to the output signal of the power controller without delay. This means the actual output value follows the set point as fast as admitted by the control elements and the typically relatively slow PI power controller has just to balance the inaccuracies or influences not acquired. Power control is activated automatically after closing the generator circuit breaker. Due to an adjustable frequency power droop, the machine may participate in maintaining the network frequency. To meet ambitious requirements in case of a weak grid the governor uses a solution with an extra speed control loop and power control loop additively connected.

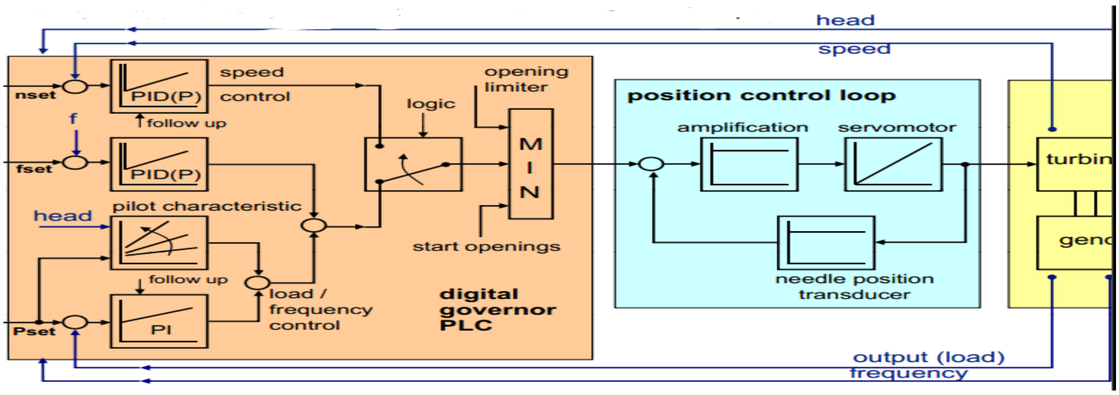

Figure 2.7 GG2 Governor Controller block diagram [15]

As we have seen in several theses, the parallel operation to network connected mode (power control and frequency control) and isolated operation to control frequency.

Operation in an isolated system

In the case of network parallel operation, the turbine governor checks permanently if the adjustable speed band is violated. This function guarantees the safe and reliable detection of grid disturbances. If the speed band is violated the governor switches automatically to speed control with isolated mode parameters. The width of the speed band can be adjusted through the parameter input function.

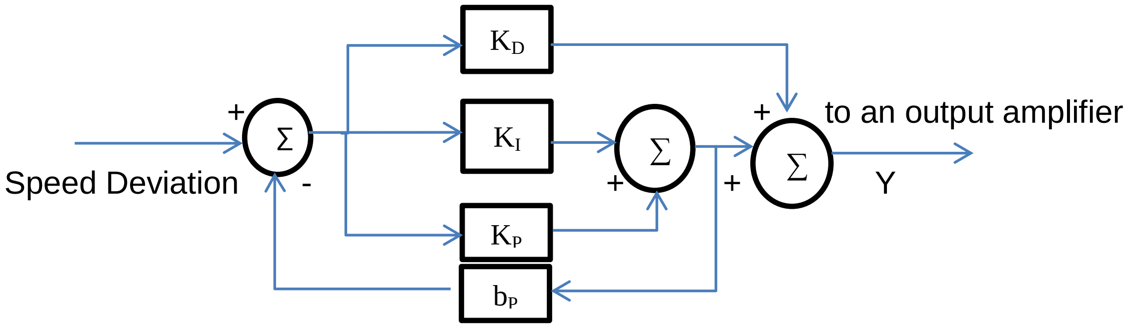

Figure 2.8 PID Governor Controller during Isolated diagram [15]

Operation in Parallel Network

When the unit is connected to the Grid, the unit's rotating speed is determined by system frequency. Change power reference signal, the nozzle opening will be changed proportionally to the reference change. If the reference signal is constant and the system frequency is changing, the unit power will change speed drop characteristics. It means that the governor is active in primary frequency regulation. The governor can operate in the parallel run in power control mode, opening control mode, or frequency mode [15].

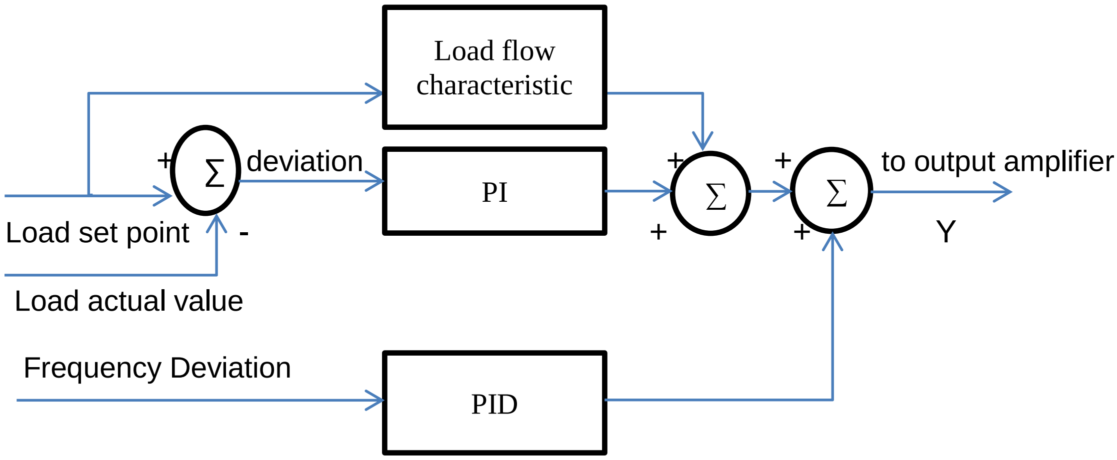

Figure 2.9 GG2 Governor Controller networked block diagram [15]

Frequency Control in Parallel Network

To ensure a working Ethiopian Power Grid, the operating frequency is defined by a standard of 50 hertz. As electric generation and consumption differs, the power transmission grid has to be balanced. There should be the same amount of input and output. Nevertheless, changes in frequency may occur if supply or demand exceeds its counterpart. In case of too much supply, the frequency will increase, while in case of too much demand it will decrease. The main task is to keep the frequencies balanced at around the 50-hertz standard to ensure a safe power supply [13]. A special mode is provided for frequency control in parallel operation. In frequency control, the unit regulates the system frequency on the level determined by the speed reference set value [15].

Power control in a parallel network

Power control is used to keep the power of the unit equal to the set value. This kind of power controller is used to be made certain rate but without overshooting or a slow periodic approaching of preset power.

2.3.2.3. Existing Conventional Controller

The diagram system overview shows the Gilgel Gibe II speed governing block diagram in the linearized presentation in its function as a closed loop control. It shows in simple blocks the governor elements, the regulated system, and the feedback of the measured speed.

The governor itself consists of the following main control elements:

- Speed error calculation from the set point and actual measured value: x = nsetp – nact
- The real PID (P) speed governor algorithm
- The servo positioner, including electric-hydraulic conversion and amplification

The first two functions, i.e. the speed error calculation and the PID (P) algorithm, are realized by software in the digital governor PLC. The servo positioning, electro-hydraulic conversion, and amplification functions are realized by external electrical and hydraulic components.

The most common controllers available commercially are the proportional-integral (PI) and proportional integral derivative (PID) controller. The PI controllers are used to improve the dynamic response as well as to reduce or eliminate the study state error. PID is made of three main components i.e. proportional, integral, and derivative [16].

Proportional gain

The proportional gain makes a change to the output that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant K_p, called the proportional gain [13].

Integral Gain

The contribution from the integral gain is proportional to both the magnitude of the error and the duration of the error. The magnitude of the contribution of the integral gain to the overall control action is determined by the integral gain, K_i [13].

Derivative gain

The rate of change of the process error is calculated by determining the slope of the error over time (i.e., its first derivative with respect to time) and multiplying this rate of change by the derivative gain K_d. the magnitude of the contribution of the derivative gain to the overall control action is termed the derivative gain, K_d.

Table 2.3 PID (p) parameters commissioned in Gilgel Gibe II HEPP [15]

Gain	Symbol		
		Isolated	Network
Proportional Gain	Kp	1.6	1.6
Permanent speed droop	bp	4	4
Integral Gain	KI	3	14
Derivative Gain	KD	3.2	3.2

2.4. Control System

A control system is a system, which provides the desired response by controlling the output. An open and closed loop system is a type of control system which are differing by having or not having feedback. The closed-loop control system is a system where the output affects the input quantity in such a manner as to maintain the desired output value. An open-loop control system becomes a closed-loop control by including feedback. This feedback will automatically correct the change in output due to disturbances. The controlled variable of the system is sensed at every instant of time, feedback, and compared with the desired input resulting in an error signal. This error signal directs the control system elements in the system to do the necessary corrective action such that the output of the system is obtained as desired.

1. System Metrics

When a system is being designed and analyzed, it doesn't make any sense to test the system with all manner of strange input functions, or to measure all sorts of arbitrary performance metrics. Instead, it is in everybody's best interest to test the system with a set of standard, simple reference functions. Once the system is tested with the reference functions, there are several different metrics that we can use to determine the system's performance.

2. Time response

The primary purpose of the time response analysis is to evaluate the system's performance concerning time. This means that the time response of the system provides an idea about the variation in output when a certain input is provided for time. The time response of the system is composed of steady-state response and transient response.

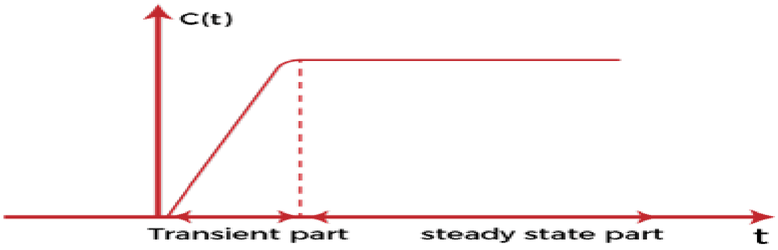

Figure 2.10 graphs of time response

After applying an input to the control system, the output takes some time to reach the steady condition. The response during this stage is known as the transient response and constitutes the transient part of the graph, as shown in Figure 2.10.

The graph that archives the steady start after the transient part is known as a steady part. To describe a system, we need to develop the relationship between the inputs and output of the system which are the functions of time. The analysis of the system can be done with the help of differential equations by applying different inputs to it. The common input signal is shown in Figure 2.11.

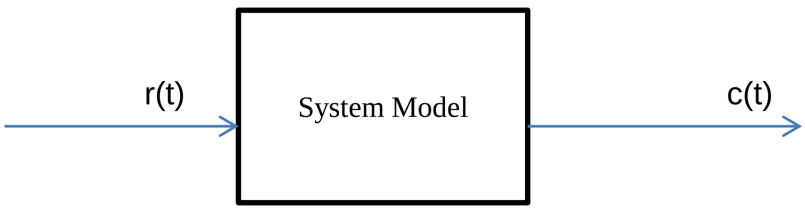

Figure 2.11 System with input and output

A test signal r (t) is applied as the input to the system which results in the response c (t). The input signal of a system can take many forms. The transient response, steady-state response, and the standard of the control system are described below.

a. Transient Response

It is a part of the time response that reaches 0 (zero) when the time becomes very large. In the graph analysis containing poles and zeros, the poles lying on the left half of the s-plane give the transient response. We can also say that it is a part of the response where output continuously increases or decreases. The transient response is known as the temporary part of the response or transient response is defined as the change in the response of the system from the equilibrium state [25].

b. Steady-state Response

The response that comes after the transient response is called the steady-state response. In the graph analysis containing poles and zeros, the poles on the imaginary axis give the steady-state response. We can also say that it is a part of the response where output remains constant. The output can also vary periodically with constant amplitude and frequency. The steady-state response is also known as the steady-state part of the response. It is a function of the input signal and is hence also known as the forced response of the system.

c. Standard inputs

Some standard inputs are considered simple enough and universal enough that they are considered when designing a system. Standard signals in the system are step, ramp, sinusoidal, and impulse input. For the positive value, the step input shows constant values of the time. It has zero value for the negative value of the signal. The initial value of the signal and the transition is in the form of step size with a constant value. If the constant value of the signal is 1, it is called a step input signal which this thesis graphical response presents.

d. Step response

The step response of a system is most frequently used to analyze systems, and there is a large amount of terminology involved with step responses. When exposed to the step inputs, the system will initially have an undesirable output period known as the transient response. The transient response occurs because a system is approaching its final output value. The steady-state response of the system is the response after the transient response has ended.

The amount of time it takes for the system output to reach the desired value (before the transient response has ended, typically) is known as the rise time. The amount of time it takes for a transient response to end and the steady-state response to begin is known as the settling time.

It is common for a systems engineer to try and improve the step response of a system. In general, it is desired for the transient response to be reduced, the rise and settling times to be shorter, and the steady-state to approach a particular desired reference output.

e. Target value

The target output value is the value that our system attempts to obtain for a given input. This is not the same as the steady-state value, which is the actual value that the system does obtain. The target value is frequently referred to as the reference value or the reference function of the system. In essence, this is the value that we want the system to produce.

f. Rise time

Rise time is the amount of time that it takes for the system response to reach the target value from an initial state of zero. It is not the amount of time it takes to achieve steady-state, only the amount of time it takes to reach the desired target value for the first time.

g. Percent Overshoot

Underdamped systems frequently overshoot their target value initially. This initial surge is known as the overshoot value. The ratio of the amount of overshoot to the target steady-state value of the system is known as the percent overshoot. A present overshoot represents an overcompensation of the system and can output dangerously large output signals that can damage a system.

h. Steady-state error

Sometimes a system might never achieve the desired steady-state value but instead will settle on an output value that is not desired. The difference between the steady-state output value to the reference input value at steady-state is called the steady-state error of the system [42].

i. Settling time

After the initial rise time of the system, some systems will oscillate and vibrate for an amount of time before the system output settles on the final value. The amount of time it takes to reach a steady state after the initial rise time is known as the settling time. Notice that damped oscillating systems may never settle completely, so we will define settling time as being the amount of time for the system to reach, and stay in, a certain acceptable range.

3. Controller

In control systems, a controller is a mechanism that seeks to minimize the difference between the actual value of a system (i.e. the process variable) and the desired value of the system (i.e. the set point). When one or more output variables of a system need to follow a certain reference over time, a controller manipulates the inputs to a system to obtain the desired effect on the output of the system. The important uses of the controllers include:

- Controllers improve the steady-state accuracy by decreasing the steady-state error
- As the steady-state accuracy improves, the stability also improves
- Controllers also help in reducing the unwanted offsets produce by the system.
- Controllers can control the maximum overshoot of the system
- Controllers can help in reducing the noise signals produced by the system.
- Controllers can help to speed up the slow response of an over-damped system

4. Conventional and Intelligent controller

The term conventional (or traditional) control is used here to refer to the theories and methods that were developed in the past decades to control dynamical systems, the behavior of which is primarily described by differential and difference equations. The conventional control system is designed today using mathematical models of physical systems. A mathematical model, which captures the dynamic behavior of interest, is chosen and then a control design technique is applied, aided by CAD packages, to design the mathematical model of an appropriate controller. The controller is then realized via hardware or software and it is used to control the physical system [42].

Note that this mathematical framework may not be general enough in certain cases. The fact is that there are problems of control that cannot be formulated and studied in the conventional differential/difference equation mathematical framework. Conventional control methods need to be enhanced, so that control systems can be designed that cope with significant changes in the plant, environment, and objective. To address these problems systematically, several methods have been developed that are collectively known as intelligent control methodologies.

Intelligent control is a computationally efficient procedure of directing to a goal of a complex system with incomplete and inadequate representation and incomplete specifications of how to do this (acting appropriately in an uncertain environment). An intelligent system can act appropriately in an uncertain environment, where appropriate action is that which increases the probability of success, and success is the achievement of behavioral sub-goals that support the system's ultimate goal. It can be observed to grow and evolve, both through growth in computational power and through the accumulation of knowledge of how to sense, decide and act in a complex and changing world.

From the viewpoint of controller theory intelligence might be defined as a knowledgeable "helmsman of behavior". Intelligence is the integration of knowledge and feedback into a sensory-interactive goal-directed control system that can make plans, and generate effective, purposeful action directed toward achieving them [42].

Problems of interest in intelligent systems require the development of novel concepts, approaches, and methods. In particular, while computer science typically deals with static systems and no real-time requirements, control systems typically are dynamic and all control laws, intelligent or not, must be able to control the system in real-time. So in most cases, one cannot just directly apply computer science methods to these problems. Modifications and extensions are typically necessary for example in the quantitative models used to study such systems.

This thesis studies the conventional type of controller taking proportional integral derivative controller and proposed fuzzy logic and Particle swarm optimization selecting from the intelligent controller based on the error optimization capacity to maintain the transient response of active power output frequency and power controlled for different operations.

2.4.1. Conventional PID Controller

Conventional PID control (proportional-integral-derivative) is the widest type of automatic control and is a generic control loop feedback mechanism widely used in industrial control systems. Even though it has a relatively simple algorithm/structure as shown in Figure 2.12, there are many small variations in how it is applied in industry. A PID controller will correct the error between the output and the desired input or set point by calculating and giving an output of correction that adjusts the process accordingly.

The PID formulas are simple and can be easily adopted to correspond to different controlled plants but they can’t yield a good control performance if a controlled system is of high order and nonlinear. The PID controller is a combination of the PI and PD controllers. The PD control, as in the case of the lead compensator, improves the. Transient-response characteristics improve system stability and increase the system bandwidth, which implies a fast rise time.

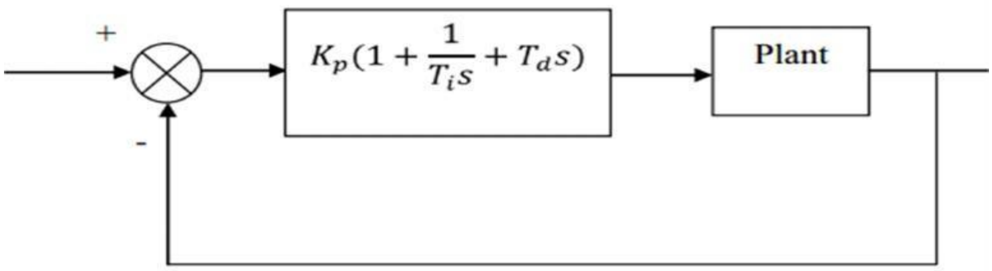

Figure 2.12 Conventional PID plant diagram

2.4.2. Intelligent Fuzzy Logic Controller

In 1965, Lotfy A. Zadeh of the University of California at Berkeley published "Fuzzy Sets" which laid out the mathematics of fuzzy set theory and, by extension, fuzzy logic. Zadeh had observed that conventional computer logic couldn't manipulate data that represented subjective or vague ideas, so he created fuzzy logic to allow computers to determine the distinctions among data with shades of gray, similar to the process of human reasoning. Fuzzy logic, as its name suggests, is the logic underlying modes of reasoning which are approximate rather than exact. FLCs are very useful when an exact mathematical model of the plant is not available; however, experienced human operators are available for providing qualitative rules to control the system. Fuzzy logic, which is the logic on which fuzzy logic control is based, is much closer in spirit to human thinking and natural language than the traditional logic systems. It provides an effective means of capturing the approximate, inexact nature of our knowledge about the real world. Viewed in this perspective, the essential part of the fuzzy logic controller (FLC) is a set of linguistic control rules related to dual concepts of fuzzy implication and the compositional rule of inference.

In essence, the FLC provides an algorithm that can convert the linguistic control strategy based on expert knowledge into an automatic control strategy. The methodology of the FLC appears very useful when the processes are too complex for analysis by conventional quantitative techniques. Fuzzy logic is a derivative from classical Boolean logic and implements soft linguistic variables on a continuous range of truth values to be defined between conventional binary i.e. [0, 1]. It can often be considered a subset of conventional set theory. Fuzzy logic is capable to handle approximate information systematically and therefore it is suited for controlling nonlinear systems and for modeling complex systems where an inexact model exists or systems where ambiguity or vagueness is common. The importance of fuzzy logic derives from the fact that most modes of human reasoning and especially common sense reasoning are approximate. In doing so, the fuzzy logic approach allows the designer to handle efficiently very complex closed-loop control problems [18].

According to the oxford dictionary, the word intelligent is derived from intellect, which is the faculty of knowing, reasoning and understanding. Intelligent behavior is therefore the ability to reason, plan and learn, which in turn requires access to knowledge.

Artificial intelligence is a b**y-**product of the information technology revolution and is an attempt to replace human intelligence with machine intelligence. An artificial intelligent control system combines the techniques from the field of artificial intelligence with those of control engineering to design an autonomous system that can sense, reason, plan, learn and act intelligently. Such a system should be able to achieve sustained desired behavior under conditions of uncertainty, which include [17].

- Uncertainty in plant models
- Unpredictable environmental changes
- Incomplete, inconsistent, or unreliable sensor information
- Actuator mal function.

The term ‘‘intelligent control’’ has a more general meaning and addresses more general control problems. That is, it may refer to systems that cannot be adequately described by a differential/difference equations framework but require other mathematical models, such for example, discrete event system models. More often, it treats control problems, where a qualitative model is available and the control strategy is formulated and executed based on a set of linguistic rules. Overall, intelligent control techniques can be applied to ordinary systems and more important to systems whose complexity defies conventional control methods. There are three basic approaches to intelligent control: knowledge-based expert systems, fuzzy logic, and neural networks. All three approaches are interesting areas of research and development. For this research fuzzy logic controller was designed.

1) Logic

Logic is the science of reasoning. Symbolic or mathematical logic has turned out to be a powerful computational paradigm. Not only does symbolic logic help in the description of events in the real world but has also turned out to be an effective tool for inferring or deducing information from a given set of facts [17].

2) Fuzzy logic

An objective of fuzzy logic has been to make computers think like people. Fuzzy logic can deal with the vagueness intrinsic to human thinking and natural language and recognizes that its nature is different from randomness. Using fuzzy logic algorithms could enable machines to understand and respond to vague human concepts such as hot, cold, large, small, etc. It also could provide a relatively simple approach to reaching definite conclusions from imprecise information. Fuzzy logic has the advantage of modeling complex, nonlinear problems linguistically rather than mathematically and using natural language processing (computing with words) [17].

2.4.2.1. Fuzzy Set Theory

Classical sets

A set is defined as a collection of objects that may share certain characteristics. For example, one may define a set of positive integers, a set of students with passing grades, and a set of honest politicians. Each object is referred to as an element or member of the set. In a classical set, an object x is either a member of a given set A (expressed as xεA) or not a member (expressed as x ∉ A); partial membership is not allowed.

- There are numerous ways to define a set:
- One may specify the properties of its elements.
- One may list all the members of the set.
- One may use a formula to define the set.

Membership function

- A membership function, μ, can be used to define a set. $\mu A(x) = 1$ if $x \in A$, and $\mu A(x) = 0$ if x ∄ A for all values of x.
- Let all the numbers under consideration, i.e. the universe of discourse, be defined as {1, 2, 3, 4, 5, 6, 7, 8, 9, 10}.
- Then, the set of odd numbers can be expressed as {(1,1), (2,0), (3,1), (4,0), (5,1), (6,0), (7,1), (8,0), (9,1), (10,0)}.
- Where each member of the universe of discourse is associated with a membership value in the form (#, μ). The numbers 1, 3, 5, 7, and 9 are associated with μ = 1 because they form the set of odd numbers extracted from the universe of discourse. This method of defining a set can be easily extended to define a fuzzy set by allowing partial membership.

Universal Set

The set that consists of all the elements of interest for a particular application (the universe of discourse) is referred to as the universal set. It is the mother of all sets; any set that is not universal is a subset. One may write A ⊂ I to mean that a set A (any set) is a subset of the universal set I.

2.4.2.2. Operations on Fuzzy Sets

The three basic logic operations are the operations most commonly used in engineering applications.

Complement

The absolute complement of a fuzzy set A is denoted by $\overline{A}$ and its membership function is defined by: $\mu\overline{A}$ (x) = 1 – μA(x) for all x ϵ X

Union

The union of two fuzzy sets A and B is a fuzzy set whose membership function is defined by μ A ∪ B (x) = max [μA(x), μB(x)]

Intersection

The intersection of two fuzzy sets A and B is a fuzzy set whose membership function is defined by μ A ∩ B (x) =min [μA(x), μB(x)]

2.4.2.3. Fuzzy Logic Controller and Design

The basic block diagram of the fuzzy logic controller is shown under.

