JIMMA UNIVERSITY

JIMMA INSTITUTE OF TECHNOLOGY

SCHOOL OF POST GRADUATE STUDIES

FACULTY OF ELECTRICAL AND COMPUTER ENGINEERING

CONTROL AND INSTRUMENTATION ENGINEERING STREAM

LOAD FREQUENCY CONTROL OF MINI HYDRO POWER GENERATION USING ADAPTIVE FUZZY LOGIC CONTROLLER (CASE STUDY AT DEBRE ZEIT KEBELE IN CHEMOGA RIVER)

A Thesis Submitted to the School of Post Graduate Studies, Jimma University, Jimma Institute of Technology, Faculty of Electrical and Computer Engineering in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Control and Instrumentation Engineering.

By

Likenesh Walle Biyazne

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Jimma, Ethiopia

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Approved by Board of Examiners

Chairman, Department of Graduate Committee ____________

Signature

Main Advisor: Dr. Prashanth A. ___________

Signature

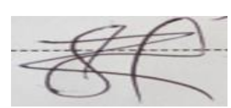
Co Advisor: Mr. Abu F. (MSc.) ___________

Signature

Internal Examiner __________

Signature

External Examiner



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DECLARATION

I declare that this thesis entitled “load frequency control of mini hydro power generation using adaptive fuzzy logic controller case study at Debre Zeit kebele in Chemoga river” is my original work and has not been submitted and presented as a requirement for the award of any degree in Jimma University or elsewhere and all sources of materials used for the thesis have been fully acknowledged.

Ms. Likenesh Walle ______________ __________

NAME SIGNATURE DATE

Jimma, Ethiopia __________

Place Date of Submission

This final thesis has been submitted with my approval as a university advisor.

Main Advisor: Dr. Prashanth A. _______________ __________

NAME SIGNATURE DATE

Co-Advisor: Mr. Abu F. (MSc.) _______________ __________

NAME SIGNATURE DATE

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ABSTRACT

Electricity is the main source of energy all over the world. Almost all the remote rural areas of Ethiopia have not benefited from the use of electricity in the same proportion as the more populated urban areas of the country either the remote location or the low population densities. Among them, Debre Zeit kebele is one of the selected remote rural area that have no access to electricity. Due to increasing energy demand and global warming, the use of new and renewable sources of energy has become necessary.

This thesis investigates load frequency control of mini hydro power generation using adaptive fuzzy logic controller case study at Debre Zeit kebele in Chemoga river. The components of mini hydro power generation (MHPG) are modeled, designed, and simulated by using MATLAB/Simulink software. The simulation results are observed by using a convectional PID controller and an intelligent AFLC. It is observed from the MATLAB simulation results, the effects of system performance measuring variables by using PID controller are tested for different load variations of 0%, 20%, 50%, 60% and 65%, are large rise time, large overshoot and also very small steady-state frequency error are obtained respectively.

The effects of system performance measuring variables by using AFLC are tested for different load variations of 0%, 20%, 50%, 60% and 65%, are very small rise time, very small overshoot and also very small steady-state frequency error are obtained respectively.

Generally, PID controller is poor control system stability performance measuring variables, it is only considering steady-state frequency error approaches to zero at various load changes. Therefore, both the transient and steady-state control system stability performance measuring variables are improved by AFLC. The controller works efficiently under all operating load conditions because, this controller is suitable for complex, nonlinear, uncertain, higher-order, and time-delay systems.

Keywords: Adaptive Fuzzy Logic Controller, Frequency Control, MATLAB/Simulink, Mini Hydro Power Generation, Renewable Energy

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LIST OF SYMBOLS

f	Frequency
Δf	Frequency deviation
p_o	Number of poles
P_m	Mechanical power
P_{th}	Theoretical output power
P_{act}	Actual output power
η	Efficiency factor
g	Force of gravity
D	Generator damping factor
ΔP_m	Change in mechanical power
ΔG	Change in gate position
V	Water velocity
a	Acceleration
ρ	Density in (kg/m3)
Q	Flow rate of water
H_d	Hydraulic net head
A	Pipe area
L	Length of penstock
G_o	Initial gate position
Q_o	Initial flow rate of water
H_{do}	Initial hydraulic neat head
V_o	Initial water velocity
ω_o	Initial angular velocity
P_{mo}	Initial mechanical power
T_m	Mechanical torque