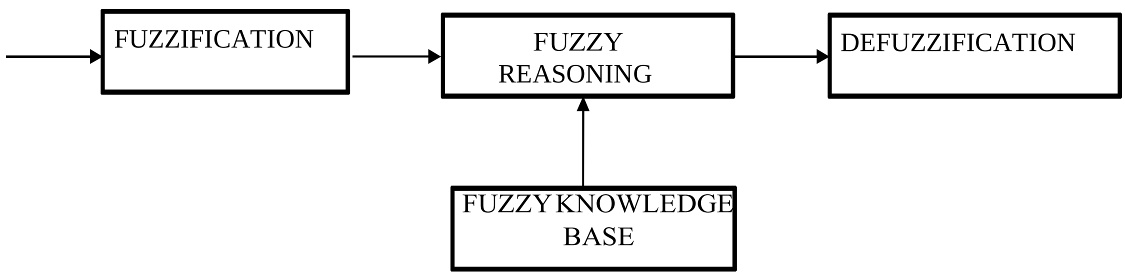

Figure 2.13 Basic structure of a fuzzy logic controller

The main building units of an FLC are a fuzzification unit, a fuzzy logic reasoning unit, a knowledge base, and a defuzzification unit. Defuzzification is the process of converting inferred fuzzy control actions into crisp control actions [17].

In the design of a fuzzy logic control system, it is assumed that: a solution exists, input and output variables can be observed and measured, an adequate solution (not necessarily an optimum one) is acceptable and a linguistic model can be created based on the knowledge of a human expert.

The basic configuration of the Fuzzy Logic Controller (FLC) consists of four main parts

- Fuzzification
- Knowledge base
- Decision-Making logic and
- Defuzzification

The functions of the above modules are described below.

The Fuzzification:

- Measure the values of input variables
- Performs a scale mapping that transforms the range of values of input variables into the corresponding universe of discourse.
- Performs the function of fuzzification that converts input into suitable linguistic values, which may be, viewed as labels of fuzzy sets.

The Knowledge Base:

It consists of a database and linguistic control rule base.

- The database provides necessary definitions, which are used to define linguistic control rules and fuzzy data, and manipulation in an FLC.
- The rule base characterizes the control goals and control policy of the domain experts through a set of linguistic control rules.

The Decision-Making Logic:

It is the most important part of FLC; it has the capability of simulating human decision-making based on fuzzy concepts and inferring fuzzy control actions employing fuzzy implications and the rules of inference in fuzzy logic.

The Defuzzification:

- A scale mapping that converts the range of values of input variables into the corresponding universe of discourse.

- Defuzzification yields a non-fuzzy, control action from an inferred fuzzy control action.

There are seven methods used for defuzzifying the fuzzy output functions. They are

- Max-membership principle,
- Centroid method,
- Weighted average method,
- Mean–max membership,
- Centre of sums,
- Bisector of area, and
- First of maxima or last of maxima

2.4.2.4. Selection of Membership Function:

The fuzzy logic system is widely used for control, system identification, pattern recognition problems, and many more applications from industry to academia. The membership functions (MFs) play a vital role in the overall performance of fuzzy representation. The MFs are the building blocks of fuzzy set theory, that is, fuzziness in a fuzzy set is determined by its MF. Accordingly, the shapes of MFs are important for the particular problem since they affect a fuzzy inference system. They may have different shapes such as triangular, trapezoidal, Gaussian, and so forth. The only condition an MF must satisfy is that it must vary between o and 1. The MFs can be of any shape and form as long as it maps the given data with a desirable degree of memberships. As far as the choice of MFs is concerned, it is for us to decide. This is where the fuzzy system offers individual degrees of freedom. With experience, one will come to know which shape of MF is good for the application under consideration.

As there are infinite numbers of ways to characterize fuzziness, there are infinite numbers of ways to graphically depict the MFs that describe this fuzziness. The choice of which of the methods to use depends entirely on the problem size and problem type. Instead of choosing the shape of the MF, setting the interval and number of MFs are also very important. For instance, to model a control system by fuzzy logic, it is really important to know how many MFs are needed and also choose the intervals of MFs. These two factors also have a great impact on the outcome of a fuzzy logic system.

In addition, looking at the distribution of the data is a good idea. Although, the trial and error method is often used for MF shape because there is no exact method for choosing the MFs. The shape of MFs depends on how one believes in a given linguistic variable. It is more a question of intuition than criteria. The only condition an MF must satisfy is that it must vary between 0 and 1. The function itself can be an arbitrary curve whose shape we can define as a function that suits us from the point of view of simplicity, convenience, speed, and efficiency. Therefore, the type of MF has a greater influence as it determines the computational time. Hence, the optimum model can be determined by varying the number/type of MFs for achieving the best system performance. Which shape is best if one uses fuzzy logic as a universal approximate is discussed in reference [39]. Also, a constrained interpolations scheme was developed for fitting an MF to a finite number of known membership values [40].

Generally speaking, triangular MF is one of the most encountered MF in practice. Of highly applied MFs, the triangular MFs are formed using straight lines. These straight-line membership functions have the advantage of simplicity. Gaussian MFs are popular methods for specifying fuzzy sets because of their smoothness and concise notation. These curves have the advantage of being smooth and nonzero at all points.

Triangular shapes represent fuzzy numbers, while trapezoid shapes represent fuzzy intervals. These are the simplest shapes. Other different shapes can be obtained from transformations of the triangle induced by linguistic modifiers, truth-functional modifiers, compositions, projections, and other operations.

The selection of MF shape is problem specific. Based on an extensive review of many works of literature, it can be concluded that the triangular MF is widely used because of its simplicity. Using various MF for given problems, usually Gaussian and triangular MFs are found to be closely performing well and better than other types of MF. In specific, the triangular MF is found to be better than

Gaussian MF. Zhao and Bose [41] compared the response of the system with various MFs and conveyed that the triangular MF is superior to any other MFs. Indeed, if one has no priority on the shape of MFs, triangular or trapezoidal shapes are simple to implement and fast for computation. However, if one has some priorities on their shapes it may be interesting to build MFs with shapes derived from these a priori shapes after some smoothing if needed.

2.4.3. Particle Swarm Optimization

Particle swarm optimization (PSO) is a population-based stochastic optimization algorithm motivated by the intelligent collective behavior of some animals such as flocks of birds or school of fish, which was developed by Kennedy and Eberhart (1995) [28]. PSO algorithm simulates animals' social behavior, including insects, herds, birds, and fishes. These swarms confirm a cooperative way to find food, and each member in the swarm keeps changing the search pattern according to the learning experiences of its own and other members.

The main design idea of the PSO algorithm is closely related to two types of research. One is the evolutionary algorithm, just like an evolutionary algorithm; PSO also uses a swarm mode which makes it simultaneously searches large regions in the solution space of the optimized objective function. The other is artificial life, namely, it studies artificial systems with life characteristics.

In studying the behavior of social animals with the artificial life theory, for how to construct the swarm artificial life systems with cooperative behavior by computer, MiIllonas proposed five basic principles (Van Deg Bergh 2001);

- Proximity; the swarm should be able to cany out simple space and time computations.
- Quality; the swarm should be able to sense the quality change in the environment and respond to it.
- Diverse response; the swarm should not limit its way to get the resources in a narrow scope.
- Stability; the swarm should not change its behavior mode with every environmental change.
- Adaptability; the swarm should change its behavior mode when this

change is worthwhile.

Note that the fourth principle and the fifth one are the opposite sides of the same coin. These five principles include the main characteristics of artificial life systems, and they have become guiding principles to establish the swarm artificial system.

In PSO, particles can update their positions and velocities according to the environmental change, namely, it meets the requirements of proximity and quality. In addition, the swarm in PSO does not limit its movement but continuously searches for the optimal solution in the possible solution space. Particles in PSO can keep their stable movement in the search space while changing their movement mode to adapt to the change in the environment. So particle swarm systems meet the above five principles.

To illustrate the production background and development of the PSO algorithm, here we first introduce the early simple model, namely the Boid (Bird-oid) model (Reynolds 1987). This model is designed to simulate the behavior of birds, and it is also a direct source of the PSO algorithm. [28]

The simplest model can be depicted as follows. Each individual of the birds is represented by a point in the Cartesian coordinate system, randomly assigned with initial velocity and position. Then run the program following “the nearest proximity velocity match rule,” so that one individual has the same speed as its nearest neighbor. With the iteration going on in the same way, all the points will have the same velocity quickly. As this model is too simple and far away from the real cases, a random variable is added to the speed item. That is to say iteration aside from meeting “the nearest proximity velocity match,” each speed will be added with a random variable, which makes the total simulation approach the real case. Heppner designed a “cornfield model” to simulate the foraging behavior of a flock of birds (Clerc and Kennedy 2002).[28]

Assume that there was a “cornfield model” on the plane, i.e., food location, and birds randomly dispersed on the plane at the beginning. To find the location of the food, they moved according to the following rules. First, we assume that the position coordinate of the cornfield is (x_o, y_0), and the position coordinate and velocity coordinate of individual birds are (x, y) and (v_x, v_y), respectively.

Distance between the current position and the cornfield is used to measure the performance of the current position and speed. The farther the distance to the "cornfield", the better the performance, on the contrary, the performance is worse. Assume that each bird has the memory ability and can memorize the best position it ever reached, denoted as P_{best}. a is velocity adjusting constant, rand denotes a random number in [0,1], and change in the velocity item can be set according to the following rules:[28]

If $x > p_{best}\,x$, $v_x = v_x - rand \times a$, otherwise, $v_x = v_x + rand \times a$.

If $y > p_{best}\,y$, $v_y = v_y - rand \times a$, otherwise, $v_y = v_y + rand \times a$.

Then assume that the swarm can communicate in some way, and each individual can know and memorize the best location (marked as g_{best}) of the total swarm so far. And b is the velocity adjusting constantly; then, after the velocity item was adjusted according to the above rules, it must also update according to the following rules:

If $x > g_{best}\,x$, $v_x = v_x - rand \times b$, otherwise, $v_x = v_x + rand \times b$.

If $y > g_{best}\,y$, $v_y = v_y - rand \times b$, otherwise, $v_y = v_y + rand \times b$.

Computer simulation results show that when a /b is relatively large, all individuals will gather to the "cornfield" quickly; on the contrary, if a /b is small, the particles will gather around the "cornfield" unsteadily and slowly. Through this simple simulation, it can be found that the swarm can find the optimal point quickly. Inspired by this model, Kennedy and Eberhart devised an evolutionary optimization algorithm, and after a sea of trials and errors; they finally fixed the basic algorithm as follows:

$$v_x = v_x + 2 * rand * (p_{best}\,x - x) + 2 * rand * (g_{best}\,x - x)$$

$$x = x + v_x$$

They abstracted each individual to be a particle without mass and volume, with only velocity and position, so they called this algorithm the "particle swarm optimization algorithm". On this basis, the PSO algorithm can be summarized as follows:

PSO algorithm is a kind of searching process based on a swarm, in which each individual is called a particle defined as a potential solution of the optimized problem in D -dimensional search space, and it can memorize the optimal position of the swarm and that of its own, as well as the velocity. In each generation, the particle information is combined to adjust the velocity of each dimension, which is used to compute the new position of the particle. Particles change their states constantly in the multi-dimensional search space until they reach a balance or optimal state, or beyond the calculating limits. The unique connection among different dimensions of the problem space is introduced via the objective functions. Many empirical shreds of evidence have shown that this algorithm is an effective optimization tool. The flowchart of the PSO algorithm is shown in Figure 2.14

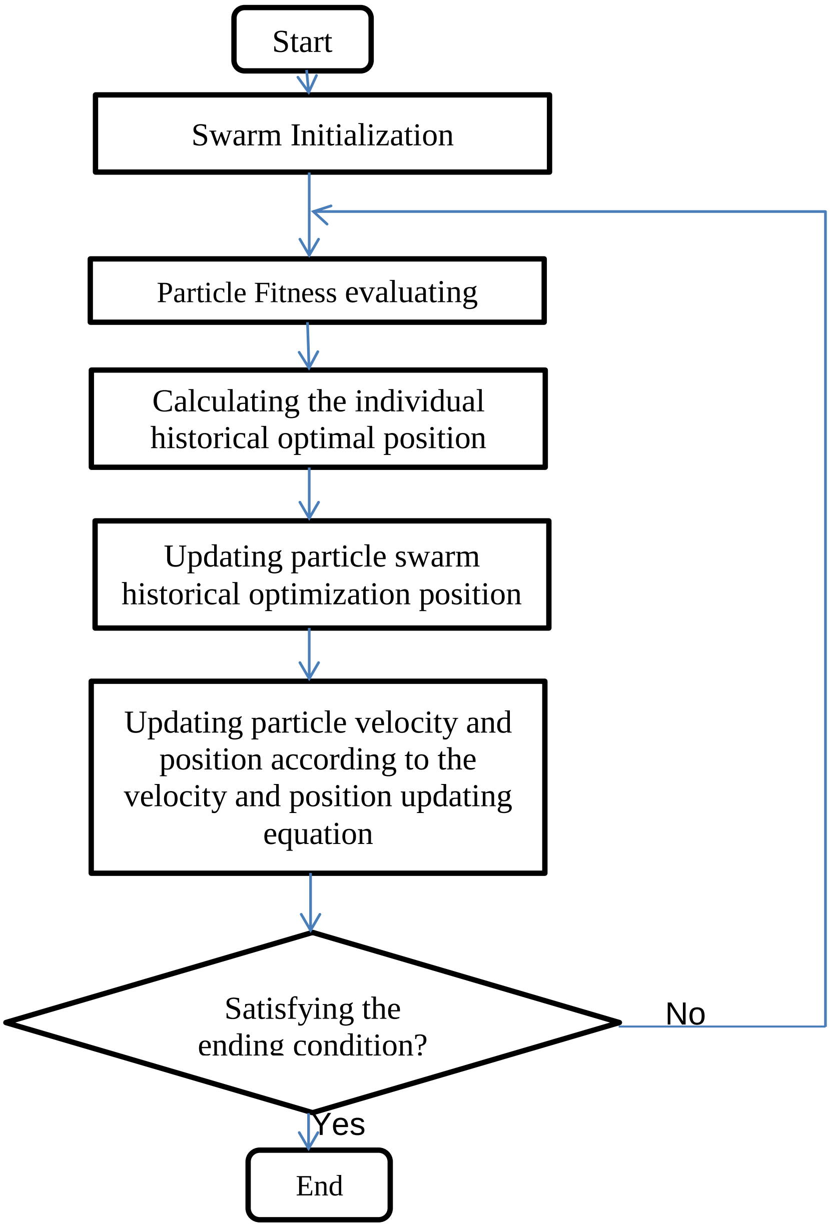

Figure 2.14 Flowchart of the particle swarm optimization algorithm [28]

The following gives a relatively complete presentation of the PSO algorithm. In the continuous space coordinate system, mathematically, the PSO can be described as follows. [28]

Assume that swarm size is N, each particle's position vector in D -dimensional space is $X_i = (x_{i1}, x_{i2}, \cdots, x_{id}, \cdots, x_{iD})$, the velocity vector is $V_i = (v_{i1}, v_{i2}, \cdots, v_{id}, \cdots, v_{iD})$, individual's optimal position (i.e., the optimal position that the particle has experienced) is $P_i = (p_{i1}, p_{i2}, \cdots, p_{id}, \cdots, p_{iD})$, swarm's optimal position (i.e., the optimal position that any individual in this swarm has experienced) is represented as $P_g = (p_{g1}, p_{g2}, \cdots, p_{gd}, \cdots, p_{gD})$. Without loss of generality, taking the minimizing problem as an example, in the initial version of the PSO algorithm, the updated formula of the individual's optimal position is:

$$p^d_{i,t+1} = \begin{cases} x^d_{i,t+1}, & \text{if } f(X_{i,t+1}) < f(P_{i,t}) \\ p^d_{i,t}, & \text{otherwise} \end{cases} \tag{2.2}$$

The swarm's optimal position is that of all the individual optimal positions. The updated formula of velocity and position is denoted as follows, respectively.

$$v^d_{i,t+1} = v^d_{i,t} + c1 * rand * (p^d_{i,t} - x^d_{i,t}) + c2 * rand * (p^d_{g,t} - x^d_{i,t}) \tag{2.3}$$

$$x^d_{i,t+1} = x^d_{i,t} + v^d_{i,t+1} \tag{2.4}$$

Since the initial version of PSO was not very effective in optimization problems, a modified PSO algorithm (Shiand Eberhart 1998) appeared soon after the initial algorithm was proposed. Inertia weight was introduced to the velocity update formula, and the new velocity update formula became:

$$v^d_{i,t+1} = \omega * v^d_{i,t} + c1 * rand * (p^d_{i,t} - x^d_{i,t}) + c2 * rand * (p^d_{g,t} - x^d_{i,t}) \tag{2.5}$$

Although this modified algorithm has almost the same complexity as the initial version, it has greatly improved the algorithm performance; therefore, it has achieved extensive applications. Generally, the modified algorithm is called the canonical PSO algorithm, and the initial version is called the original PSO algorithm. By analyzing the convergence behavior of the PSO algorithm, Clerc and Kennedy (2002) introduced a variant of the PSO algorithm with a constriction factor χ which ensured convergence and improved the convergence rate. Then, the velocity update formula became:

$$v^d_{i,t+1} = \chi(v^d_{i,t} + \phi_1 * rand * (p^d_{i,t} - x^d_{i,t}) + \phi_2 * rand * (p^d_{g,t} - x^d_{i,t})) \qquad (2.6)$$

There is no essential difference between the iteration formulas (2.5) and (2.6). If appropriate parameters are selected, the two formulas are identical.

PSO algorithm has two versions, called the global version and the local version, respectively. In the global version, two extremes of the track of the particle are the optimal position of p_{best} of their own and the optimal position g_{best} of the swarm. Accordingly, in the local version, aside from tracking its optimal position p_{best}, the particle does not track the swarm optimal position g_{best}, instead, it tracks all particles' optimal position n best in its topology neighborhood. For the local version, the velocity update equation (2.5) became:

$$V^d_{i,t+1} = \omega * v^d_{i,t} + c1 * rand * (p^d_{i,t} - x^d_{i,t}) + c2 * rand * (p^d_{l,t} - x^d_{i,t}) \qquad (2.7)$$

Where p_l was the optimal position in the local neighborhood. In each generation, the iteration procedure of any particle is illustrated in Figure 2.15. Analyzing the velocity update formula from a sociological perspective, we can see that in this updated formula, the first part is the influence of the particle's previous velocity. It means that the particle has confidence in its current moving state and conducts inertial moving according to its velocity, so the parameter ω is called inertia weight. The second part depends on the distance between the particle's current position and its optimal position, called the "cognitive" item. It means a particle's thinking, i.e., a particle's movement resulting from its own experience. Therefore, parameter c_1 is called the cognitive learning factor (also called the cognitive acceleration factor). The third part relies on the distance between the particle's current position and the global (or local) optimal position in the swarm, called the "social" factor. It means the information shared and cooperation among the particles, namely, particle moving coming from other particles' experiences in the swarm. It simulates the movement of good particles through cognition, so the parameter c_2 is called the social learning factor (also called the social acceleration factor).

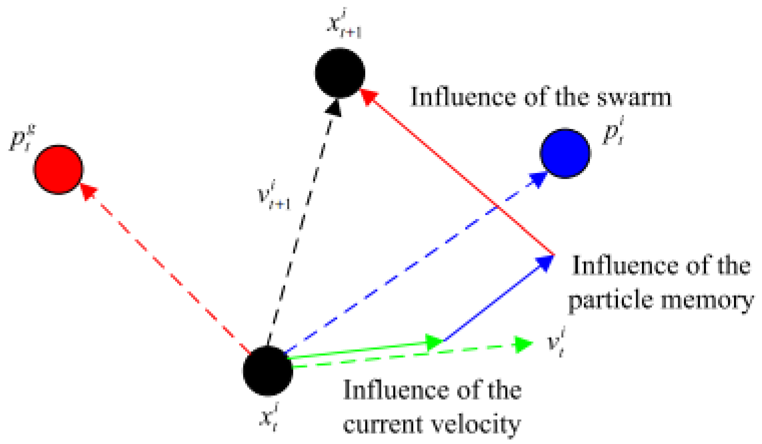

Figure 2.15 Iteration scheme of the particles

Due to its intuitive background, simplicity, ease of implementation, as well as wide adaptability to different kinds of functions, since the PSO algorithm has been proposed, it has obtained great attention. In the past twenty years, both the theory and application of the PSO algorithm have achieved great progress. Researchers have had a preliminary understanding of the principle, and its application has been realized in different domains.

2.4.3.1. Parameters Selection

There are several important parameters in the PSO algorithm, i.e., inertia weight ω (or constriction factor χ), learning factors c_1 and c_2, speed limits V_{max}, position limits X_{max}, swarm size, and the initial swarm. Some researchers fixed other parameters and only studied the influence of a single parameter on the algorithm, while some researchers also studied the effect of multiple parameters on the algorithm.

- **Inertia weight**

Generally, it is believed that in PSO, inertia weight is used to balance the global search and the local search, and a bigger inertia weight is tended for the global search while a smaller inertia weight is tended for the local search, so the value of inertia weight should gradually reduce with the time. Shi and Eberhart (1998) suggested that inertia weight should be set to [0.9, 1.2] and a linearly time-decreasing inertia weight could significantly enhance the PSO performance.

- **Learning factors c_1 and c_2**

The learning factors c_1 and c_2 represent the weights of the stochastic acceleration terms that pull each particle toward p_{bes}t and g_{best} (or n_{best}). In many cases, c_1 and c_2 are set to 2.0 which searches cover the region centered in p_{best} and g_{best}.

- **Speed limits V_{max}**

The speed of the particles was constrained by a maximum speed V_{max} which can be used as a constraint to control the global search ability of the particle swarm. In the original PSO algorithm, $\omega = 1$, $c_1 = c_2 = 2$.

Particles' speed often quickly increases to a very high value which will affect the performance of the PSO algorithm, so it is necessary to restrict particle velocity.

- **Position limits X_{max}**

Positions of the particles can be constrained by a maximum position X_{max} that can avoid particles flying out of the physical solution space. Robinson and Rahmat-Samii (2004) put forward their different control techniques, namely absorbing wall, reflecting wall, and an invisible wall. Once one of the

dimensions of a particle hit the boundary of the solution space, the absorbing wall set the velocity in that corresponding dimension to zero, while the reflecting wall changed the direction of particle velocity, and the particle was eventually pulled back to the allowable solution space by the two walls. To reduce the calculation time and avoid affecting the motions of other particles, the invisible walls did not calculate the fitness values of the particles flying out of the boundary.

- **Population size**

The selection of population size is related to the problems to be solved, but it is not very sensitive to the problems. The common selection is 20–50. In some cases, a larger population is used to meet special needs.

- **Initialization of the population**

Initialization of the population is also a very important problem. Generally, the initial population is randomly generated, but there are also many intelligent population initialization methods, such as using the nonlinear simplex method (Parsopoulos and Vrahatis 2002a), centroidal Voronoi tessellations (Richards and Ventura 2004), and orthogonal design. (Zhan et al. 2011) [28], to determine the initial population of the PSO algorithm, making the distribution of the initial population as evenly as possible, and helping the algorithm explore the search space more effectively and find a better solution.

Automatic control systems have assumed an increasingly important role in the development and advancement of modern civilization and technology. PID controller is the most popular in the automatic system. The setting and optimization of PID parameters are always important to study topics in the automatic control field. The control effect depends on proportion, differential, and integral which are the parameters of the PID controller. An original optimization method is a time-consuming method and cannot get a satisfactory control effect. To solve this problem, Particle Swarm Optimization (PSO) is applied to the PID controller. Establish a PID controller parameters model based on PSO, in which PID parameters act as a particle in the particle swarm, using minimizing integral of time-weighted absolute error (ITAE) as the optimization objective function, thereby performing PID control parameters optimization.

Therefore, Optimizing the PID controller parameter is significant. PID controller parameters are mainly adjusted by a person, which not only consumes much time but also cannot guarantee optimum performance. PSO has been widely used in the optimization of function neural networks pattern classification and other applications. In this case, I will design PID controller parameters by using PSO.

2.5. Gaps Identified

Following are the gaps identified in the modeling and simulation of the hydropower plant as per the literature review:

- Most of the articles are modeled by neglecting the tunnel and surge tank of a power plant, but in this, all component of the power plant is modeled.
- The control mechanisms used in most research are using conventional PID controllers which don’t tune by an intelligent optimization tool.
- Frequency Control is used more but here power control for both operation modes is studied in this thesis.

CHAPTER THREE

3. GG2 HEPP DYNAMIC MODEL

Physical description and mathematical deduction of the equations describing appropriate models of the hydraulic turbines, synchronous generators, and turbine governing systems, respectively, for their representation in power system dynamic studies, are required to model any power plant. This section presents a mathematical model of hydraulic systems, turbine, hydraulic actuator, and generator are modeled and complete Simulink block diagrams with all operating mechanisms are described.

3.1. Model of the Power Plant

Generating unit of the hydropower plant can be modeled by the superposition of two dependent sub-models, which are [19]

1. The turbine-governor model considers;
    - Mechanical dynamics of the generating unit.
    - Maintaining the power output.
2. The generator and excitation system model
    - Maintaining the voltage at the generator terminals. This model is not considered in this thesis.

The model considered here for the Gilgel Gibe II power plant was implemented in SIMULINK / MATLAB software and comprises the following dynamic sub-models:

- Hydraulic System
- Turbine Model
- Hydraulic Actuator
- Turbine Regulator (PID controller, Fuzzy Logic Controller, and PSO)

The block schemes of the complete model with its sub-model are presented in Figure 3.1

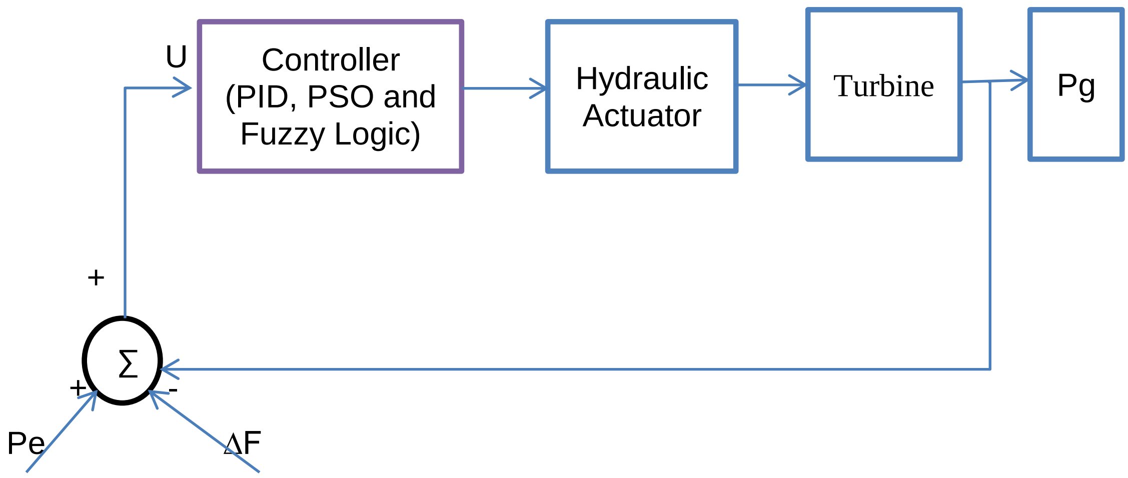

Figure 3.1General Representation of Sub-Model

All is in per unit, i.e. every signal is given in per unit (Pu). This simplifies an interface between the parts and the algorithm makes for modeling easier. Per unit value is calculated in the following way [20].

$$\text{Per unit} = \frac{\text{Actual}}{\text{Base}} \tag{3.1}$$

3.2. Basic Mathematical Models of GG2 HEPP

A typical layout of a hydroelectric power plant with a surge tank is shown in Figure 3.1 it consists of a reservoir with water level H_R (in meters), tunnel length L_1 (m), tunnel cross-section area A_1 (m^2), head of surge tank H_s (m), cross-section area of the surge tank As (m^2), penstock length L_2 (m), penstock cross-section area A_2 (m^2) and tail water head H_0 (m). Both H_R and H_0 are assumed to be constant [22].

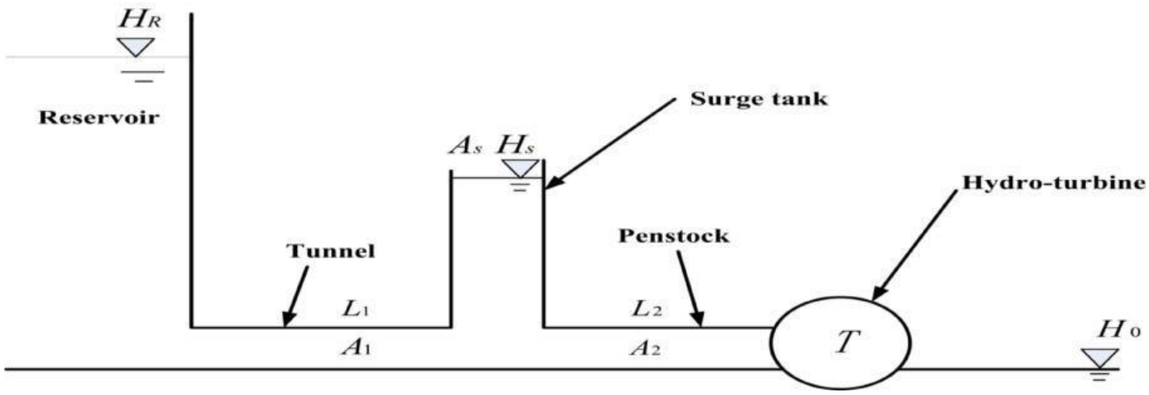

Figure 3.2 Typical Piping Structure of Gilgel Gibe II Hydro Power Plant

3.2.1. Model of the Hydraulic System

In a hydroelectric power plant, stored water flows from a high elevation to the hydro turbine; gravitational potential energy is converted into kinetic energy. Then, the turbine shaft, getting mechanical energy from the conversion, drives the machine to generate electricity. In a turbine, the power is controlled by regulating the flow into the turbine using the position of the nozzles. This regulation is achieved by the turbine governor, which is also called the speed governing system or turbine digital governing system. The digital governing system assures turbine-governor speed regulation and therefore frequency and active power, upon detecting load variations [7].

For dynamic stability studies, accurate mathematical modeling of power system components is necessary. The hydraulic system from wear to each unit turbine consists commonly of four (4) units comprising:

- Head race tunnel,
- Surge tank,
- Penstock

I. Head Race Tunnel

It joins the reservoir/wear and upstream surge tank together as shown in Figure 3.2. Since the inlet of the head race tunnel is constant for H and Q during hydrodynamic transients. Therefore, using the equation of continuity flow rate from the head is distributed to a surge tank and turbine admission as equation below [5].

$$q_2 = q_1 - q_s \tag{3.2}$$

Where:

- q_1 is the per unit flow rate deviation of the tunnel
- q_2 is the per unit flow rate deviation of penstock
- q_s is the per unit flow rate deviation of the surge tank.

The dynamics of the Head Race Tunnel is

$$h_1(s)\frac{d_{q1}}{d_t} = \frac{-h_1}{T_{W1}} \tag{3.3}$$

$$\frac{h_1(s)}{q_1(s)} = -T_{W1}(s) \tag{3.4}$$

Where:-

h_1 (per unit) is the head deviation of the tunnel input and output,

h_S is the hydraulic loss in the tunnel and

$T_{w1}(S)$ is the water inertia time of the tunnel represented by equation (3.5)[22].

$$T_{W1} = \frac{L_1 Q_R}{A_1 g H_r} \tag{3.5}$$

Gilgel Gibe II hydroelectric power plant parameter from Appendices A is inserted in equation (3.5)

$$T_{W1} = \frac{26000 * 24.53}{31.2 * 9.81 * 485} = 4.3sec$$

The water inertia time of the tunnel is 4.3 sec; in this thesis, the friction effect is neglected to reduce the complexity of the mathematical equation, so the transfer function used for the tunnel is represented in Figure 3.3.

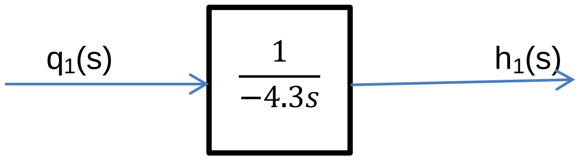

Figure 3.3 Head Race Tunnel Simplified Model

II. Surge Tank

The occurrence of pressure fluctuations, caused when the systems undergo the changes from one operational steady state to another is the water hammer effect. The classical problem with this water hammer is to insert a device called a surge tank [23]; the Dynamics of the surge tank can be expressed as equation (3.6).

$$h_s = \frac{1}{T_S} \int q_s \, d_t \tag{3.6}$$

$$\frac{d_h s}{d_q s} = \frac{1}{T_S S} \tag{3.7}$$

Where h (per unit) is the water head deviation of the surge tank, and T_S (is the filling time of the surge tank), the surge tank filling time is represented as the equation (3.8)[24]

$$T_S = \frac{A_S H_r}{Q_r} \tag{3.8}$$

By inserting the value of Gilgel Gibe II hydroelectric power plant from Appendices A into equation (3.8)

$$T_S = \frac{490.63 * 485m}{24.53} = 9700.4sec$$

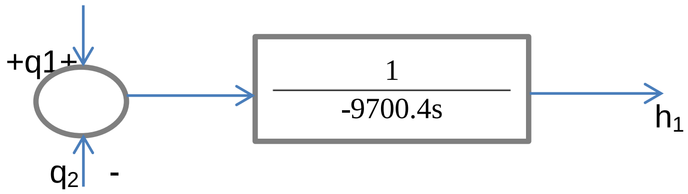

Figure 3.4 Surge Tank Simplified Modeled

III. Penstock

Penstock carries water from a surge tank to a turbine; the transfer function of penstock is related to the incremental head (H) and flow (Q) of penstock with a surge tank. Turbine power is the function of the head across the turbine and guide vane opening, in the model the traveling effects are represented by an equation, and then the penstock friction effect is neglected. [31] & [32]. The transfer function relating head and flow at the turbine end of the penstock

$$\frac{h_2}{q_2} = -Z_p \tanh\,(T_e S) \qquad (3.9)$$

$$Zp = \frac{T_{W2}}{T_e}$$

Where Zp normalized hydraulic impedance of penstock

T_e, elastic time of penstock

Thus, Z_pT_e is equal to the water starting time T_{w2} of the penstock at the rated load. With friction neglected. The approximation is therefore equivalent to assuming the water column to be an inelastic equation (3.9) gives

$$\frac{h_2}{q_2} = \frac{T_{W2}}{T_e} \tanh\,(T_e S) \qquad (3.10)$$

Under the assumption of the inelastic water hammer effect, the equation above is represented as tanh(TeS) approximated to TeS, then

$$\frac{h_2(S)}{q_2(S)} = -(T_{W2}S) \quad (3.11)$$

Where h_2 is per unit head deviation of penstock and T_{w2} is water starting time in penstock is represented by the formula of

$$T_{W2} = \frac{L_2 Q_R}{A_2 g H_R} \quad (3.12)$$

Inserting the value of Gilgel Gibe II hydroelectric power plant from Appendices A into equation (3.12), give

$$T_{W2} = \frac{1200 * 24.53}{6.154 * 9.81 * 485} = 0.996sec$$

Figure 3.5 Penstocks Simplified Modeled

Then the hydraulic system is modeled by an interconnected head race tunnel, surge shaft, and Penstock, the complete block diagram of the hydraulic system modeled is represented in Figure 3.6.

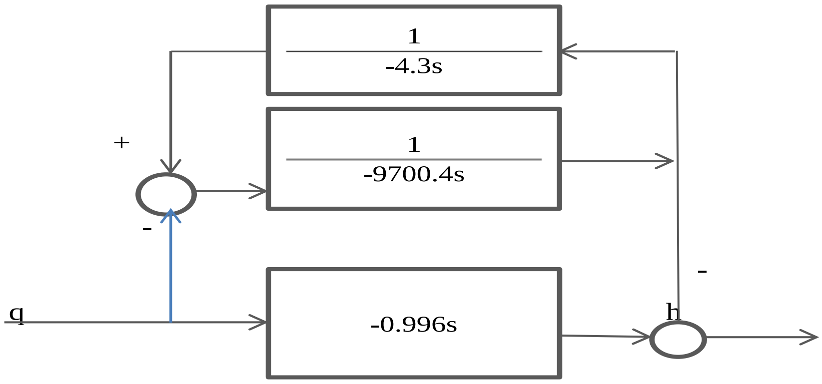

Figure 3.6 Complete Dynamic Block diagram of Hydraulic System

Where q is per unit hydraulic system flow rate deviation and h is per unit hydraulic system head deviation admission to the turbine, the power generated in the turbine is as proportional to these two parameters, so the next step is to model the mechanical system called turbine model.

3.2.2. Turbine Model

The turbine converts the potential energy of the water into the rotational kinetic energy turbine. The turbine used for the implementation of the Gilgel Gibe II hydroelectric power plant is the impulse turbine because of its high head (485m). As parameters describing the mass transfer and energy transfer in the turbine, we will consider the water flow through the turbine Q and the moment M generated by the turbine, and that is transmitted to the electrical generator.

For small variations around an equilibrium point the turbine can be represented by the following linearized equations:

$$q = a_{11}\,h + a_{12}\,\omega t + a_{13}\,y \tag{3.13}$$

$$m = a_{21}\,h + a_{22}\,\omega t + a_{23}\,y$$

Where:

ωt (s): is the differential angular speed of the turbine (p.u.),

y (s): is the differential gate opening (p.u.),

m s): is the differential mechanical torque (p.u.).

Parameters a_{ij} are the partial derivatives of q & m with respect to h, $\omega_{t,}$ and y respectively, and they remain constant for variations near the equilibrium point (q_0, m_0). The values of these parameters depend upon the initial steady state point of the machine, and they have to be measured accurately in the field, or taken from model tests. The influence of these coefficients on the model accuracy is critical. [33]

From equations (3.13) & (3.10) the following equation may be deducted:

$$m = G_y y + G\omega \quad (3.14)$$

Where the transfer functions $G_y(s)$ & $G_\omega(s)$ relate the mechanical torque with the gate opening and speed respectively

$G_y(s) = a_{23}\,[1+A\,(T_{w2}/T_e)\tanh(T_e s)]/[1+a_{11}(T_{w2}/T_e)\tanh(T_e s)]$

$G_\omega(s) = a_{22}\,[1+B\,(T_{w2}/T_e)\tanh(T_e s)]/[1+a_{11}(T_{w2}/T_e)\tanh(T_e s)]$

$$A = a_{11} - a_{21}a_{13}/a_{23} \quad (3.15)$$

$$B = a_{11} - a_{21}a_{12}/a_{22}$$

As it can be seen from (3.15) the gain and phase of these transfer functions depend upon the operating point, using parameters a_{ij}.

A close examination of $G_y(s)$ reveals that this transfer function gain varies between two limit values at the odd and even harmonics of its characteristic hydraulic frequency $f_h = 1/4\,T_e$ respectively :

$$\text{limit1} \quad |G_y(s)| = a_{23}\,|A|_{|a11} \quad (3.16)$$

$$\text{limit2} \quad |\,Gy(s)\,| = a23 \quad (3.17)$$

It has to be noted here that this characteristic frequency f_h in the order of about 1 H_z, does not vary with load and depends only upon the dimensions of the penstock.

The transfer function $G_\omega(s)$ has similar behavior, and the same equations hold for its maxima and minima, except that parameters A and a_{23} are replaced by B and a_{22} respectively.

Standard values for parameters a_{ij} for an ideal lossless turbine at full load are: [33]

$a_{11} = 0.5$, $a_{12} = 0$, $a_{13} = 1$

$a_{21} = 1.5$, $a_{22} = 0$, $a_{23} = 1$

Where the dependence upon speed has been neglected partial derivatives can be extracted by differentiation of the following equations representing the laws of similitude:

$$Q = G\, H^{1/2} \tag{3.18}$$

$$M = Q\, H\, (n/n_b)/\Omega$$

Where capital letters have been used for the absolute p.u. values and $n = n_0/nb$ is the ratio of efficiencies at the current operating point over that of base values. For deviations around rated speed and head, the partial derivatives versus load are deduced:

$$a_{11} = 0.5G_0,\ a_{13} = 1.0, \tag{3.19}$$

$$a_{21} = 1.5\, n\, G_0,\ a_{23} = n$$

Where G_0 is the p.u. piston displacement at the current operating point "0". Variation of flow rate with speed, a_{12}, is usually considered to be negligible, [34], in which case the transfer function Gg(s) depends mainly on the so-called turbine gain a_{23}. Turbine gain is a critical parameter for an accurate approximation of unit dynamics and has to be measured precisely in the field. The deviation of mechanical torque with speed, a_{22}, known as the turbine's self-regulation, is negative with an absolute value usually near unity. In case this dependency of mechanical torque deviation upon speed is neglected, the transfer function $G_\omega(s)$ disappears. It is worth noting that more accurate values of turbine parameters, (23), can be deduced from the characteristic curves of the turbine, drawn from model tests, [35].

The water flow through the turbine Q and the moment M generated by the turbine variables can be expressed as non-linear functions of the turbine rotational speed N, the turbine gate position Y, and the net head H of the hydro system.

$$Q = Q\,(H, N, Y) \qquad (3.20)$$

$$M = M\,(H, N, Y) \qquad (3.21)$$

The above power of the turbine is nonlinear, to use simplify the method of control mechanism or to reduce the complexity of the system I can linearize the system at the operating system, and a better understanding of the model is possible via linearized representation.

Linearization of equations (3.20) and (3.21) around steady value is obtained:

$$\Delta M = \frac{\partial M}{\partial H}\Delta H + \frac{\partial M}{\partial N}\Delta\omega + \frac{\partial M}{\partial Z}\Delta Y \qquad (3.22)$$

$$m_t = a11\ h + a12\ \omega + a13y$$

$$\Delta Q = \frac{\partial Q}{\partial H}\Delta H + \frac{\partial Q}{\partial N}\Delta\omega + \frac{\partial Q}{\partial Z}\Delta Y \qquad (3.23)$$

$$q = a_{21}h + a_{22}\omega + a_{23}y$$

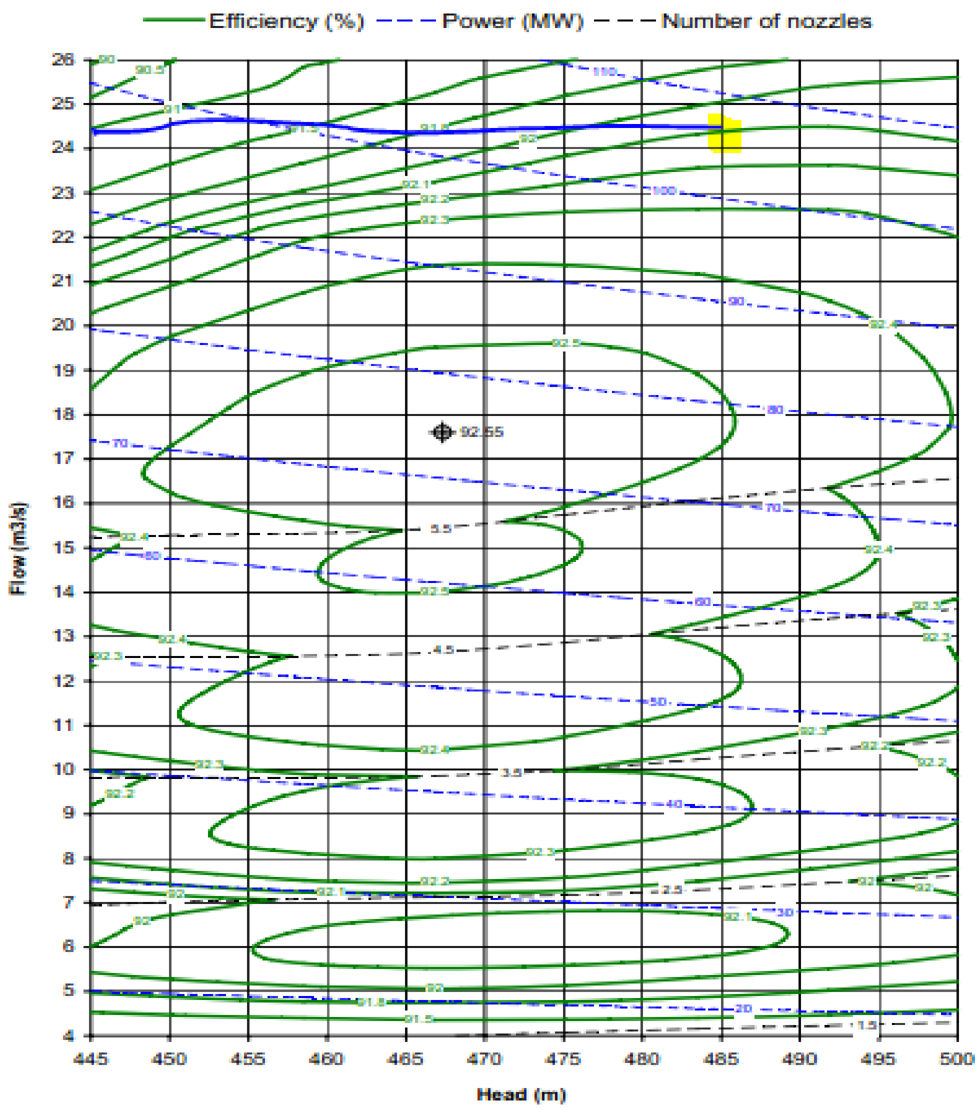

Figure 3.7 Hill chart for Gilgel Gibe Two HEPP vertical Pelton turbine

The six constants/ coefficients of equations (3.22) and (3.23) represent the main non-linear characteristics of the turbine depending on machine loading. Some proposed values of these constants from turbine characteristic equations can be used [33]. According to the Hill chart of the Gilgel Gibe II HEPP vertical Pelton turbine Figure 3.7 shows at the operating point, the efficiency has become 92.1%. [24]. at the maximum opening of the gate is 97.5%.

Table 3.1 Value of linear Turbine Coefficients

Turbine linear coefficient	Standard Ideal (p.u)	Reference (p.u) [33]	Value of linear coefficients of GG2 HEPP Turbine Model (p.u)
a_{11}	0.5	0.5G0	0.4
a_{12}	0	0	0
a_{13}	1	1	1
a_{21}	1.5	1.5 n G0	1.3
a_{22}	0	0	0
a_{23}	1	n	0.921

Substitute the value of linearized coefficients of GG2 HEPP Turbine model from above Table 3.1 in the equation of (3.24)and (3.25)

$$m(t) = 1.3h + 0\omega + 1y \quad (3.24)$$

$$q = 0.4h + 0\omega + 0.921y \quad (3.25)$$

The corresponding transfer function block diagram is shown bellow

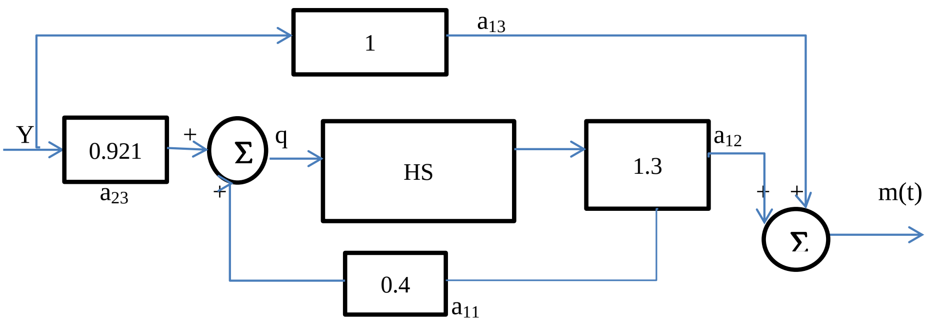

Figure 3.8 Block Diagram Representing Linearized Turbine

From this power generated can be calculated as the product of linearized turbine moment and rated speed [26][43].

$$Pg = mt * \omega = mt * \frac{2\pi n}{60} \quad (3.26)$$

Inserting the value of rated speed n, 333.33rpm, and the value is generated power bellow

$$Pg = mt * \frac{2 * \pi * 333.33\, rpm}{60}$$

$$Pg \;=\; mt \;*\; 34.91 \quad (3.27)$$

Per unit power generated value is represented as, where the rated unit of Gilgel Gibe II is 105MW

$$p_g\,(pu) = \; m_t * \frac{34.91}{105} = m_t * 0.33$$

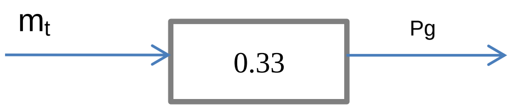

Figure 3.9 Generating Power Simplified Model

3.2.3. Gate Servo Mode

Gate movement is driven by the hydraulic system, and the relationship between the control signal Y_{ref} and the gate Servomotor stroke Y can be expressed with a first-order equation (3.28) [27]

$$\frac{y}{Y_{ref}} = \frac{1}{T_S S \; + \; 1} \quad (3.28)$$

T_s is the response time of the gate servomotor, Subsisting the value time constant for a hydraulic actuator for Gilgel Gibe II hydroelectric power plant (Ta=0.3second) the got, the hydraulic actuator transfer function is as follows:

$$\frac{y}{Yref} = \frac{1}{0.3S \ + \ 1} \tag{3.29}$$

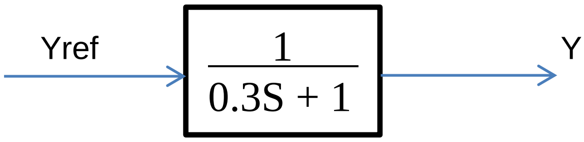

Figure 3.10 Opening gate modeled

3.2.4. Generator Unit and Network

If the generator unit supplies for an isolated load, then the dynamic process of the generator unit considering the load characteristic is represented as the equation below [21], for the isolated operation the equation used is modeled as equation (3.30)

$$\frac{d[x(t)]}{d[m(t) - mgo]} = \frac{1}{TaS + eg} \tag{3.30}$$

Where Ta (s) is the generator unit mechanical time and eg is the rotational loss coefficient. Ta is determined by

$$T_a = \frac{J_g X^2 r 10^{-3}}{3600 s P_r} \tag{3.31}$$

Where, J_g (KN/m2) is the generator unit inertia torque, Pr (kW) is the generator-rated power output and Xr (r/min) is the rated speed.

$$T_a = \frac{612.9 * 10^4 \, Nm^2 * (333.33rpm)^2 * 10^{-3}}{3600s * 105 * 10^6 W}$$

$$T_a = 6.5sec$$

Inserted the value of Gilgel Gibe II hydroelectric power plant, the Gilgel Gibe II hydroelectric power plant generator unit mechanical time is 6.5sec and where rotation loss coefficient is neglected. Inserted the value to the equation (3.30) yield that the transfer function below

$$\frac{d[x(t)]}{d[m(t) - mgo]} = \frac{1}{6.5s}$$

As well as power generated as the product of the momentum of the turbine and rated speed of the turbine, the power load is the same as the product of this load momentum and rated speed.