T_e	Electrical torque
K	Constant of proportionality
t	Time in second
H	Generator inertia constant
G	Machine rating/base
P_e	Electrical power generated
$\overline{P}_e$	Per unit electrical power generated
$\overline{\omega}_r$	Per unit angular velocity
δ	Angular position of the rotor
$\Delta\overline{\omega_r}$	Per unit change in angular velocity
$\Delta\overline{G}$	Per unit change in gate position
$\Delta\overline{G_{TDC}}$	Per unit change gate transient droop compensator
$\Delta\overline{P_e}$	Per unit change in electrical load power
$\Delta\overline{H_d}$	Per unit change in hydraulic head
$\Delta\overline{Q}$	Per unit change in flow rate of water
$\Delta\overline{P_m}$	Per unit change in mechanical power
$\Delta\omega_r$	Change in angular velocity
ΔH_d	Change in hydraulic neat head
ΔQ	Change in flow rate of water
KE	Kinetic energy
J	Rotor moment of inertia
M	Moment of inertia
T_T	Hydraulic amplifier transient droop time
T_R	Hydraulic amplifier rise time
T_w	Hydraulic turbine water starting time

LIST OF ABBREVIATIONS

AFLC	Adaptive Fuzzy Logic Controller
AGC	Automatic Generation Control
ALC	Automatic Load Control
ANFS	Artificial Neural Fuzzy Inference System
ANN	Artificial Neural Network
CFL	Compact Fluorescent Light
EEP	Ethiopian Electric Power
FA	Firefly Algorithm
FIS	Fuzzy Inference System
FLC	Fuzzy Logic Controller
GSA	Gravitational Search Algorithm
HPP	Hydro Power Plant
Kg	Kilogram
KW	Kilowatt
KWh	Kilowatt-hour
LFC	Load Frequency Control
LHPG	Large Hydro Power Generation
LQR	Linear Quadratic Regulator
MFs	Membership Functions
MHPG	Mini Hydro Power Generation
MPC	Model Predictive Control
MW	Megawatt
NB	Negative Big
NM	Negative Medium
NM	Newton Meter
NS	Negative Small
P.U	Per Unit
PB	Positive Big
PD	Proportional Derivative
PI	Proportional Integrator
PID	Proportional Integrator Derivative
PM	Positive Medium

PNN	Probabilistic Neural Network
PS	Positive Small
PSO	Particle Swarm Optimization
RBFNN	Radial Basis Function Neural Network
RSE	Renewable Sources of Energy
SHPPs	Small Hydro Power Plants
SMC	Sliding Mode Control
TV	Television
V_1	Village one
V_2	Village two
V_3	Village three
V_4	Village four
V_5	Village five
V_6	Village six
V_7	Village seven
V_8	Village eight
V_9	Village nine
ZE	Zero

CHAPTER ONE

INTRODUCTION

1.1. Background of the study

Today, electricity is a fundamental entity for the socio-economic development of any country. It has many advantages such as improved health care, improved education, better transportation systems, improved communication systems, a higher standard of living, and economic stability. Especially for economic growth, the use of energy plays a big role in household activities, industries, hospitals, railways, universities, transportation, factories, companies, and other organization in daily work [1].

Human civilization depends on various sources of energy. The two major sources of energy can be classified under conventional sources of energy and non-conventional sources of energy. Conventional sources of energy are also known as non-renewable sources of energy and are available in limited quantity apart from hydroelectric power. Non-conventional sources of energy are also known as renewable sources of energy like photovoltaic, steam, solar, wind, biogas or biomass, hydropower plant, etc. The generation of electricity from non-conventional hydropower sources of energy is essential for nature protection. Among all non-conventional sources of energy, water has a cost-effective, most reliable resource, and is environment-friendly. Only water is used which is the natural source our country Ethiopia is rich off. Water is very important deliberated as a more powerful and efficient source of energy as compared to the other renewable sources of energy. Hydropower is a form of non-conventional source of energy, which comes from flowing water. When generating electricity, the water should be in movement. When the water is falling with the help of gravitational force, its potential energy converts into kinetic energy [2]. Due to the high cost of transmission lines, electricity is not transported to remote rural areas. In remote rural areas of Ethiopia, the rivers are used for agricultural purposes, drinking for humans as well as animals, and washing clothes, but these rivers can be a source of electrical energy. Hydropower is classified as super, large, medium, mini, micro and Pico according to their power generation capacity. MHPG is a multi-significant role in electrifying these areas where peoples are sparely live and the population is a less or small community. The cost of connectivity of these areas is far away therefore, MHPG can easily provide electricity at less cost and can change the remote rural people's lifestyle without grid installation [3].