3.3. Power and Frequency Control

A power controller is used to keep the power of a unit equal to the set value. This kind of power controller is used to enable power changes to be made at a certain rate. Up to synchronization, the frequency control is active.

Power Control Structure

By eliminating speed control, power control may directly drive the guide vanes and perform primary control action. Since the speed control is deactivated, power control settings are tuned to perform satisfactory primary control action.

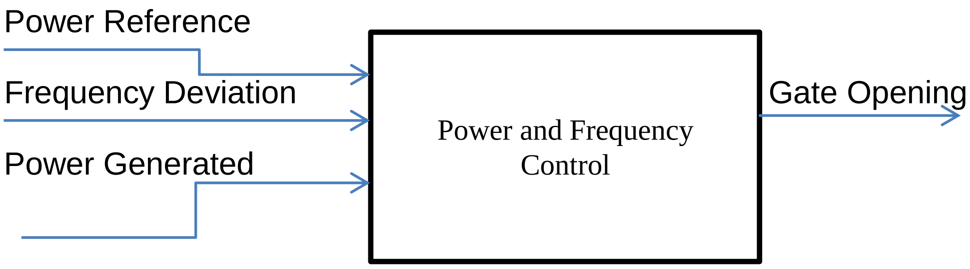

Figure 3.11 Power Control Model block diagram

The controller tries to diminish the error signal generated by three inputs;

- Active power reference
- Output power generated and
- Frequency change
- Speed droop

The active power reference is received from the national load dispatch networked system. This signal may be received for each unit or total generation in a plant. The received reference signal is changed by frequency bias. All the variables in the governor system are per-unit values. This power control is designed by PID-tuned particle swarm optimization, existed PID controller, and a Fuzzy logic controller.

The grid-connected mode has two control modes

- Power control mode and Frequency control mode

The isolated mode only in

- Frequency control mode

3.3.1. Speed Governor for Isolated and Network Operation

The governor system with various for different operating conditions and control modes is studied. In case of frequency increase (decrease) in the grid, each power generation unit reduces (adds) a fixed percentage of its total rating output power multiplied by the amount of the change in the network frequency from (to) its output power. The amounts of this power can be calculated from equation (3.32). [37]

$$\frac{\Delta f}{fn} = -\rho\frac{\Delta Pg}{Pn} \tag{3.32}$$

Where: ρ is speed drop, fn is the nominal frequency (1pu), and pn is nominal power (1pu). The speed drop was taken from Gilgel Gibe II hydroelectric power plant for different operating principles.

3.3.2. Existing Conventional PID controller

The PID controller in this thesis regulates the active power production as a response to the variation of load demand; hence the frequency of the system network at nominal value, By regulating the guiding unit of the impulse wheel, power regulation is possible. The system of Gilgel Gibe 2 a hydropower plant currently uses a PID controller. A PID controller continuously calculates an error (t) as the difference between a set point (t) and a measured process value (t). The PID controller tries to minimize the error over time by adjusting the control value u (t), in a standard for proportional integral derivative control can be expressed as equation(3.3). [37]

$$U(t) = Kp(e(t) + \frac{1}{Ti}\int_0^i e(t)dt + Td\frac{d}{dt}e(t)) \tag{3.33}$$

Where u is the control value, K_P is the gain; T_i is the integral time and T_d is the derivative time. For this thesis the value of all proportional, integral, and derivative coefficients is taken from the manual of the Gilgel Gibe II hydroelectric power plant but, this value of the coefficient is different for a different mode of operation.

3.3.3. Fuzzy Logic Controller

It gathers plant output data, compares it to the reference input, and then decides what the plant input should be to ensure that the performance objectives will be met.

I take the frequency and power difference from the measuring system as an input for the Fuzzy inference system. Plant frequency and power are compared with references to find frequency deviation. This frequency difference is input for the Fuzzy inference system. The output control signal of the Fuzzy inference system is a control signal for the Gate opening mechanism. The gate-opening mechanism comprises a servomotor. This control signal drives the servomotor which intern controls the gate opening. It uses error and change in error as input and gate opening as an output of the variable, to open and close the nozzle according to the rule given in the rule. The triangular membership function is selected because of its better performance than other membership function linguistic sets.

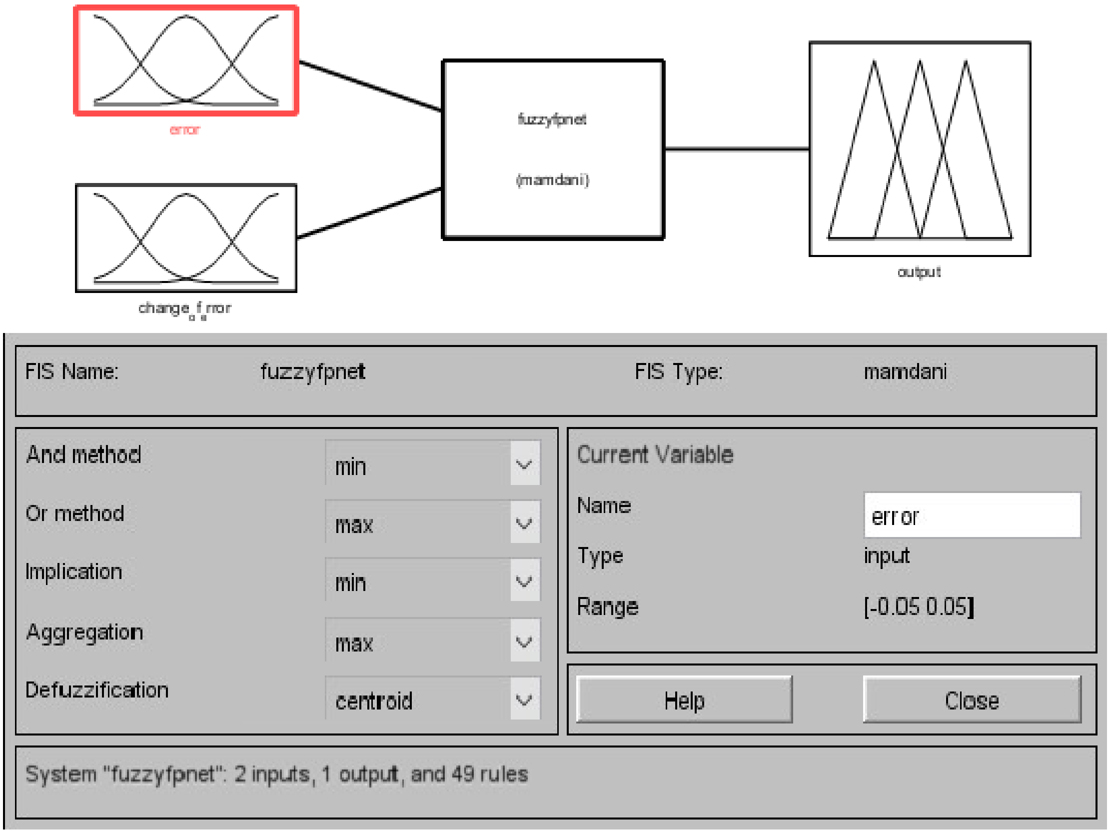

Figure 3.12 Mamdani Fuzzy Logic Controllers

3.4. Operating Principle and Overall System

Interconnected all models in one complete block diagram as shown in Figure 3.13 and Figure 3.14 for different operation modes to get all desired values by the control system is PSOPID, PID, or Fuzzy Logic Controller, and all of the whole transfer functions and blocks are shown in section 3 above. All value is given as per unit. For normal operation, which means the isolated and the network-connected operation with load, there are two control modes: frequency and power control. This study established a governor model with a switchover function of control mode. The S_1 and S_2 are selectors between different frequency and power signals, and the zero input to the selector means no input signal. S_3, S_4, and S_5 selectors to select the existing PID, Fuzzy logic, and PSOPID controller for the input of servo to control the gate operation.

3.4.1. Grid Connected Operation

For simulations in a grid-connected environment, the model has been seen in Figure 3.13. In Figure 3.13 much of the same signal processing occurs but the regulator loop is power dependent, and the governor regulates towards a power reference and droops characteristics. Changing the value of grid frequency provides a change in the system's stability. The system will then automatically regulate the power output from the turbine to the value decided by the droop.

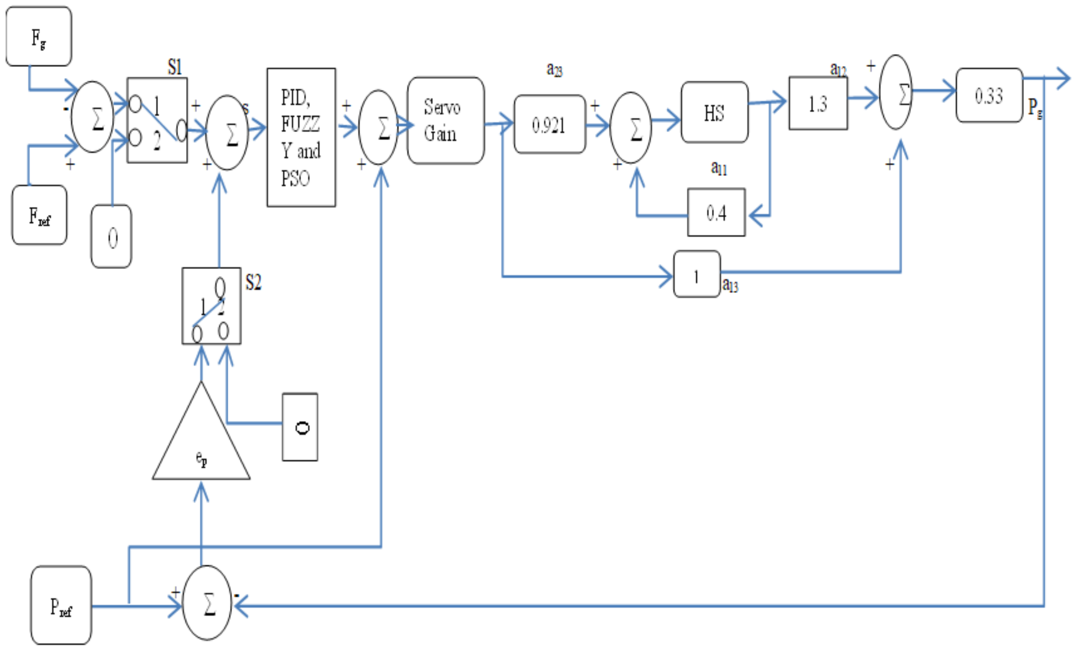

Figure 3.13 Overall Simplified Model of Interconnected Operation

3.4.2. Isolated Operation

The model comprises a change in frequency reference value that sends the signal to a summation block. The summation block subtracts the process frequency value which becomes an end and sends it into the PSOPID tuned, existing PID controller and fuzzy logic controller. The controller then transfers the signal into what is then represented as the guide vane opening y. Through turbine dynamics, the amount of flow q is then given by the guide vane opening and sent into the hydraulic system.

The hydraulic system is then transferring the signal into the pressure head, h. This pressure is then processed through turbine dynamics one last time giving turbine power as an output that is power generated from the turbine. The speed is then represented after the torque (m_t)/power (P_g) signal has gone through the generator dynamics also called the electromechanical system. The power provided to the generator is turbine power subtracted from power demands (P_L) giving P. Since the system is in per unit values, the values can easily get converted by multiplying with the base value of power (105MW). The same counts for the speed which can be multiplied with both the base value of the grid frequency (50Hz) and the rated generator speed (333.33 rpm). The general block model is shown in Figure 3.14.

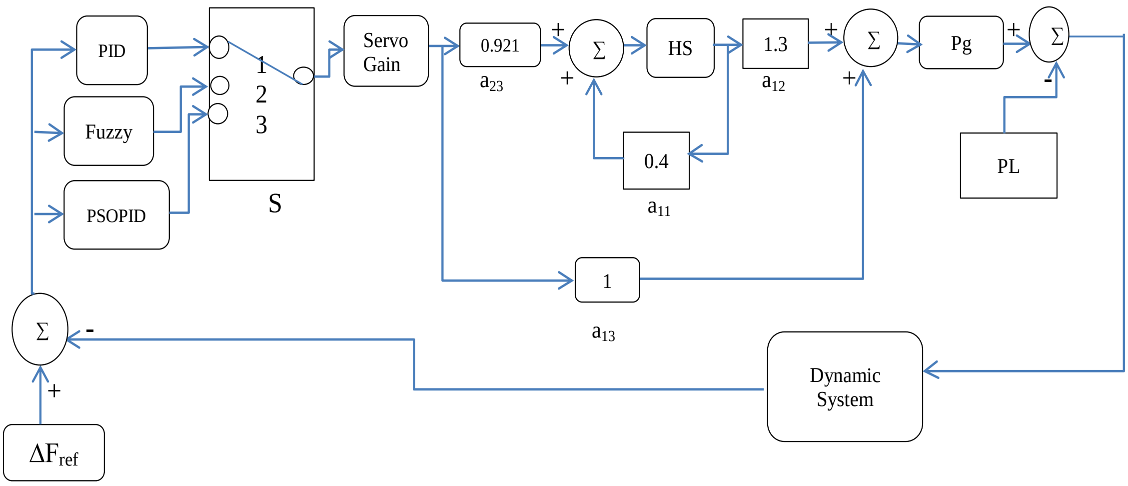

Figure 3.14 Overall Modeled block Diagram for Isolated Operation

CHAPTER FOUR

4. CONTROLLER DESIGN

This chapter presents the design and analysis of the proposed control system for a hydropower plant. Particle swarm optimization (PSO) code for tuning conventional PID, Existing PID conventional controller, and fuzzy logic controller designed in MATLAB R2013a environment.

4.1. Existing PID Controller

The electrical power and the mechanical turbine rotor speed have been compared as the model is simulated in per unit (Pu) form. Figure 4.1 shows the structure of the error acquisition system to get the error signal which is the input of the PID controller.

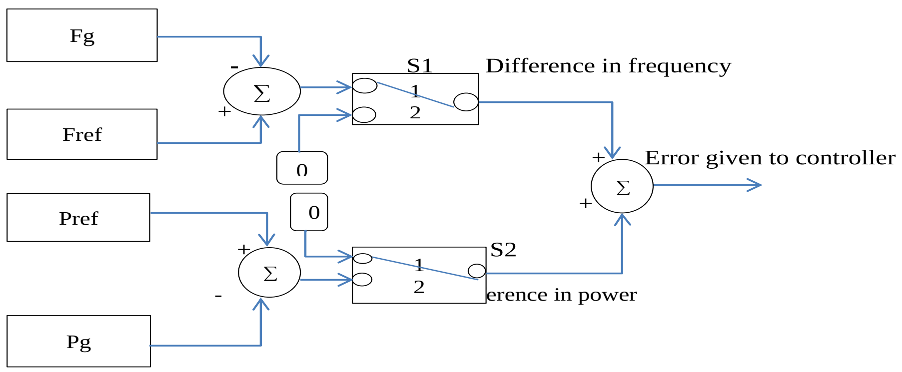

Figure 4.1 Structure of Error Acquisition System

The difference in frequency can be obtained by comparing the reference frequency (F_{ref}) and actual generator frequency (F_g). The comparison of reference power (P_{ref}) and a generator output active power (P_g) provides the difference in power. The error from the difference in frequency and the difference in power sums up and is given to the controller. In stable situations, the error should be zero thus; the divergence of frequency and power is fed into the PID controller to take corrective action maintaining the stabilization of the power generation system.

A PID controller tries to correct the error between a measured process variable and the desired set point by calculating and then outputting a corrective action that can adjust the process accordingly and rapidly, to keep the error minimal. The proportional value determines the reaction to the current error, the integral value determines the reaction based on the sum of recent errors, the derivative value determines the reaction based on the sum of recent errors, and the derivative value determines the reaction based on the rate at which the error has been changing, by tuning the three constants in the PID controller algorithm, the controller can provide a control action designed for specific process requirements. Note that the use of the PID algorithm for control does not guarantee optimal control of the system or system stability. The input for the PID controller for all cases in Gilgel GibeII hydroelectric power plant is taken from Gilgel Gibe II hydroelectric power plant manual and tuned at its operation mode. [15]

Table 4.1 Value of PID controller for Isolated Operation

Parameter	Value
Kp	1.6
Ki	14
Kd	2
ep	4

Table 4.2 Value of PID Controller for Network Connected Operation

Parameter	Value
Kp	1.6
Ki	3
Kd	2
ep	5

4.2. Fuzzy Logic Controller Design

This thesis describes a Fuzzy logic control system for the Gilgel Gibe II hydroelectric power plant to compare with the proposed PSOPID and existing PID to determine the best intelligent controller. We take the frequency difference and power difference as input for the fuzzy interference system. Frequency deviation and power deviation selectively as input for the Fuzzy inference system, and the output control signal of Fuzzy is the control signal for the Gate opening mechanism. This control signal drives the servomotor which intern controls the gate opening [27].

The following steps are applied to design the fuzzy logic controller.

- First, all the information about the system is collected.
- The control elements are identified to apply fuzzy logic.
- Input and output variables for the fuzzy logic controller are identified.
- The universe of discourse is defined by input and output.
- The fuzzy sets and the corresponding membership function shape are determined.
- The rule table is defined.
- The system is simulated with the defined fuzzy controller under different conditions of operation.

4.2.1. Input Variables

For load frequency changes, the process operator is assumed to respond to variables selectively such as the sum of power error or frequency error called error (e) and the rate of change of error de (t) they are the inputs to the fuzzy logic controller. These input variables are mathematically represented by the equation below.

$$e(t) = r(t) - y(t) \quad (4.1)$$

$$de(t) = e(t) - e(t-1) \quad (4.2)$$

Where r (t) is the desired output value and y (t) is the output of the controller, and e(t) and de(t) are the two fuzzy sets defined for fuzzification. Change in error is shown in MATLAB error minus error multiply with transport delay [10].

The type of membership function has a greater influence as it determines the computation time. Hence, the optimum model can be determined by varying the number/type of MFs for achieving the best system performance. The selection of MF shape is problem specific. Based on an extensive review of many works of literature, it can be concluded that the triangular MF is widely used because of its simplicity. Using various MF for given problems, usually Gaussian and triangular MFs are found to be closely performing well and better than other types of MF. In specific, the triangular MF is found to be better than Gaussian MF. Zhao and Bose [41] compared the response of the system with various MFs and conveyed that the triangular MF is superior to any other MFs.

I used it in this thesis as triangular because of its simplicity to understand and superior to any other MFs. Then the following seven triangular membership functions have been identified and applied. The linguistic variables assigned to the Mamdani-type fuzzy logic controller are**:**

Table 4.3 Membership of Fuzzy Logic Controller

EL	Extremely Large
VL	Very Large
L	Large
N	Negative
H	High
VH	Very High
EH	Extremely High

The range of the fuzzy logic controller is determined from the reference Gilgel Gibe II hydroelectric power plant unit wet commissioning, Digital Turbine governor. Where speed droop (bρ) =4 for isolated operation and network connected operation, the range of error and change in error as per the formula of equation (3.2) for both modes of operation.

Isolated System

At no load (PL=0) the change in frequency is zero and at full load rejection (full load added) change in frequency is 0.04. This means the system is isolated the base value of 50Hz frequency of Gilgel Gibe 2 varies from 47.5 Hz to 51,5 Hz or per unit varies from (-0.04 to 0.04), so the discourse of fuzzy logic controller for error and change in error in the isolated operation of Gilgel Gibe 2 is [-0.04 0.04].

Network Connected Operation

For the network connected to the Gilgel Gibe II hydroelectric power plant value of speed droop is 5 percent. i.e. 0.05. The range of frequency is deviated by 0.05pu. The range of frequency is 47.5 Hz to 52.5 Hz, so the universe of discourse for error and change in error in grid-connected operation is [-0.05 0.05].

I. **Membership function of error (e)**

The limits of the power system frequency error (Δf) and power error (Δp) were decided based on the variation of the system frequency of the existing power system, and power fluctuation This is shown in Figure 4.2 for isolated and Figure 4.3 for connected models.

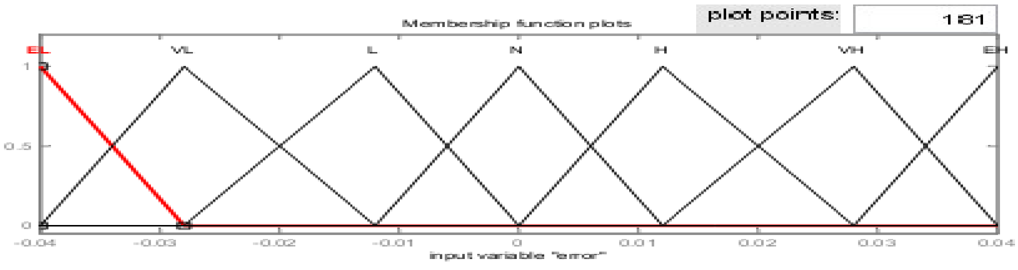

Figure 4.2 Error Input Fuzzy membership isolated system

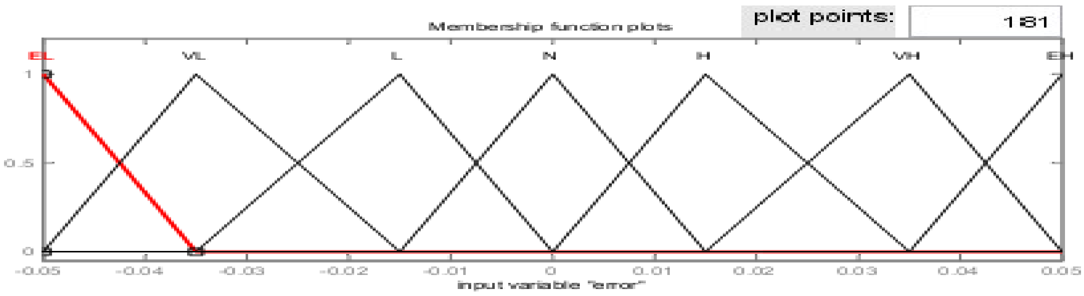

Figure 4.3 Error input membership for grid-connected

II. Membership Function for Rate Change of Error (de (t))

Here, a derivative has to be used to predict the error in the future, based on the current slope of the error. The limits of membership values are used to reflect the frequency error (Δf) and power error exactly**.** The universe of discourse here too is selected from -0.04 to 0.04 as shown in Figure 4.4,

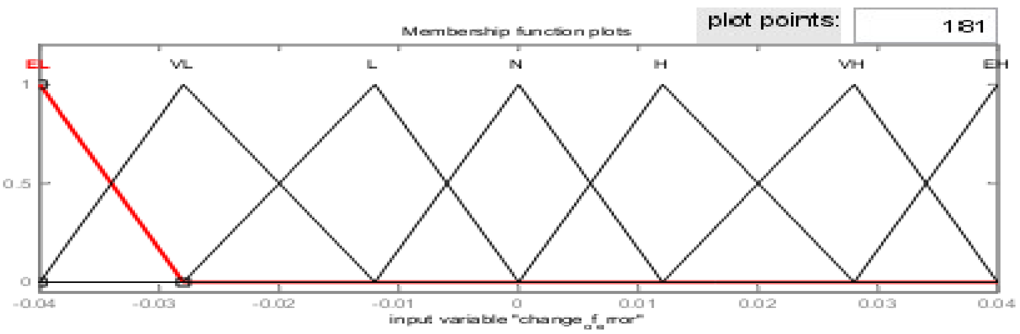

Figure 4.4 Changes in Error Input Membership isolated

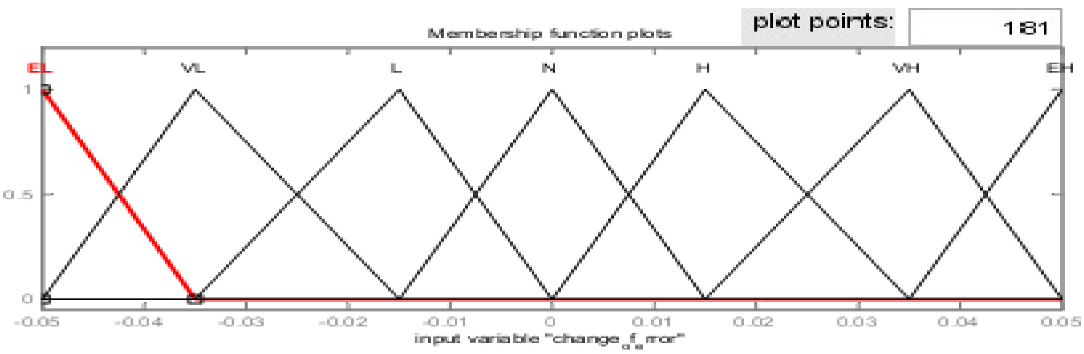

Figure 4.5 Change in Error input for interconnected operation

4.2.2. Output Variable

The output variable identified here is the reference gate opening (Δy) Gilgel Gibe II hydroelectric power plant gate opening for both interconnected operation and isolated operation minimum gate opening = 0.01pu (1%) and Maximum gate opening =0.975pu (97.5%), from this change in gate opening in fuzzy universe discourse, is [-0.975 0.975] this shown in Figure 4.6.

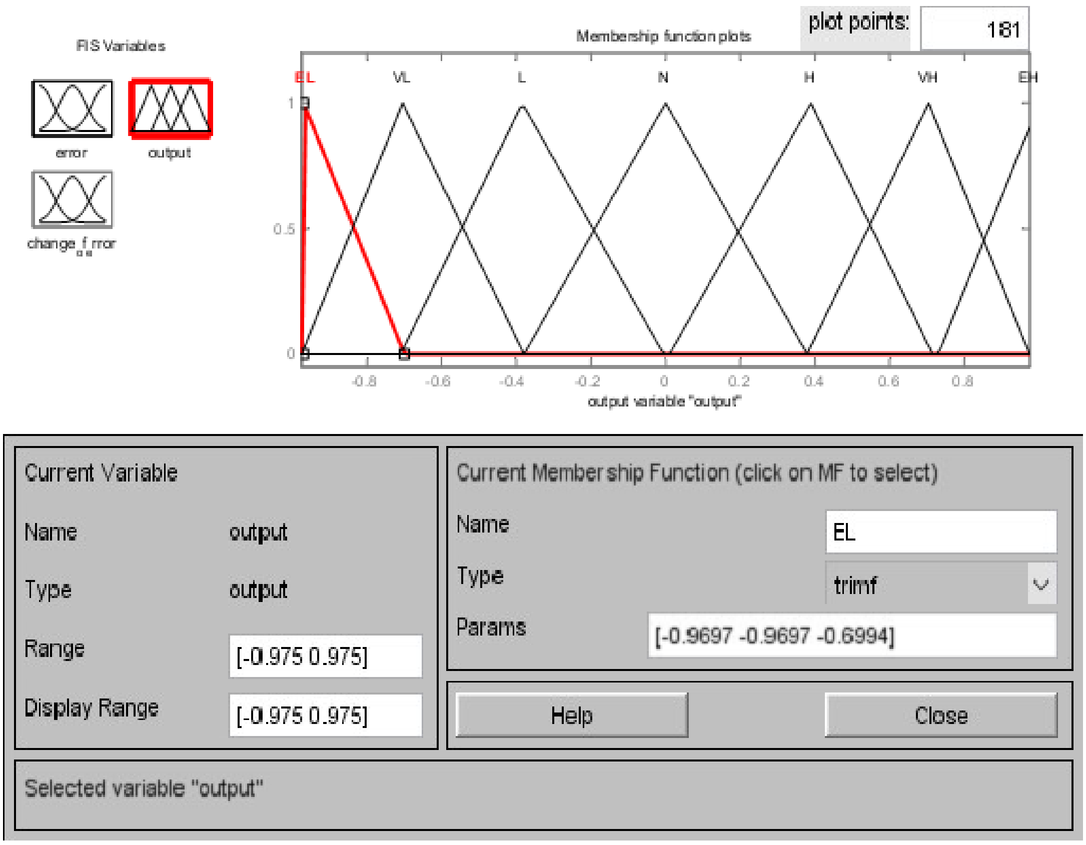

Figure 4.6 Output Membership functions

4.2.3. Fuzzy Control Rules

Fuzzy control rules can be considered as the knowledge of an expert in any related field of application. The fuzzy rule is represented by a sequence of if-then, leading to algorithms describing what action or output should be taken in terms of the currently observed information, which includes both inputs and feedback if a closed-loop control system is applied.

Fuzzy Inference Rule for the Proposed Controller

In this study, input and output membership functions are the same and seven segment triangular membership functions are used as stated earlier. Since each input has seven membership functions, the number of fuzzy-based rules is forty-nine and they are presented in table (Table 4.4) which consists of 49 rules Working of the fuzzy logic controller is based on 49 rules. These rules can be placed in form of the table below here error and cumulative error are two inputs of the fuzzy logic controller.

Table 4.4 Rule Base of Fuzzy Membership

	Change of Error							
		EL	VL	L	N	H	VH	EH
Error	EL	EL	EL	EL	EL	EL	L	N
	VL	EL	EL	EL	EL	L	N	H
	L	EL	EL	EL	L	N	H	VH
	N	VL	EL	L	N	H	VH	VH
	H	EL	L	N	H	VH	VH	EH
	VH	L	N	H	VH	VH	EH	EH
	EH	N	H	VH	EH	EH	EH	EH

Rule viewer from Matlab

All rules were written in Matlab and the view of all rules is shown in Figure 4.7 and Figure 4.8

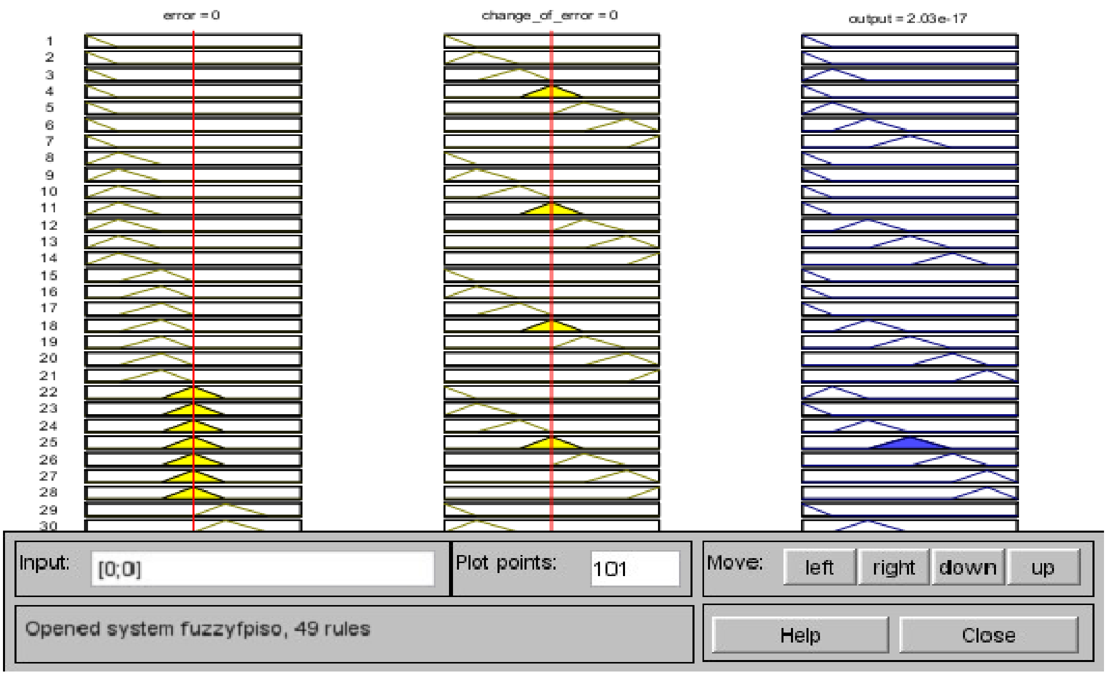

Figure 4.7 Rule viewer for Gilgel Gibe 2 hydroelectric power plant

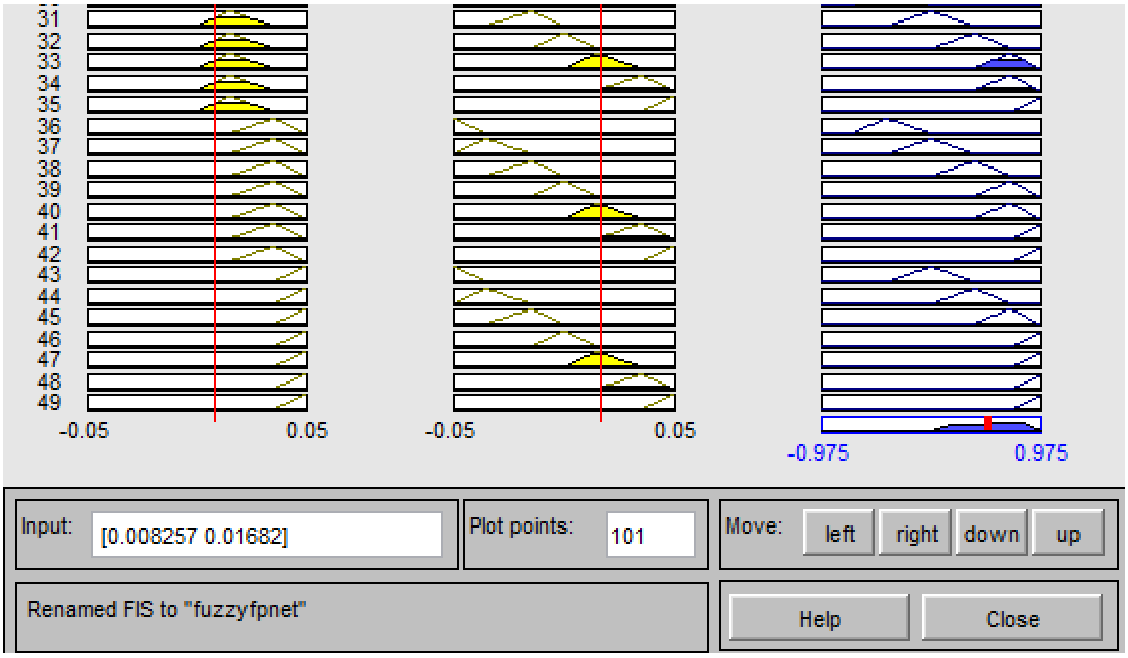

Figure 4.8 Rule viewer for Gilgel Gibe 2 hydroelectric power plant for networked

4.2.4. Defuzzification

Defuzzification is a process of producing the crisp control action from the output of the fuzzy control action. The last step in the fuzzy inference process is defuzzification; the final output of a fuzzy system has to be a crisp number. The input for the defuzzification process is the aggregate output fuzzy set and the output is a single number; Defuzzification method used in this proposed model is the Centre of Area (COA) method.

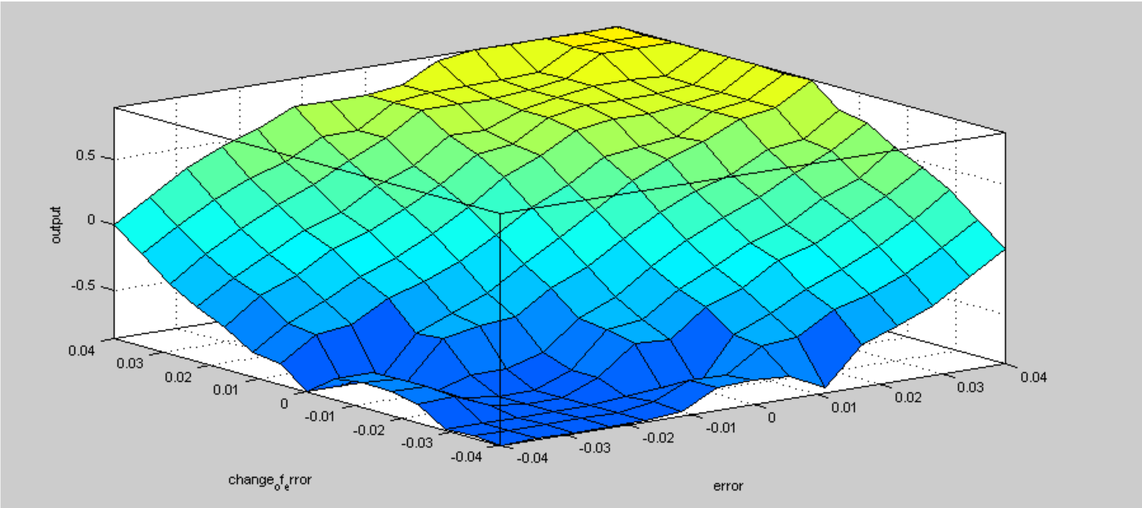

Figure 4.9 Surface viewers for Isolated

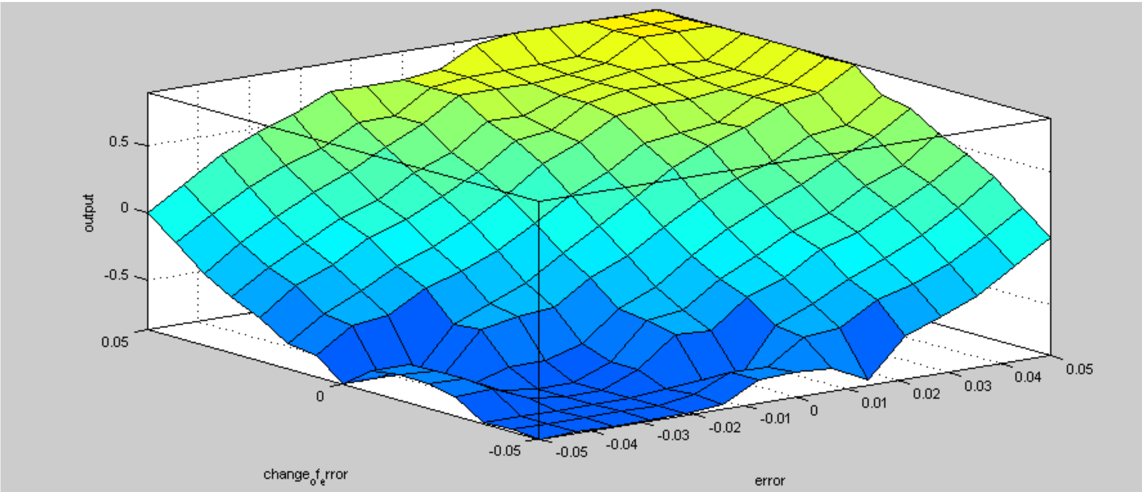

Figure 4.10 Surface viewers for network-connected

4.3. Particle Swarm Optimization Algorithm

PSO is an iterative algorithm that finds the optimal solution for a specified objective function through search space. The algorithm scans the search space and reaches the optimal solution considering the movement of each particle as well as the swarm as a whole. Each particle starts a random scan of the search space based on its own best knowledge and the knowledge of the swarm. It is drifted towards the current global best position Xg_{best} and its own best position Xp_{best}.

The search process can be represented by simple equations using the position vector $X_i = [X_{i1}, X_{i2}, X_{i3} \ldots X_{in}]$ and the velocity vector $V_i = [V_{i1}, V_{i2}, V_{i3} \ldots V_{in}]$ in the search space.

In the PSO algorithm, the population dynamics simulates a "bird flocks" behavior, where social sharing of information takes place and individuals can profit from the discoveries and previous experiences of all the other companions during the food search. Thus, each companion, called a particle, in the population, which is called a swarm, is assumed to fly in many directions over the search space to meet the demand fitness function.

A PID controller requires exact mathematical modeling of a system that be controlled; the performance of the system is questionable if there is parameter variation. However, the PID controller is still extensively used in the industry this is due to its simplicity and the ability to apply in a wide range of situations. On the other hand tuning, a PID controller is rather difficult and can be a time-consuming process.

In recent years, many intelligence algorithms are proposed to tune the PID parameters. Tuning PID parameters by the optimal algorithms such as the Simulated Annealing (SA), Genetic Algorithm (GA), and Particle Swarm Optimization (PSO) algorithm. Chent et al. Proposed a method to tune PID parameters by SA. [36] However, it is slow to search for the best solution. (PSO), first introduced by Kennedy and Eberhart, is one of the modern heuristics algorithms. It was developed through the simulation of a simplified social system and is robust in solving continuous non-linear optimization problems. [36]

In this paper, the objective is to determine solutions for a problem and implement the optimal PID controller parameters that realize efficient control of frequency and power regulating of active power response in the networked and isolated mode of the Gilgel Gibe II hydroelectric power plant. The model of the Gilgel Gibe 2 hydroelectric active power system is determined by using Simulink in MATLAB. The PSO algorithm is presented to find the optimum Proportional, Integral, and Derivative gains values of the controller without using the conventional solutions for all control set point problems.

4.3.1. Implementing PSO –PID Controller

A. Fitness Function:

The objective functions considered are based on the error criterion. Many such criteria are available and in this paper controller's performance is evaluated in terms of Integral time absolute error (ITAE) error criteria. Evaluation of a given set of controller gains is achieved by simulating a unit-step response of the resulting closed-loop system. To obtain a measure of the transient response performance of the system, the integral of time multiplied by the absolute value of error (ITAE) is taken as the objective function. The error criterion is given as a measure of the performance index given by equation (4.3):

$$ITAE = \int_0^\infty t \mid e(t) \mid dt \tag{4.3}$$

Where; t is the time of integration. The required PID gains minimize the objective function in the time domain, i.e. the performance indicators (overshoot, settling time, rise time, and steady-state error).

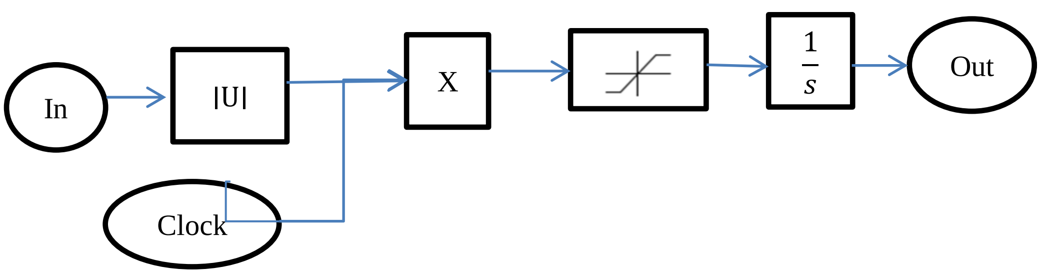

Figure 4.11 Simulink model representation of ITAE

PSO simulations are conducted based on the following steps;

i. The fitness of each particle is calculated by a fitness function that takes the current position of a particle as an input.

ii. The change of the particle position is calculated at every iteration by adding the updated velocity vector to the current position.

iii. The change of the particle velocity vector is determined by the previous particle velocity vector, the previous best position, and the group's best position.

Particles that are immediate neighbors of each other form a group. The memory of each particle's best position is called the history best (h-best) position. It is used to model simple nostalgia, a tendency of particles to return to the place that most satisfied them in the past. The group best position (g-best) is the position with the highest fitness that was discovered by the particles of the same group.

The Particle swarm optimization PID tuning controller has been chosen for governor operation which tasks, as it has all components under its operation parameter setting, are required for the implementation of frequency and power control to overcome the best settling time response of active power output as outlined below;

- The proportional controller will be responsible for maintaining a balance between load and generation i.e. Reduces the rise time but also results in oscillatory performance.
- The Integral controller will be responsible for the restoration of the system frequency to nominal value i.e. reduces the steady state error to zero.
- The Derivative controller will be responsible for limiting system overshoot as load fluctuates i.e. providing appropriate damping which results in improved transient performance with stability.

The PSOPID-optimized controller improves the transient response to decrease inaccuracy in amplitude with every oscillation and then the output is ultimately settled to a final required value. A suitable combination of proportional, integral, and derivative actions can provide all the desired performances: fast response, zero steady-state error, and less offset.

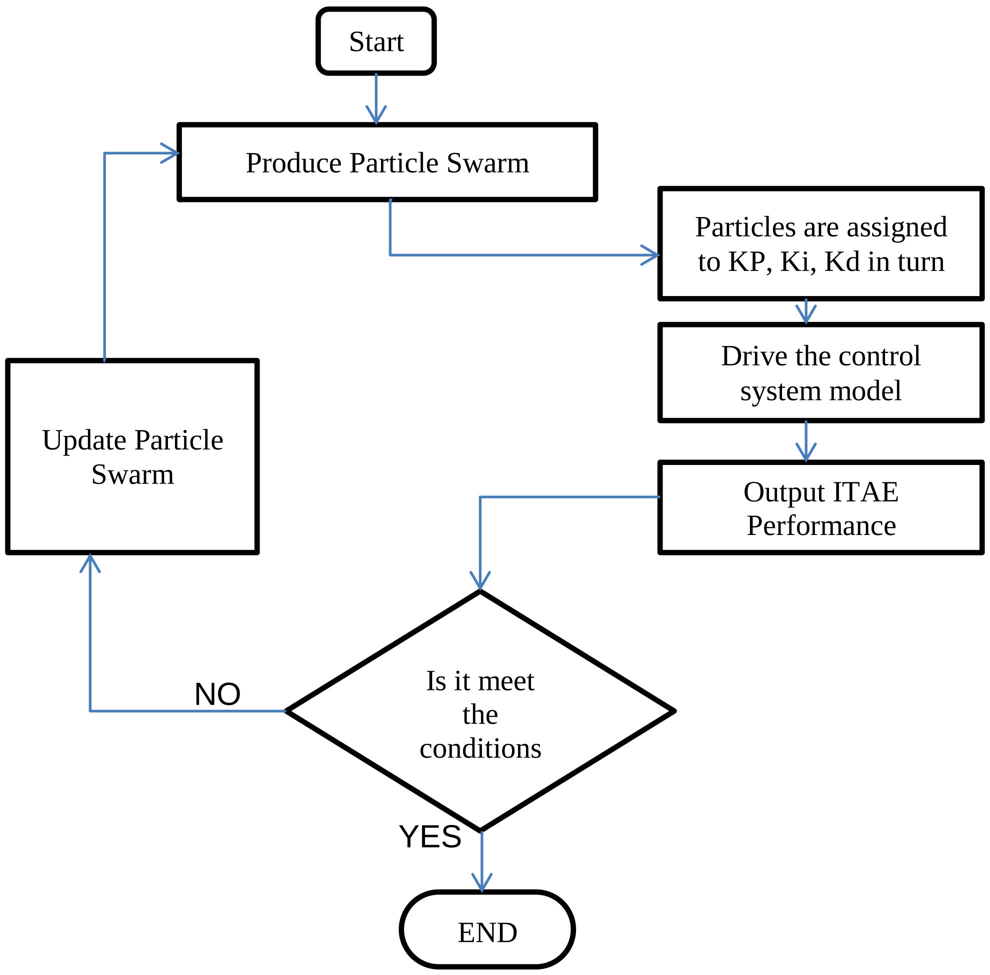

Figure 4.12 The Process of tuning

Simulation of the power system was done in MATLAB/SIMULINK and the PSO code in Appendix B was run in MATLAB for tuning of PID controllers. After seeing different research and repeated try and minimizing the steady state zero error, for different iterations parameter values are selected based on integral time absolute error value and best step response of the output of the design indicated in this thesis. PSO parameters taken for best optimizations were:

- Population size = 50,
- Maximum number of iterations = 100,
- c1 = 2;
- c2 = 2 and
- Simulation time = 50s.

Particle Swarm Optimization (PSO) algorithm, parameter values are:

Table 4.5 Value of PSOPID Tuned Controller for Isolated Operation

Parameter	Value
Kp	937.3
Ki	769.7
Kd	393.6
ITAE absolute value error	0.059165

Table 4.6 Value of PSOPID Tuned Controller for Network Connected Operation

Parameter	Value
Kp	765.52
Ki	795.2
Kd	186.8
ITAE absolute value error	0.0017087

CHAPTER 5

5. SIMULATION RESULTS AND DISCUSSIONS

This section explains simulation results obtained from tests performed on the Gilgel Gibe 2 hydroelectric power plant using MATLAB Simulink with a different type of controller. The Simulink model shown below is used to carry out simulation studies and analyze the performance of the controller by comparing the simulation of existing PID, PID tuned by PSO, and fuzzy logic controller.