Mini hydro power generation should be made on runaway water, small streams, canals, and river branches in the mountainous areas where the building of a dam, reservoir, or water storage is not required. This makes mini hydro power technology advantageous. However, selecting suitable hydro power potential river and developing are many aspects which have been taken into consideration, covering many disciplines ranging from business, engineering, financial, legal, and administration.

There are so many rivers found at Debre Zeit kebele area among them Chemoga river was the best selected and prioritized river which is a high amount of water available by meeting several small rivers and streams, high water storage capacity, by considering the head of water is better when compared to other rivers in that area. Chemoga river catchment in figure 1.1 is a tributary of Abay or Upper Blue Nile basin, which is located south of Lake Tana and extended between approximately 10°10’00’ to 10°40’00’N latitude and 37°30’00’to 37°54’00’E longitude [4]. This river flow starts from Choke Mountain at an elevation of 4,000 meters above mean sea level. Mount Choqa also known as Mount Birhan a part of the Choke Mountains with an elevation of 4,154 meters above sea level.

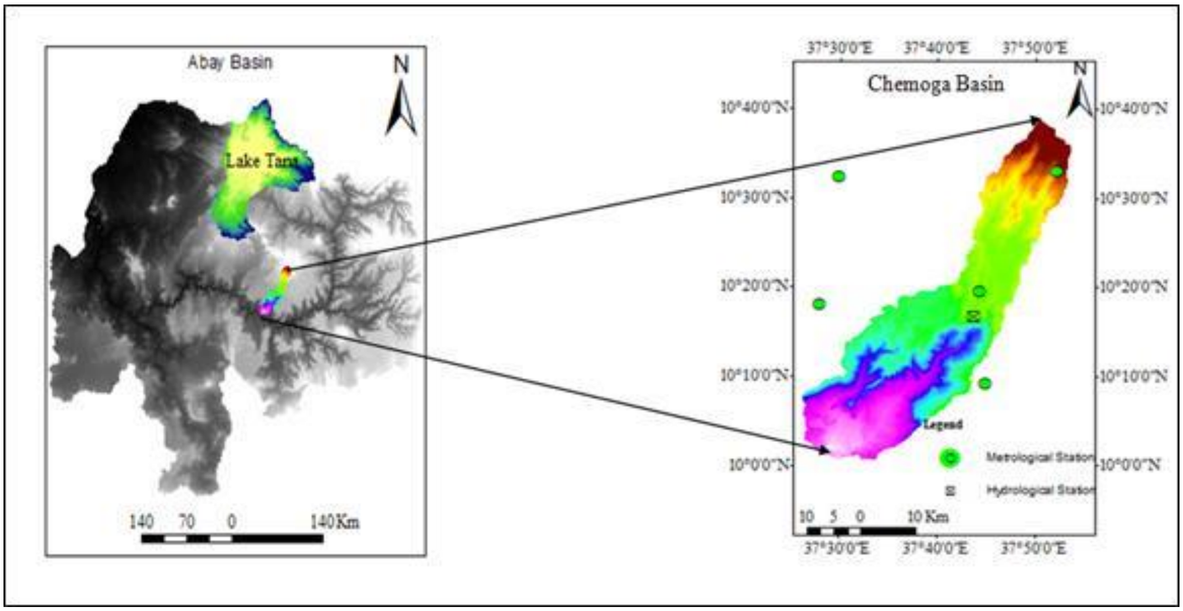


Figure 1.1. Location map of the selected hydro power potential river [5]

The communities in the selected remote rural area with schools, church’s, masjid’s and health center requires electricity for lighting, refrigeration, medical tools, communication equipment, water pumping, sterilization, medical and night education, etc. Therefore, this thesis investigates load frequency control of mini hydro power generation by using Chemoga river can easily provide electricity at less cost and can change the lifestyle of people living at Debre Zeit kebele area.