As the thesis is objected with transient and steady-state response though it selects the transfer function whose plot has to trace from the workspace and chooses the “stepinfo”. stepinfo compute step-response characteristics for a dynamic system model or an array of step-response data. For a step response, stepinfo computes characteristics relative to the initial offset, that is, the value before the step is applied, and the steady-state value of the response. It gets the plot and then it can point to overshoot, settling time, rise times, etc.

- S=stepinfo(pid.Data,pid.Time)
- S=stepinfo(fuzzy.Data,fuzzy.Time)
- S=stepinfo(pso.Data,pso.Time)

5.1. Simulation Results

To discover the realization of the proposed method, simulation is carried out using MATLAB Simulink. The following active power output was developed when the system has different operation modes, optimum settings for the existing PID controller, design of a fuzzy logic controller, and PSOPID tuning for machines at Gilgel Gibe 2 hydroelectric power plant executed and compared each response respectively.

Two modes of operations were simulated

- Machine Network Connected Operation
- Machine Isolated Operation

5.1.1. Machine Operating in Networked Mode

The model made in a described manner was verified after a connection of the sub-models in one complete power plant model. The overall MATLAB Simulink diagram for a power-regulated turbine connected to a system network for existing PID, fuzzy logic, and PSOPID tuned controller is seen in Figure 5.1, Figure 5.2, and control characteristics in Figure 5.3 respectively. With this model, the grid at rated frequency is set as input, as well as power and frequency references to the turbine too. In the governor model with a switchover function of control mode, the S_1 and S_2 are selectors between different frequency and power signals, and the zero input to the selector means no input signal. S_3, S_4, and S_5 selectors to select the existing PID, Fuzzy logic, and PSOPID controller for the input of servo to control the gate operation during networked operation.

Table 5.1 States of selectors in different control modes and controllers

Control Mode	S_1 State	S_2 State	Controller	S_3 State	S_4 State	S_5 State
Frequency Control	1	1	FL	2	1	1
			PID	1	1	2
			PSO	1	2	2
Power Control	2	1	FL	2	1	1
			PID	1	1	2
			PSO	1	2	2

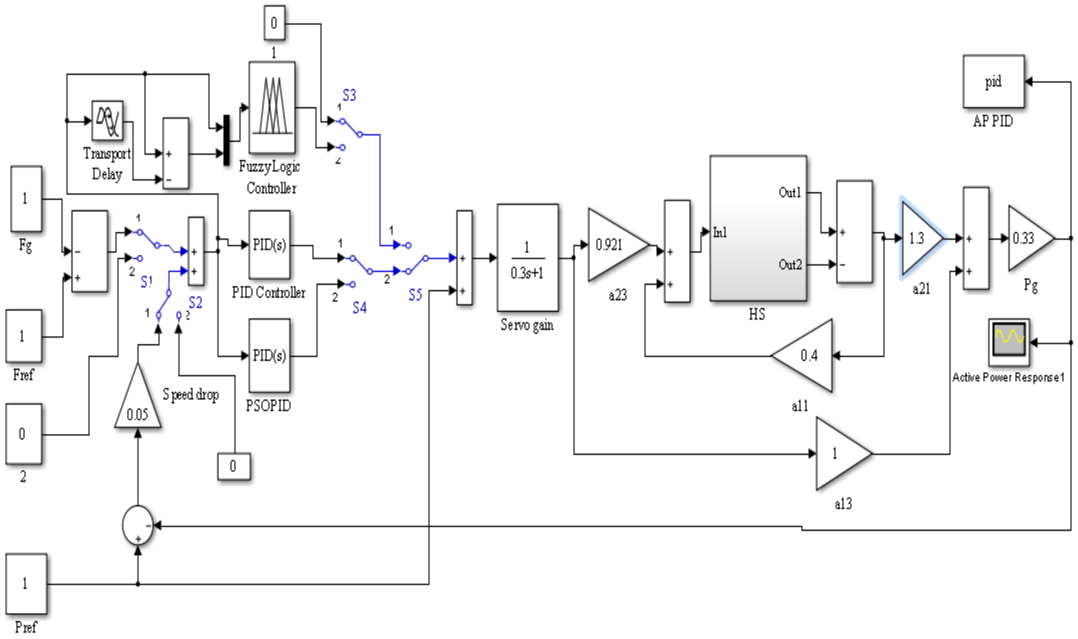

Figure 5.1 GG2 HEPP power and frequency control connected to the network

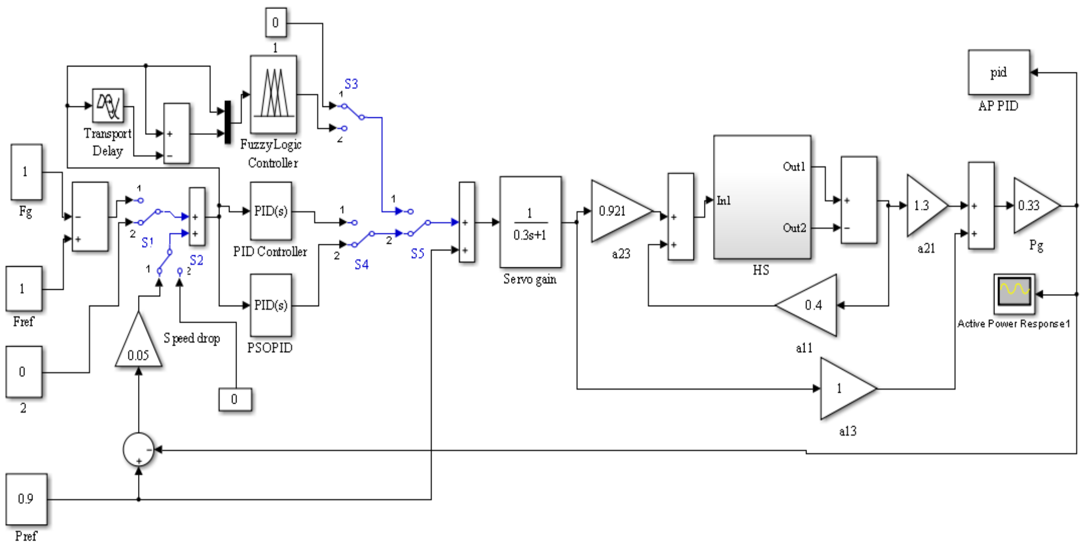

Figure 5.2 Simulink model of GG2 HEPP unit power control

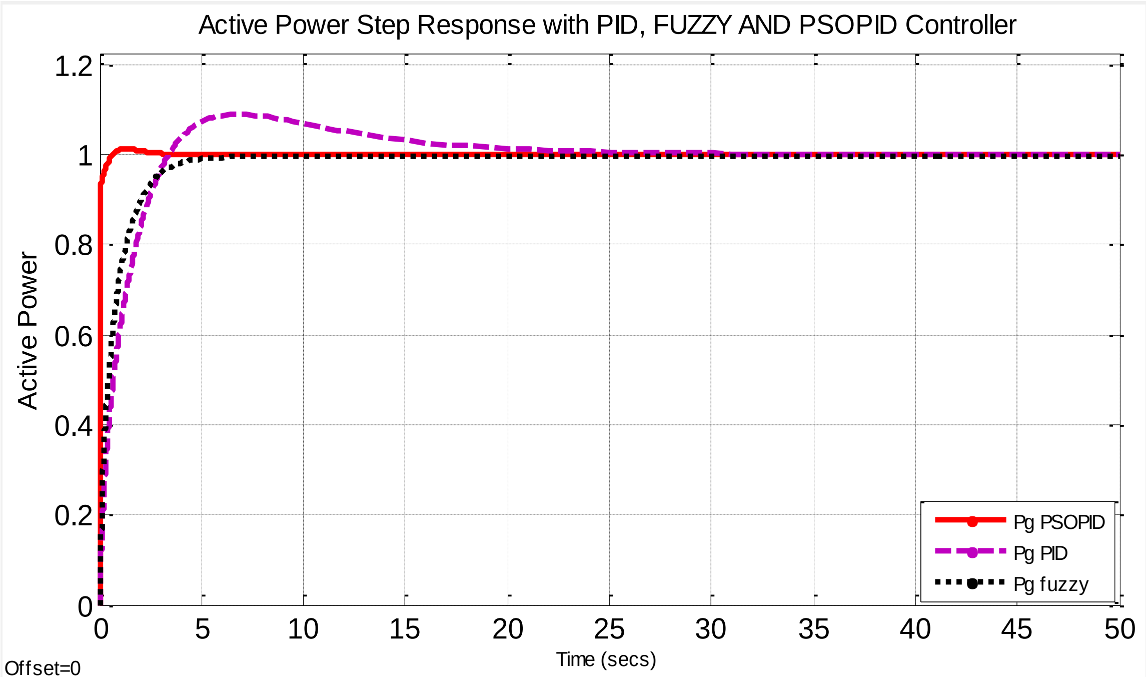

Figure 5.3 Response at nominal power and frequency in networked operation

Table 5.2 Step Response characteristics at nominal power and frequency

Time Response	CONTROLLER FOR NETWORKED MODE		
	PID	FUZZY LOGIC	PSOPID TUNING
Rise Time (s)	2.3491	1.9753	0.0033
Settling Time (s)	17.5964	3.6842	0.3911
Overshoot (%)	8.8862	0	1.2850

The input for the connected system is a frequency difference from (47.5 to 52.5) for interconnected operation & Reference power (0MW to 105MW). Then power generated MATLAB Simulink is displayed by using time scope for two control mechanisms, which are

- Frequency Control Mode and
- Power Control Mode

5.1.1.1. Frequency Control Mode

The frequency control mode in a system is operated automatically depending on irrespective of change in load. When the load in the system increases frequency can drop, and when the load in the system decrease frequency in the system will increase. So, depending on this the gate valve opens and closes on the change of frequency value given from the grid but for simplicity, I would give frequency in form of a set point value, In this control mode, the feedback signal contains not only the frequency value but also the power as shown on Simulink model of Figure 5.1.

In this model of the control system, the unit power production was controlled when the frequency of a grid deviated from the set point; the simulation result shows that frequency deviation depends on the speed drop rated for the hydropower plant. For the simulation of this thesis, I have discussed three cases with different deviations.

1. **One Percent Increase in the Frequency of Network**

When one percent in frequency is increased, the load is droop from the system network; the power generated is decreased as per speed drop calculation, and the result is a decrease in the power production of 0.2pu, equivalent to 21MW from the rated power of 105MW.

$$\Delta Pg = \frac{Pre}{fn} * \frac{\Delta f}{\rho} \qquad (5.1)$$

The equation found in (5.1) shows the mathematical relationship between changes in generated power as a function of change in frequency [37]

$$\Delta Pg = \frac{Pre}{fn} * \frac{\Delta f}{\rho} = \frac{1pu}{1pu} * \frac{0.01pu}{0.05pu} = 0.2pu$$

$$\Delta Pg = 0.2 * 105MW = 84MW$$

$$\Delta Pg(pu) = \frac{84MW}{105MW} = 0.8pu$$

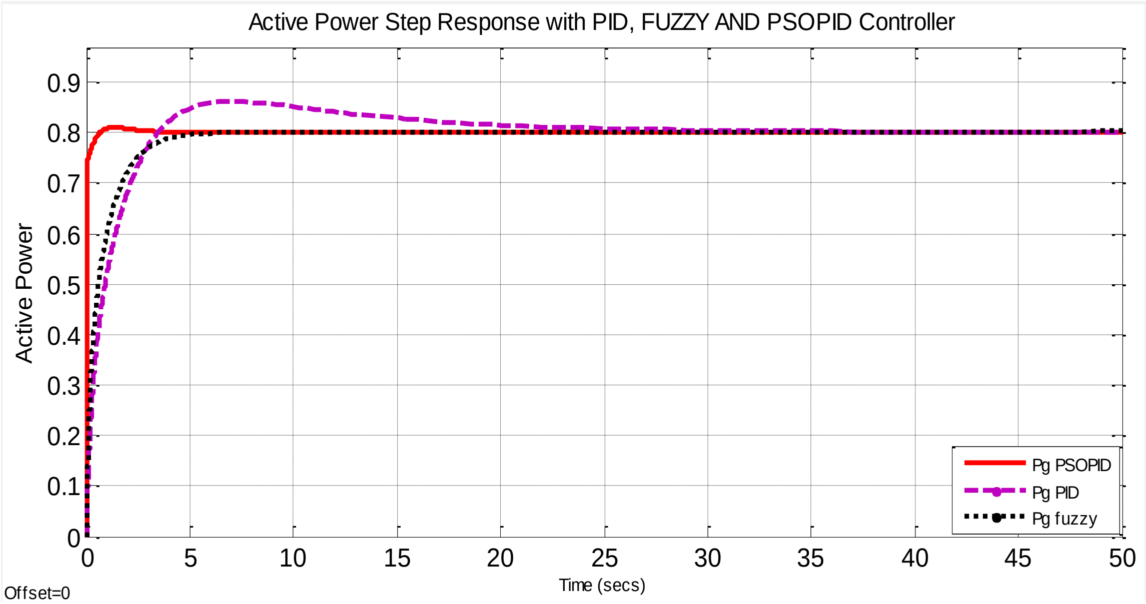

Figure 5.4 One Percent step response increase in frequency

Table 5.3 One Percent step response increase in frequency

Time Response	CONTROLLER FOR NETWORKED OPERATION		
	PID	FUZZY LOGIC	PSOPID TUNING
Rise Time (s)	2.2812	1.9637	0.0034
Settling Time (s)	19.0154	3.8288	0.4052
Overshoot (%)	7.5610	0	1.2430

2. **One Percent Increase in the Frequency and a 0.5 pu Decrease in the Power of the Network**

The power set point given to the production of the unit by the operator is 0.5pu or 52.05MW, so the power generated after the 0.01pu increase of frequency is 0.3pu to make load balance again as shown in Figure 5.6, and the control characteristics in Table 5.4.

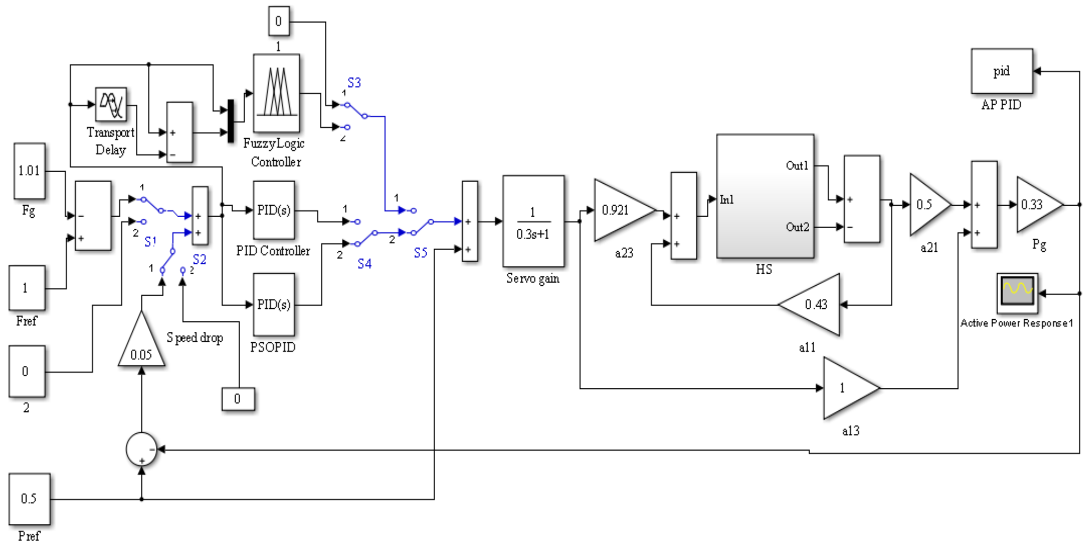

Figure 5.5 One Percent step increase in frequency and half power set point

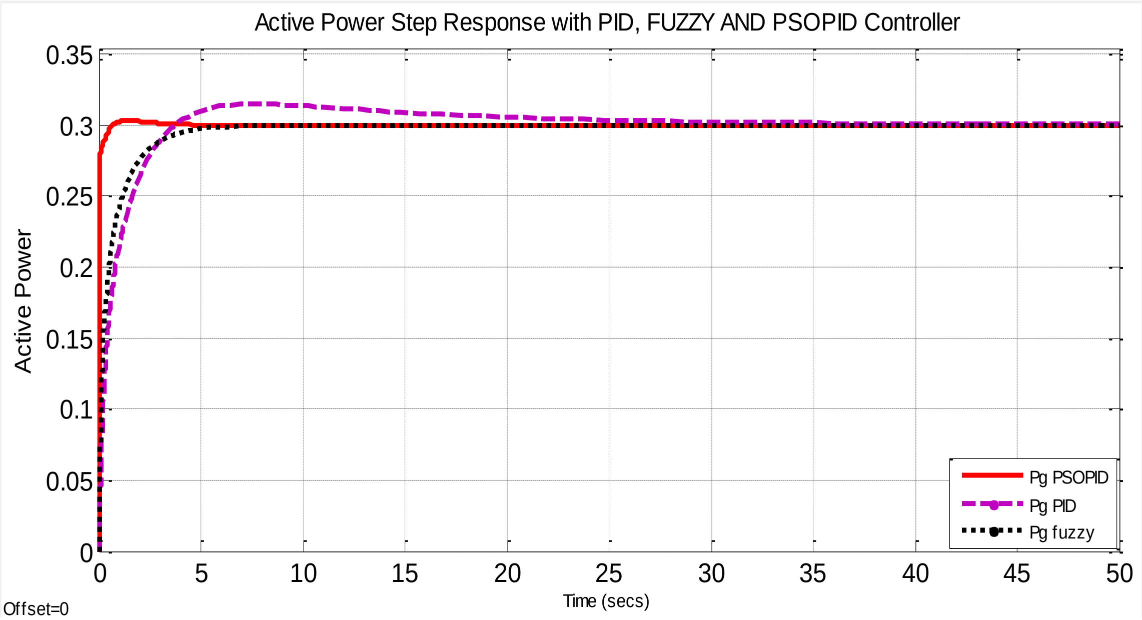

Figure 5.6 One Percent step Increase in Frequency and half power set point

Table 5.4 One percent step increase frequency and 0.5pu power drop

Time Response	CONTROLLER FOR NETWORKED OPERATION		
	PID	FUZZY LOGIC	PSOPID TUNING
Rise Time (s)	2.2475	1.7922	0.0033
Settling Time (s)	18.8057	4.0738	0.4090
Overshoot (%)	4.7233	0	1.0822

From the graph in Figure 5.3, Figure 5.4, and Figure 5.6 MATLAB simulation results PID tuned by particle swarm optimization showed better performance difference when compared with fuzzy logic controller and existing PID controller. The performance evaluation is shown in Table 5.2, Table 5.3, and Table 5.4 for different scenarios comparatively.

3. One Percent Drop In Frequency of Network

The frequency system is decreased when the amount of power demand is greater than the amount of power produced to synchronize the network, the amount of power generated is increased as per the formula of speed drop, so the power generated increased by 0.2pu and the change in power generated is 0.7pu, Figure 5.7 shows the response of PSOPID, fuzzy logic, and existing PID controller.

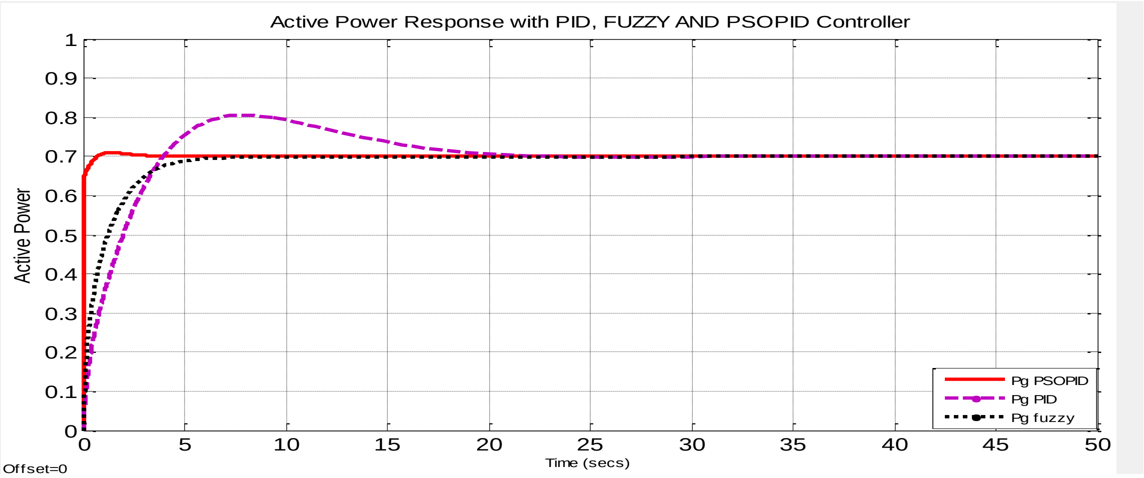

Figure 5.7 One Percent step drops in Frequency for 0.5 pu Power set point

The result is an increase in the power production of 0.2pu, equivalent to 21MW the rated turbine of unit 105MW, the value corresponds well to theory, the result of the graph shows that the PSOPID tuned controller is a good transient step response compared to the fuzzy logic controller and existed PID controller. The control characteristics are shown in Table 5.5.

Table 5.5 Control characteristics for one percent step drop frequency

Time Response	CONTROLLER FOR NETWORKED MODE		
	PID	FUZZY LOGIC	PSOPID TUNING
Rise Time (s)	3.0043	2.5846	0.0033
Settling Time (s)	17.8423	4.7648	0.4283
Overshoot (%)	15.0374	0	1.3177

5.1.1.2. Power Control Mode

In the power control mode, the governor controls the opening according to power signals, leading the power output to achieve the given value, which is used to keep the power of a unit equal to a set value. The unit generated the power reference this implies the power generated cannot vary with load demand or didn’t depend on frequency variation if the system is in power control mode, and so generated power is always referenced power signal. The result of a PID tuned by particle swarm optimization, fuzzy logic, and existing PID controller for power control at reference power of 0.9pu or 94.5MW is given by the operator for unit one of Gilgel Gibe 2 hydroelectric power plant is shown in Figure 5.8.

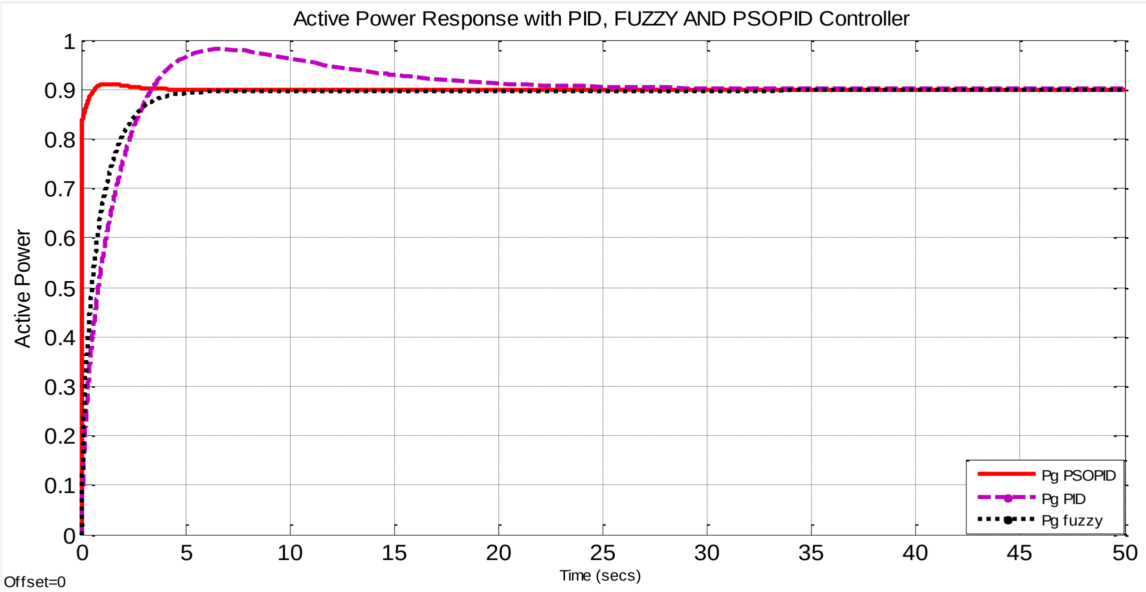

Figure 5.8 Step response of Power Control at 0.9 Value of Power Input

From the graph in Figure 5.8 PID tuned by particle swarm optimization showed performance difference when compared with the fuzzy logic controller and existing PID controller, the performance evaluation shown in Table 5.6 is a comparison of the PSOPID, fuzzy logic controller, and PID controller.

Table 5.6 Performance of Controller for Power Control at 0.9pu step response

Time Response	CONTROLLER FOR NETWORKED OPERATION		
	PID	FUZZY LOGIC	PSOPID TUNING
Rise Time (s)	2.3414	1.9543	0.0033
Settling Time (s)	17.5334	3.6409	0.3907
Overshoot (%)	8.9637	0	1.2850

From Table 5.6 PSOPID tuned is less percentage of overshot, less settling time, and less rise time when compared with fuzzy logic controllers and existing PID controller, when the system of the unit is in power control mode.

4. Power Control Mode at the Reference Value of 0.5pu

For a reference value of 0.5pu, the power generated must follow the reference signal as shown in Figure 5.9

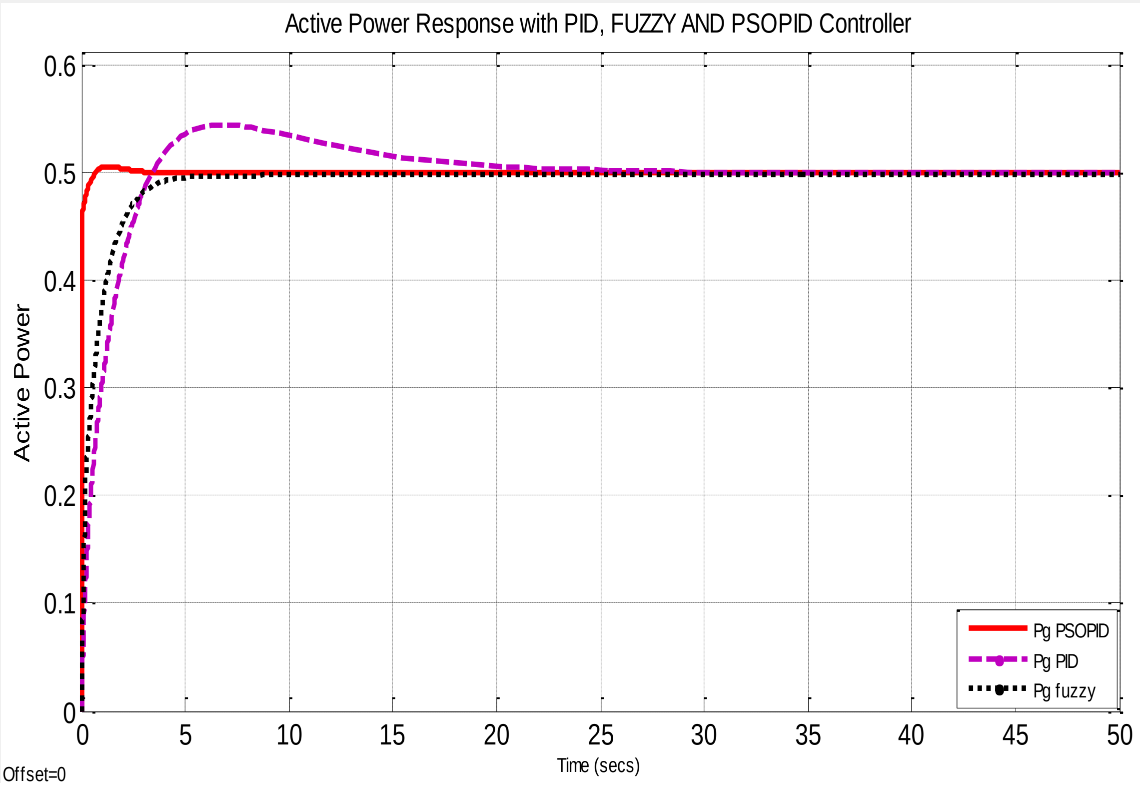

Figure 5.9 step response of power control at 0.5pu

For small power reference, the response of the hydropower unit is better than the high power reference, PSOPID gives a fast response in power control mode.

Table 5.7 Time-response specifications of power control at 0.5pu

Time Response	CONTROLLER FOR NETWORKED MODE		
	PID	FUZZY LOGIC	PSOPID TUNING
Rise Time (s)	2.3444	1.8446	0.0034
Settling Time (s)	17.5343	3.5023	0.3906
Overshoot (%)	8.9488	0	1.2803

5.1.2. Machine Operating in an Isolated Mode (Island Operation)

The overall interconnected MATLAB Simulink model in Figure 5.10 is frequency-regulated unit one of Gilgel Gibe 2 hydroelectric power in island mode. It is a single-machine single-load environment designed with fuzzy logic, particle swarm optimization tuned PID, and existing PID controller parameters for Gilgel Gibe 2 hydroelectric power plant. The governor models with a switchover function of control mode. The S_3, S_4, and S_5 are selectors to select the existing PID, Fuzzy logic, and PSOPID controller for the input of the servo to control the gate operation during isolated operation, and the zero input to the selector means no input signal.

Table 5.8 States of selectors for frequency control modes and controllers

Control Mode	Controller	S_3 State	S_4 State	S_5 State
Frequency Control	FL	2	1	1
	PID	1	1	2
	PSOPID	1	2	2

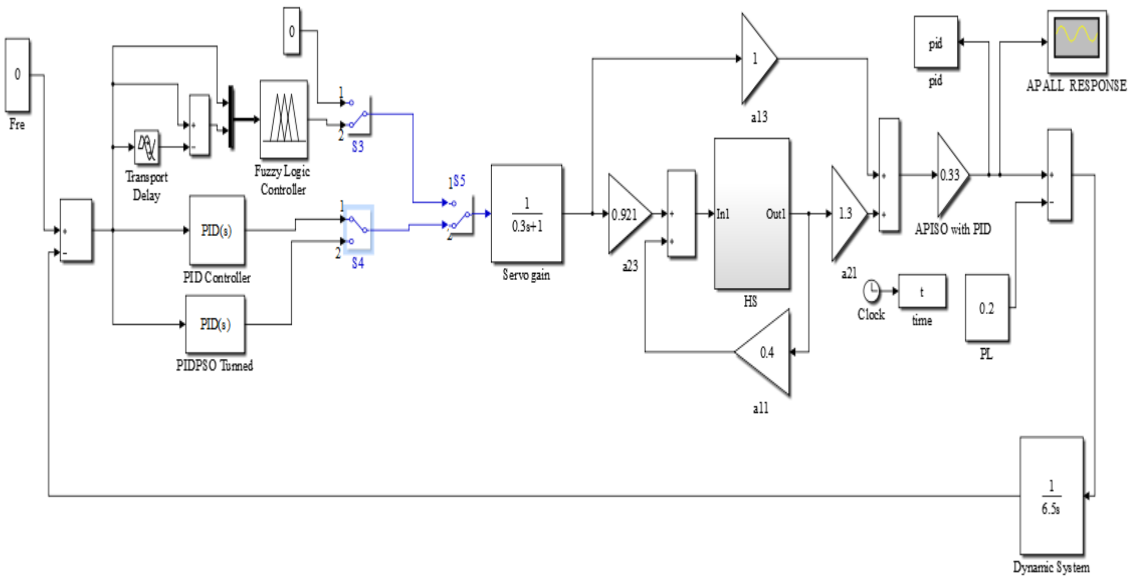

Figure 5.10 MATLAB Simulink Modeled of Isolated mode with Controller

Input for isolated operation

- Reference frequency deviation

Output for isolated operation

- Generated power deviation

Matlab Simulink model of Figure 5.10 the generated power is shown in different simulation response cases

1. **When 0.2 Power of load is added to the Isolated Network**

When the change in power generated is equal to the change in load power added to the system and the frequency of the system decreases. Simulation in Figure 5.11 shows that the power generated is equal to 0.2 per unit value.

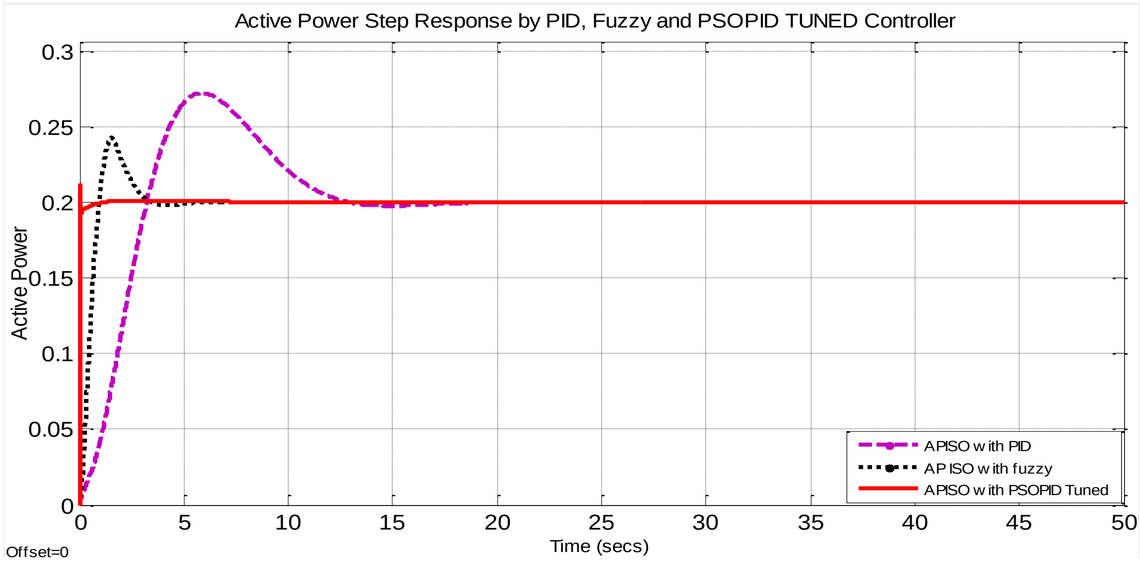

Figure 5.11 Power generated at 0.2pu load added with Controller

From Figure 5.11 Particle swarm optimization PID tuning is more robust and has better transient response than the fuzzy logic and existing PID controller, for the value of twenty percent load is added to the system. The change in power generated is increased by twenty percent to synchronize the system i.e. Power generated must be equal to power demand.

The system slowly increased power generation at startup. It reached the maximum point at 0.0492sec peak value reached 0.2111pu and stables the system to 0.2pu at 0.2983sec by using particle swarm optimization PID tuned controller. The fuzzy logic controller also exhibits at 0.2427 seconds reaches a peak value at 1.5502pu and stables the system to 0.2pu at 3.0322sec. For the existing PID controller, the system's start operation increased to a peak value of 0.2722pu at 5.8086sec and stabled the system to 0.2pu at 11.9418sec as Table 5.9 showed.

Table 5.9 Step Response specification under 0.2pu power is added

Time Response	CONTROLLER FOR ISOLATED OPERATION		
	PID	FUZZY LOGIC	PSOPID TUNING
Rise Time (s)	2.3915	0.6732	0.0237
Settling Time (s)	11.9548	3.0323	0.2979
Overshoot (%)	36.0858	21.3560	5.5459

2. When 0.1pu load is added to the system

At ten percent load is added to the system network, the frequency of the system is decreased to normalize frequency change at zero, the Gilgel Gibe 2 hydroelectric power plant unit generates 10% of rated power and, the graph result is shown in Figure 5.12.

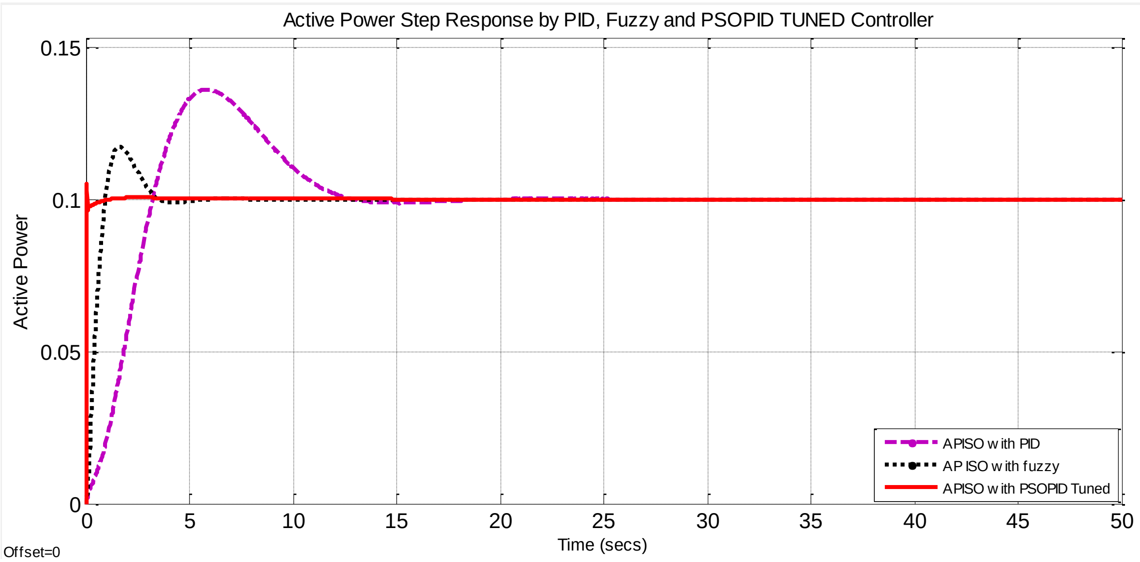

Figure 5.12 0.1pu load added with Controller

The system time response control specification is shown in Table 5.10 system is improved using PID tuned by particle swarm optimization comparatively from fuzzy logic and existing PID controller.

Table 5.10 Time-response specifications of 0.1pu load added

Time Response	CONTROLLER FOR ISOLATED MODE		
	PID	FUZZY LOGIC	PSOPID TUNING
Rise Time (s)	2.3909	0.6548	0.0237
Settling Time (s)	11.9353	3.1643	0.2979
Overshoot (%)	36.1032	17.1315	4.8435

3. When 0.25pu load is added to the Isolated Unit Network

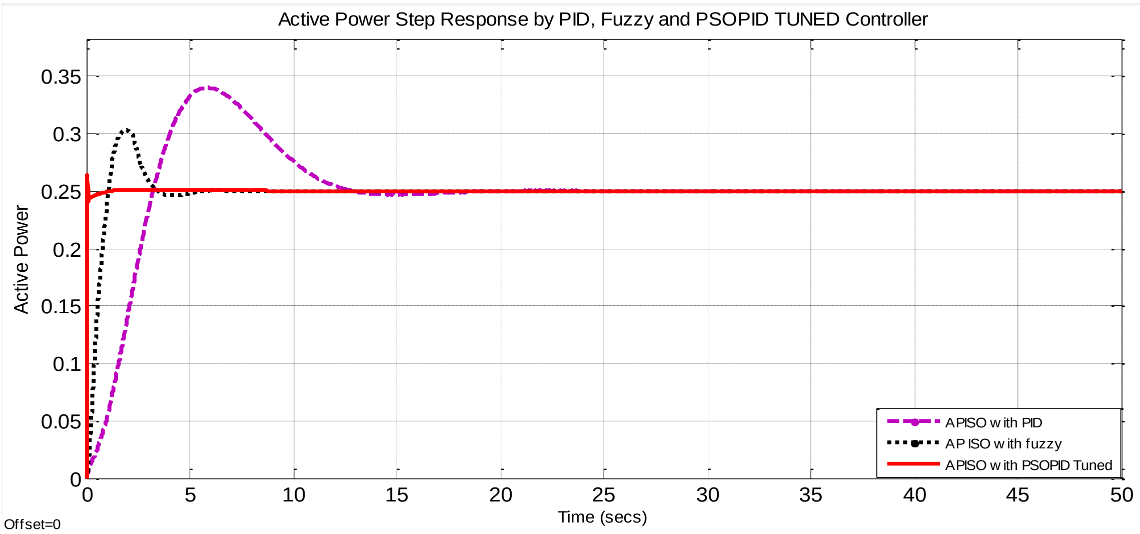

Figure 5.13 Step response of 0.25pu load added to the system with Controller

Table 5.11 Step response specifications of 0.25pu load added

Time Response	CONTROLLER FOR ISOLATED MODE		
	PID	FUZZY LOGIC	PSOPID TUNING
Rise Time (s)	2.3913	0.7712	0.0236
Settling Time (s)	11.9530	3.1588	0.2979
Overshoot (%)	36.0369	21.4014	5.6302

4. Load Rejection at 0.2pu Power is Reduced from the Load

Load rejection in an electric power system means a sudden load trip in the system, which causes the generation side to be over frequency, Figure 5.14 show illustrates the comparison of particle swarm optimization tuned PID, fuzzy logic, and existing controller under twenty percent load rejection. For two percent load is removed from the system the time control specification is shown in Table 5.12.

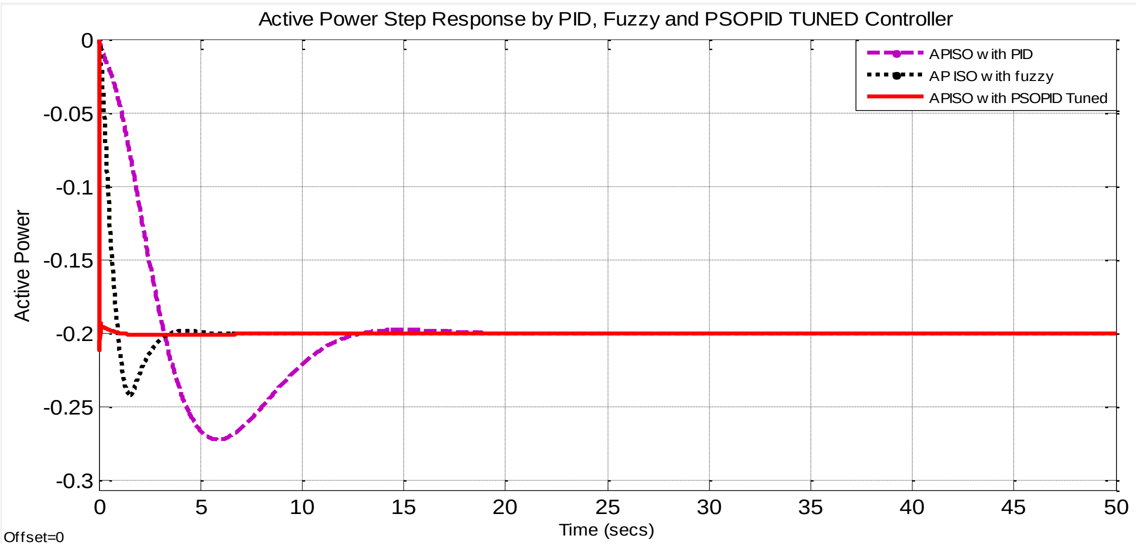

Figure 5.14 Isolated mode system removed by load 0.2pu with Controller

Table 5.12 Step response Performance under 0.2pu Power is removed

Time Response	CONTROLLER FOR ISOLATED OPERATION		
	PID	FUZZY LOGIC	PSOPID TUNING
Fall Time (s)	2.3902	0.6758	0.0237
Settling Time (s)	11.9357	3.0434	0.2979
Undershoot (%)	- 36.1666	- 21.1195	- 5.5405

5. When 0.1PL Drop from the System

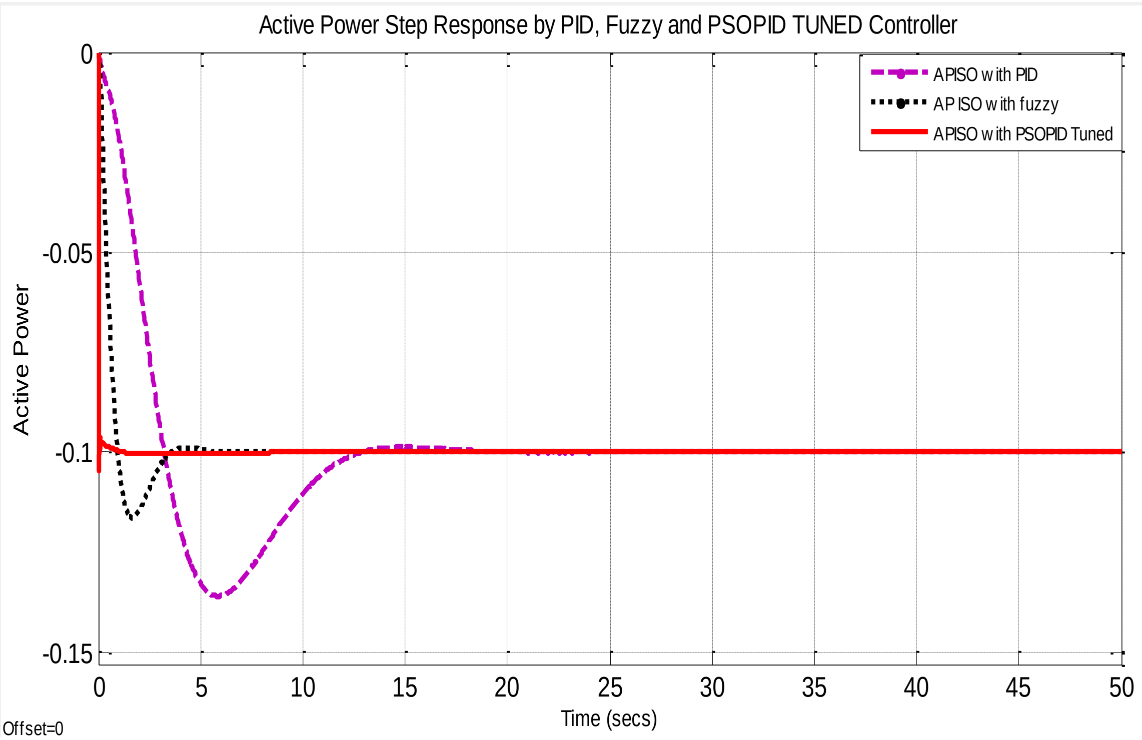

Figure 5.15 Isolated mode system removed by load 0.1pu with Controller

Table 5.13 Step response specifications of 0.1pu load dropped

Time Response	CONTROLLER FOR ISOLATED MODE		
	PID	FUZZY LOGIC	PSOPID TUNING
Fall Time (s)	2.3917	0.6580	0.0236
Settling Time (s)	11.9573	3.2113	0.2979
Undershoot (%)	-36.0556	-16.3920	- 4.8632

6. Isolated Operation when 0.25pu Load is Droop from Network

The unit produces 0.25pu power to equalize the power generated and power demand to make the system frequency at a nominal value. From the graph below, the system decreases the power generated by 0.25pu, the system is fluctuate up to 0.25pu value, and then stabilizes at some point.

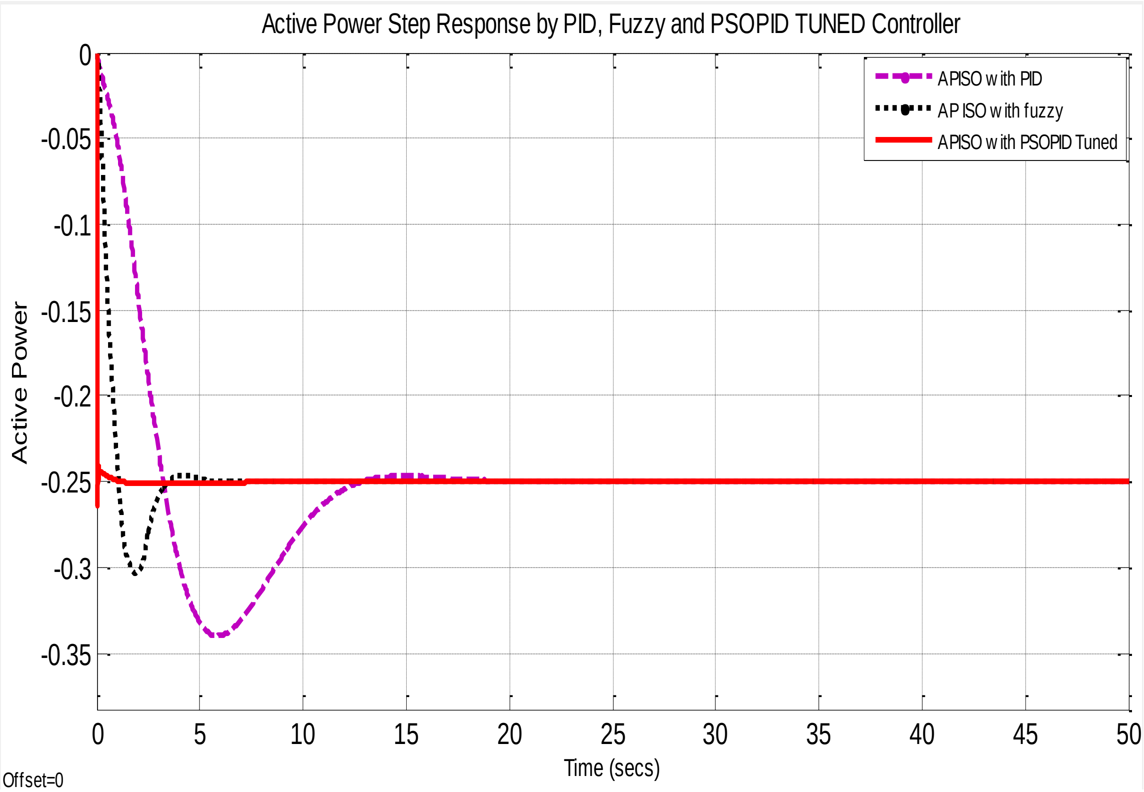

Figure 5.16 Isolated mode system removed by load 0.25pu with Controller

Table 5.14 Time-response specifications of 0.25pu load dropped

Time Response	CONTROLLER FOR ISOLATED MODE		
	PID	FUZZY LOGIC	PSOPID TUNING
Fall Time (s)	2.3915	0.7668	0.0237
Settling Time (s)	11.9320	3.1322	0.2979
Undershoot (%)	- 36.0849	-21.2782	- 5.6367

5.2. Discussion

Considering the main goal of the thesis, it is analyzed and compared the frequency and power control of Gilgel Gibe 2 HEPP transient response of the active power to get the desired output of the system and to minimize or diminish error between the set point given to the intelligent controller and feedback in the above, all results.

The comparative analysis discussion part is divided into two main parts

1. **Network Connected Operation**

Simulation performed in networked connection mode can be seen in Figure 5.3, Figure 5.4, Figure 5.6, Figure 5.7, Figure 5.8, and Figure 5.9 for frequency and power control respectively at the set point value defined. Both simulations show power regulation as the frequency droops and increases by 0.01pu.

The controller is supposed to increase production as the frequency drops and decrease power output as the frequency decreases. Comparing the three controllers all behave similarly informing of power production value during governing action and final steady-state values. The controlled behaves accordingly to theory and the Proportional integral derivative tuned by the particle swarm optimization controller is better transient response and robustness than fuzzy logic and existing proportional integral derivative controller for both power control and frequency of network connected operation as shown in the time response control characteristics in Table 5.5, Table 5.7, Table 5.9, Table 5.10 and Table 5.11.

The summarized full comparison chart will be included to have an overall overview of the work done to decide on the best controlling method. From the data in Table 5.5 - Table 5.11, it can be concluded that based on existing PID, Fuzzy logic controller, and PSOPID tuning controlling methods the active power transient response is evaluated and the best controller from them is the PSOPID controller which gives a fast system in its rising with best settling time and the overshoot is very small under networked operation as shown in comparative analysis studies between Table 5.15. The steady-state signal is zero. The transient response of the existing PID controller is maintained by the PSO optimizer and is updated by 99.8%. its rising time, 97.7% settling time, and 85.54% of overshoot. But fuzzy logic cleared the transient error by 15.92% rising time, 79.1% settling time, and zero overshoot during no variation/set point change occurred for the networked mode of operation.

Table 5.15 Comparative studies between controllers during networked mode

TIME RESPONSE	UNDER RATED POWER AND FREQUENCY			POWER CONTROL MODE					
				0.9pu			0.5pu		
	Existing PID	Fuzzy Logic	PSOPID	Existing PID	Fuzzy Logic	PSOPID	Existing PID	Fuzzy Logic	PSOPID
Rise Time (s)	2.3491	1.9753	0.0033	2.3414	1.9543	0.0033	2.3444	1.845	0.0034
Settling Time (s)	17.5964	3.6842	0.3911	17.533	3.6409	0.3907	17.534	3.502	0.3906
Overshoot (%)	8.8862	0	1.285	8.9637	0	1.285	8.9488	0	1.2803
	FREQUENCY CONTROL MODE								
	Frequency one percent added			Frequency one percent dropped			One percent increase in frequency and 0.5pu power dropped		
	Existing PID	Fuzzy Logic	PSOPID	Existing PID	Fuzzy Logic	PSOPID	Existing PID	Fuzzy Logic	PSOPID
Rise Time (s)	2.2812	1.9637	0.0034	3.0043	2.5846	0.0033	2.2475	1.792	0.0033
Settling Time (s)	19.0154	3.8288	0.4052	17.842	4.7648	0.4283	18.806	4.074	0.409
Overshoot (%)	7.561	0	1.243	15.037	0	1.3177	4.7233	0	1.0822

2. Isolated Operation

The model responded as expected from the theory. When the load demand drops, an increase in frequency occurs. Both simulation results responded by changing the guide vane opening (y) and reducing the hydraulic force to the turbine wheel. By doing so, the system speed is getting regulated back to its point of reference, as system speed is proportional to the system frequency.

The response can be linked to system frequency and turbine and generator speed. This tendency of regulation can be seen in all simulations done in isolated operations with frequency control.

Three simulations are done with power load drooped and power load added as shown in Figure 5.9 up to Figure 5.14, and the model behaves as expected. They gave the same steady-state response result for PSOPID tuned, existing PID, and fuzzy logic controller, but with a different transient response, as per table from Table 5.9 up to Table 5.14.

The simulation result showed that PID tuned by particle swarm optimization controller is a more robust and better transient response when compared with fuzzy logic and existing PID controller. PID tuned by particle swarm optimization less overshot, fewer settling time, and less rise time when compared with fuzzy logic and existing PID controller under the isolated mode of operation in the comparative analysis as shown in 82% only at 0.2 load power is added to the isolated system Table 5.16.

The transient response of the existing PID controller is maintained by the PSO optimizer and is updated by 99.1%.its rising time, 97.5% its settling time, and 84.64% of overshoot. But fuzzy logic cleared the transient error by 71.86% rising time, 74.64% settling time, and 40.82% only at 0.2 load power added to the isolated system.

Table 5.16 Comparative studies between controllers during isolated mode

TIME RESPONSE	**LOAD ADDED**								
	0.1pu			0.2pu			0.25pu		
	Existing PID	Fuzzy Logic	PSOPID	Existing PID	Fuzzy Logic	PSOPID	Existing PID	Fuzzy Logic	PSOPID
Rise Time (s)	2.3909	0.6548	0.0237	2.3915	0.6732	0.0237	2.3913	0.771	0.0236
Settling Time (s)	11.9353	3.1643	0.2979	11.955	3.0323	0.2979	11.953	3.159	0.2979
Overshoot (%)	36.1032	17.132	4.8435	36.086	21.356	5.5459	36.037	21.4	5.6302
	LOAD REDUCED								
	0.1pu			0.2pu			0.25pu		
	Existing PID	Fuzzy Logic	PSOPID	Existing PID	Fuzzy Logic	PSOPID	Existing PID	Fuzzy Logic	PSOPID
Fall Time (s)	2.3917	0.658	0.0236	2.3902	0.6758	0.0237	2.3915	0.767	0.0237
Settling Time (s)	11.9573	3.2113	0.2979	11.936	3.0434	0.2979	11.932	3.132	0.2979
Undershoot (%)	-36.056	-16.39	-4.8632	-36.167	-21.12	-5.5405	-36.08	-21.3	-5.6367

CHAPTER 6

CONCLUSION AND RECOMMENDATION

6.1. Conclusion

This thesis has presented a comparative analysis of proportional integral derivative, particle swarm optimization, and fuzzy logic controller to select the best optimizer to control the frequency and active power for a Gilgel Gibe 2 hydroelectric power plant unit. To achieve this possibility of implementation the existing control system of the Gilgel gibe 2 hydroelectric power plant was discussed. Hydraulic systems (tunnel, surge tank, and penstock), mechanical systems (linearized turbine), governor systems, and generators were first modeled. The individual component of the Gilgel Gibe 2 hydroelectric power plant considering primary control was modeled to form a hydropower plant and simulated for the network-connected and isolated mode of operation.

The simulation result shows that the overall system transient response output performance of a stabilized closed loop system is improved using the proposed particle swarm optimization by tuning the existing PID controller comparatively from fuzzy logic and the existing PID controller. When one percent in frequency is increased, the load is drooped from the system network, and the control response shows that PID Tuned by particle swarm optimization resulted in less than 1.243 % overshoot, fewer settling times at 0.4052sec, and fewer rising times at 0.0034sec as compared to the fuzzy logic controller and existing PID controller. And also, it is improved the transient response of the existing PID controller is maintained by the PSO optimizer and is updated by 99.1%.its rising time, 97.5% its settling time, and 84.64% of overshoot. But fuzzy logic cleared the transient error by 71.86% rising time, 74.64% settling time, and 40.82% only at 0.2 load power added to the isolated system.

So, the comparison and analysis indicate that intelligent control of particle swarm optimization tool efficiently, accurately and without ambiguity tuned the existing PID as well as optimized the Gilgel Gibe 2 hydroelectric power plant frequency and power control during network connected and isolated mode of operation, and also to enhance the power quality of the power plant control than fuzzy logic and existing PID controller.

6.2. Recommendation

As it is shown in the result discussion part, the designed intelligent controls Particle swarm optimization proportional integral derivative tuning of Gilgel Gibe 2 hydroelectric power plant unit have shown a better result as compared to that of the fuzzy logic controller and conventional one. This is already validated by simulation only. So, who is interested can take this design and it can be implemented including each limit with consideration of electrical torque.

It is recommendable this robust controller will be applied on each part of the plant which used to minimize the controlling error or faults occurring on outgoing and incoming line in switchyard, excitation, protection and online monitoring systems to check the performance of the hydropower plants. The stability of the hydropower system depends on active power and reactive power, by considering frequency and voltage respectively at the admissible range, active power is controlled in this thesis, studying introducing a voltage controller in an excitation system is the other option.

This intelligent method of controller performed on the study area of the real time power plant problem. This helped to model and design seeing the real problem and to reach the required aim. Such, stakeholders can use it to solve instability and improve operation performance of each control system parts and the general system accordingly.

REFERENCES

1. Weijia Yang, “Dynamic Processes and Active Power Control of Hydropower Plant”. Semantic Scholar, published 2015
2. P. Kundur, N. J. Balu, and M. G. Lauby, Power system stability and control vol. 7: McGraw-hill New York, 1994.
3. K. Nagode and I. Škrjanc, "Modelling and internal fuzzy model power control of a Francis water turbine," Energies, vol. 7, pp. 874-889, 2014.
4. P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, et al., "Definition and classification of power system stability," IEEE Transactions on Power Systems, vol. 19, pp. 1387-1401, 2004.
5. J. D. Sharma and A. Kumar, "Development and Implementation of Non-Linear Hydro Turbine Model with Elastic Effect of Water Column and Surge Tank," International Journal of Electrical and Electronics Research, vol. 2, pp. 234-243, 2014.
6. M. Eremia and M. Shahidehpour, Handbook of electrical power system dynamics: modeling, stability, and control vol. 92: John Wiley & Sons, 2013.
7. I. A. I. Nassar, Improvements of primary and secondary control of the Turkish power system for interconnection with the European system, 2010.
8. P. Santos, "Primary frequency control in isolated power grids."
9. A. Deepak, C. J. Roger, and J. Gerald, "The Impact of Hydroelectric Power and Other Forms of Generation on Grid Frequency Stability for the WECC Region,” HydroVision International, Sacramento, CA, July, pp. 19-22, 2011.
10. C. S. Chin, K. T. K. Teo, and P. Neelakantan, "Rotor Speed Control of Micro Hydro Synchronous Generator Using Fuzzy PID Controller."

11. Tilahun Weldcherkos, Ayodeji OlalekanSalau, AderajewAshagrie “Modeling and design of an automatic generation control for hydropower plans using Neuro-Fuzzy controller Science Direct Energy Reports 7 (2021) 6626–6637 Availableonline13October2021

12. Surya Prakash and S. K. Sinha “Application of artificial intelligence in load frequency control of interconnected power system” International Journal of Engineering, Science and Technology Vol. 3, No. 4, 2011, pp. 264-275

13. Yuksel Oguz, Ahmet Kaysal, Selim Koroglu “Adıguzel Hydroelectric Power Plant’s Modelling and Load-Frequency Control by Fuzzy Logic Controller” Int. Journal of Engineering Research and Applications, Vol. 6, Issue 5, (Part - 5) August 2016, pp.61-66

14. Ethiopian Electric Power website “https://www.eep.com.et/en/power-generation”.

15. GG2 HEPP Function Transfers of Speed Governor (Speed Governor Regulation Characteristics) A 2.2 Frequency Governor Dtwg.- No. 2.42-00770 Rev. 1

16. M. R. Sathya and M. M. T. Ansari, "Load frequency control using Bat inspired algorithm based dual mode gain scheduling of PI controllers for interconnected power system," International Journal of Electrical Power & Energy Systems, vol. 64, pp. 365-374, 2015.

17. H. T. Nguyen and V. Kreinovich, "Fuzzy logic, logic programming, and linear logic: towards a new understanding of common sense," pp. 546-550.

18. L. A. Zadeh, “Fuzzy sets,” Information and Control, vol. 8, pp. 338-353, 1965.

19. I. A. Nassar and H. Weber, "Dynamic Model of Unit 1 of Ataturk Hydro Power Plant in Turkey."

20. D. Qian and L. Yu, "Governor design for hydropower plants by intelligent sliding mode variable structure control," Journal of AI and Data Mining, vol. 4, pp. 85-92, 2016.

21. C. Xu and D. Qian, "Governor Design for a hydropower plant with an

upstream surge tank by GA-based Fuzzy reduced-order sliding mode," Energies, vol. 8, pp. 13442- 13457, 2015.

22. W. Yang, J. Yang, W. Guo, W. Zeng, C. Wang, L. Saarinen, et al., "A mathematical model and its application for hydropower units under different operating conditions," Energies, vol. 8, pp. 10260-10275, 2015.
23. D.G. Ramey, J.W. Skoglund, “Detailed Hydro Governor Representation for System Stability Studies”, IEEE Trans. PAS, vol. PAS-89, no. 1, Jan. 1970, pp. 106-112.
24. GG2 HEPP Operation and Maintenance Manual for Vertical shaft Pelton Turbine Dwg. SA-EM-1013 Dwg No 2.82-029086
25. W. Yang, J. Yang, W. Guo, and P. Norrlund, "Response time for primary frequency control of the hydroelectric generating unit," International Journal of Electrical Power & Energy Systems, vol. 74, pp. 16-24, 2016.
26. M. E. Cebeci, U. Karaağaç, O. B. Tör, and A. Ertaş, "The effects of hydropower plants’ governor settings on the stability of Turkish power system frequency."
27. R. A. Nanaware, S. R. Sawant, and B. T. Jadhav, "Fuzzy Based Turbine Governor for Hydro Power Plant," power electronics, vol. 14, p. 15.
28. Dongshu Wang1 · Dapei Tan1 · Lei Liu2, “Particle swarm optimization algorithm: an overview” © Springer-Ve rlag Berlin Heidelberg 2017
29. Copyright (c) 2015, Project Code: YPEA102, Project Title: Implementation of Particle Swarm Optimization in MATLAB Publisher: Yarpiz (www.yarpiz.com)
30. Mr. Gabriel Musonda, Prof. Webby Mwaku, Mr. George Mugala “Load Frequency Control Optimization Using PSO (A case of the Power System in Zambia)” Published by: International Journal of Engineering Research & Technology (IJERT) ISSN: 2278-0181 Vol. 7 Issue 06, June-2018
31. D.J. Trudnowski, J.C. Agee, “Identifying a Hydraulic - Turbine Model from Measured Field Data”, IEEE Trans. EC, vol. EC-10, no. 4, Dec. 1995, pp.768-773.

32. R. Oldenburg, J. Donelson, “Dynamic Response of a Hydroelectric Plant”, AIEE Trans., Oct. 1962, pp. 403-419.

33. Konidaris, D.N.; and Tegopoulos, J.A.; “Investigation of oscillatory problems of hydrodynamic generating units equipped with Francis turbines”, IEEE Trans. on Energy Conversion, vol. 12, no. 4, Dec.1997, Page(s):419-425.

34. L. Wozniak, “ A Graphical Approach to Hydro generator Governor Tuning”, IEEE Trans. EC, vol. EC-5, no. 3, Sept. 1990, pp.417-421.

35. H. Brekke, “A Study of the Influence of Turbine Characteristics on Turbine Governing”, 2 International Conference on Pressure Surges, paper J2, The City University, London, England, 1976.

36. Zwe-Lee Gaing, “A particle Swarm Optimization Approach for Optimum Design of PID Controller in AVR(Automatic Voltage Regulator) System”, IEEE Transactions on Energy Conversion, Vol.19, No.2, pp384-391, 2004.

37. E. Rognaldsen, "Modeling and Simulation of Hydropower Plant in Scilab," 2017.

38. Stephen Bassi Josepha,∗, Emmanuel Gbenga Dadab, Afeez Abidemic, David Opeoluwa Oyewolad, Ban Mohammed Khammase, “Metaheuristic algorithms for PID controller parameters tuning: review, approaches and open problems ” Heliyon 8 (2022) e09399, Received 4 November 2021

39. Kosko B, Mitaim S. What is the best shape for a fuzzy set in function approximation? Proceedings of the 5th IEEE International Conference on Fuzzy Systems (FUZZ-96); September 1996. pp. 1237-1243

40. Chen JE, Otto KN. Constructing membership functions using interpolation and measurement theory. Fuzzy Sets and Systems. 1995;73(3):313-327

41. Zhao J, Bose BK. Evaluation of membership functions for fuzzy logic

controlled induction motor drive. 28th Annual IEEE Conference of the Industrial Electronics Society 2002; Sevilla; Spain

42. P. J. Antsaklis, "On Intelligent Control: Report of the IEEE CSS Task Force on Intelligent Control," Technical Report of the ISIS (Interdisciplinary Studies of Intelligent Systems) Group, No. ISIS-94-001, Univ of Notre Dame, January 1994

43. Weijia Yang, “Dynamic Processes and Control for Stable and efficient Operation” Acta Uiversitatis Upsaliensis Uppsala 2017

APPENDICES A

The parameter value of the Gilgel Gibe II hydroelectric power unit

A parameter value of Pelton Turbine	
Type of turbine	Impulse Vertical shaft Pelton Turbine
Diameter of turbine	2.65m
The equivalent cross-section of the penstock	6.15m^2
Maximum output	4* 105 MW
Maximum discharge	4* 24,53m^3/s
Turbine efficiency (η)	0.92
The nominal rotational speed of the turbine	333,33 rpm
Net head	485 m
Maximum gross head	492 m
A parameter value of Penstock	
Number	2
Diameter	2.8m
Length	1200m (1.2km)
Area	6.1544 m^2
A parameter value of Tunnel	

Length	26000m (26km)
Diameter	6.3 m
Area	31.2 m^2
A parameter value of the Surge shaft	
Diameter	25 m
Height	14m
Area	490.625 m^2
A Parameter value Servomotor	
Servo-motor time Ts	0.3
A parameter value of Governor	

No	Sign	Units/Description	Frequency control	Parallel power control
1	K_P		1.6	0.2
2	K_I	Sec^{-1}	0.5	0.1
3	K_D	Sec	1.6	0.3
4	e_p	%	4	0

APPENDICES B

Particle Swarm Optimization MATLAB Code for Networked operation

```
function cost = networked(KK)
assignin('base','KK',KK);
sim('PSO_gg2_networked_PID.slx');
cost= ITAE(length(ITAE));
end
clear all
close all
clc

% Define the details of the table design problem
nvar = 3;           % number of variables
ub = [1000 1000 1000];      %upper bounds of variables
lb = [0 0 0];        %lower bounds of variables
fobj = @networked;   %Objective function Name

% Define pso's parameters values
nop = 50;          % population size
maxIter = 100;     % maximum iteration
wMax = 1;          % inertia weight
wMin = 0.1;        % inertia weight
c1=2;          % acceleration factor
c2=2;          % acceleration factor
vMax = (ub - lb) .* 0.5;
vMin = -vMax;

% pso main program

% Initialization of the particles
   for k = 1 : nop
      swarm.particles(k).X = (ub-lb) .* rand(1,nvar)+ lb;
      swarm.particles(k).V = zeros(1,nvar);
      swarm.particles(k).PBEST.X = zeros(1,nvar);
      swarm.particles(k).PBEST.a = inf;

      swarm.GBEST.X = zeros(1,nvar);
      swarm.GBEST.a = inf;
   end
   % Main loop
      for t = 1 : maxIter

         % Calculate the objective value
       for k = 1 : nop
            currentX = swarm.particles(k).X;
            swarm.particles(k).a = fobj(currentX);

         % Update the PBEST
```

```
        if swarm.particles(k).a < swarm.particles(k).PBEST.a;
            swarm.particles(k).PBEST.X = currentX;
            swarm.particles(k).PBEST.a = swarm.particles(k).a;
        end

        %Update the GBEST
        if swarm.particles(k).a < swarm.GBEST.a
            swarm.GBEST.X = currentX;
            swarm.GBEST.a = swarm.particles(k).a;
        end
     end

    %Update the X and V vectors
    w = wMax - t .* ((wMax - wMin) / maxIter);

    for k = 1 : nop
        swarm.particles(k).V = w .* swarm.particles(k).V + c1 .* rand(1,nvar) .*
(swarm.particles(k).PBEST.X - swarm.particles(k).X)
        + c2 .* rand(1,nvar) .* (swarm.GBEST.X - swarm.particles(k).X);

        % Check velocities
        index1 = find(swarm.particles(k).V > vMax);
        index2 = find(swarm.particles(k).V < vMin);

        swarm.particles(k).V(index1) = vMax(index1);
        swarm.particles(k).V(index2) = vMin(index2);

        swarm.particles(k).X = swarm.particles(k).X + swarm.particles(k).V;

        % Check positions
        index1 = find(swarm.particles(k).X > ub);
        index2 = find(swarm.particles(k).X < lb);

        swarm.particles(k).X(index1) = ub(index1);
        swarm.particles(k).X(index2) = lb(index2);
    end

    outmag = {'Iterations ', num2str(t) , ' swarm.GBEST.a = ' ,
num2str(swarm.GBEST.a)};
    disp(outmag);

    egcurve(t) = swarm.GBEST.a;
    end

semilogy(egcurve);
xlabel('Iterations')
ylabel('Height')
```

Particle Swarm Optimization MATLAB Code for Isolated operation

```
function cost = isolated(kk)

assignin('base','kk',kk);

sim('pso_gg2_isolated_PID.slx');

cost= ITAE(length(ITAE));

end
clear all
close all
clc

% Define the details of the table design problem
nvar = 3;            % number of variables
ub = [1000 1000 1000];      %upper bounds of variables
lb = [0 0 0];         %lower bounds of variables
fobj = @isolated;   %Objective function Name

% Define pso's parameters values
nop = 50;          % population size
maxIter = 100;     % maximum iteration
wMax = 1;          % inertia weight
wMin = 0.1;        % inertia weight
c1=2;           % acceleration factor
c2=2;           % acceleration factor
vMax = (ub - lb) .* 0.5;
vMin = -vMax;

% pso main program

% Initialization of the particles
  for k = 1 : nop
    swarm.particles(k).X = (ub-lb) .* rand(1,nvar)+ lb;
    swarm.particles(k).V = zeros(1,nvar);
    swarm.particles(k).PBEST.X = zeros(1,nvar);
    swarm.particles(k).PBEST.a = inf;

    swarm.GBEST.X = zeros(1,nvar);
    swarm.GBEST.a = inf;
  end
  % Main loop
    for t = 1 : maxIter

      % Calculate the objective value
     for k = 1 : nop
        currentX = swarm.particles(k).X;
```

```
            swarm.particles(k).a = fobj(currentX);

          % Update the PBEST
          if swarm.particles(k).a < swarm.particles(k).PBEST.a;
             swarm.particles(k).PBEST.X = currentX;
             swarm.particles(k).PBEST.a = swarm.particles(k).a;
          end

          %Update the GBEST
          if swarm.particles(k).a < swarm.GBEST.a
             swarm.GBEST.X = currentX;
             swarm.GBEST.a = swarm.particles(k).a;
          end
        end

       %Update the X and V vectors
       w = wMax - t .* ((wMax - wMin) / maxIter);

       for k = 1 : nop
          swarm.particles(k).V = w .* swarm.particles(k).V + c1 .* rand(1,nvar) .*
(swarm.particles(k).PBEST.X - swarm.particles(k).X)
          + c2 .* rand(1,nvar) .* (swarm.GBEST.X - swarm.particles(k).X);

          % Check velocities
          index1 = find(swarm.particles(k).V > vMax);
          index2 = find(swarm.particles(k).V < vMin);

          swarm.particles(k).V(index1) = vMax(index1);
          swarm.particles(k).V(index2) = vMin(index2);

          swarm.particles(k).X = swarm.particles(k).X + swarm.particles(k).V;

          % Check positions
          index1 = find(swarm.particles(k).X > ub);
          index2 = find(swarm.particles(k).X < lb);

          swarm.particles(k).X(index1) = ub(index1);
          swarm.particles(k).X(index2) = lb(index2);
       end

       outmag = {'Iterations ', num2str(t) , ' swarm.GBEST.a = ' ,
num2str(swarm.GBEST.a)};
       disp(outmag);

       egcurve(t) = swarm.GBEST.a;
       end

semilogy(egcurve);
xlabel('Iterations')
ylabel('Height')
```