1.2. Statement of the problem

One of the most important infrastructures for sustainable socio-economic development is the availability of electricity all over the world. The major limitation of this development almost all in the remote rural societies has been the lack of this usable electricity. Among them, Debre Zeit kebele is one of the selected remote rural areas which have no access to electricity. This remote rural area is still now without electric access due to either being far away from the national grid or the people living sparsely populated. But electrification in these communities is very essential especially, to ensure the socio-economic development of the community as well as the country. To satisfy their energy needs, people at Debre Zeit kebele area use non-renewable sources of energy like kerosene for lamps, diesel for flour mills, coal, fire wood, sometimes petroleum or natural gas for cooking food and dry cells for radio and tape recorder, but those are causing rapid growth of deforestation, soil erosion, environmental pollution, as a result to increase global warming and also which leads to health problems.

People living in this remote rural area cannot use technologies like a smart phone, TV, refrigerator, electric bulb, electric oven, stove and also are not able to benefit from social services such as clinics, hospitals, hotels, and schools sufficiently due to lack of access to electricity. If people cannot use technologies, necessary information is not addressed due to this reason their life would be hard to live.

1.3. Objective of the study

1.3.1. General Objective

The general objective of this thesis is load frequency control of mini hydro power generation using adaptive fuzzy logic controller at Debre Zeit kebele area.

1.3.2. Specific Objectives

- To select the best hydro power potential river from various rivers
- To estimate theoretical and actual output power potential from the selected river
- To model and design the appropriate mini hydro power components based on the mathematical equations and using associated transfer functions
- To develop control mechanism by using PID controller and an intelligent AFLC
- To simulate the overall mini hydro power models by using MATLAB/Simulink software

1.4. Significance of the study

This study has a multi-dimensional significance for the society of Debre Zeit kebele area. The first and the most significant is to get optimum electricity access for the communities. This optimum electricity access which leads to improve the life standard of the society by increasing education possibilities for the pupils and the students to study at night time, to operate health center at night time, avoid unhealthy kerosene lamps which leads to improve health conditions. Moreover, optimum electrifying in this selected remote rural area are also further advantages such as, to reduce rapid growth of deforestation, to avoid soil erosion, increase environmental protection or decrease environmental pollution as a result to decrease global warming and another significance to initiate decision-makers to establish hydro power development program for the future generation.

1.5. Scope and Limitations of the study

The scope of this thesis is limited to only the target populations for the intervention problems are bounded at Debre Zeit kebele area. Therefore, this study does not include the other Keeble's problems due to time, cost, and available resource limitations during the time of data collection.

The other limitation of this thesis only focuses on the feasibility of mini hydropower source of energy among various renewable sources of energy at Debre Zeit kebele area, like biogas, solar, biomass, and wind. This study has no any practical implementation, it is only forecasting the mathematical models, designs, and simulates for load frequency control of mini hydropower generation using a convectional PID controller and an intelligent AFLC in MATLAB/Simulink software.

1.6. Methodology

The overall goal of this thesis paper is to electrify at Debre Zeit kebele area which is far away from the national grid with reasonable cost. The methodologies are involving several different tasks that are performed to leads towards the completion of this thesis as follows:

1. Literature review: the work of this thesis is necessarily based on other scholars have been done related to this selected topic to look into the works of these scholars and get necessary and important information, different kinds of literature are referred from different available sources such as books, articles, papers, journals, published materials and searching internet related to load frequency control of mini hydro power generation system.

2. Site selection and observation: the primary work includes site selection and observation, know total number of populations, and total number of households to evaluate the living style of the community as well as calculating theoretical and actual output power and energy demand of the community. The field data is supported by photographs to show equipment used by the community in daily life and activity related to energy consumption. The power or energy demand of each household has been estimated based on the need of the community.

3. Data collection: the data required for the designing, modeling, and simulating for load frequency control of mini hydro power generation have been collected from different sources such as books, papers, journals, searching internet, articles, published materials, previous works by other scholars and also by observing related videos.

4. Data analysis: is a process of inspecting, modeling, and designing of mini hydro power system feasibility is analyzing from the collected data by using theoretically proved formulas.

5. Modeling and designing: the overall model and designs of the proposed adaptive fuzzy logic frequency controller of mini hydro power generation have been simulated using MATLAB/Simulink software depending on the data analysis to get the best optimizing solution.

6. Finally, paper documentation: the final work is showing the overall works of the thesis starting to ending including, MATLAB simulation results, conclusion, recommendation, and future work that have been made based on the research finding and the simulation studies.

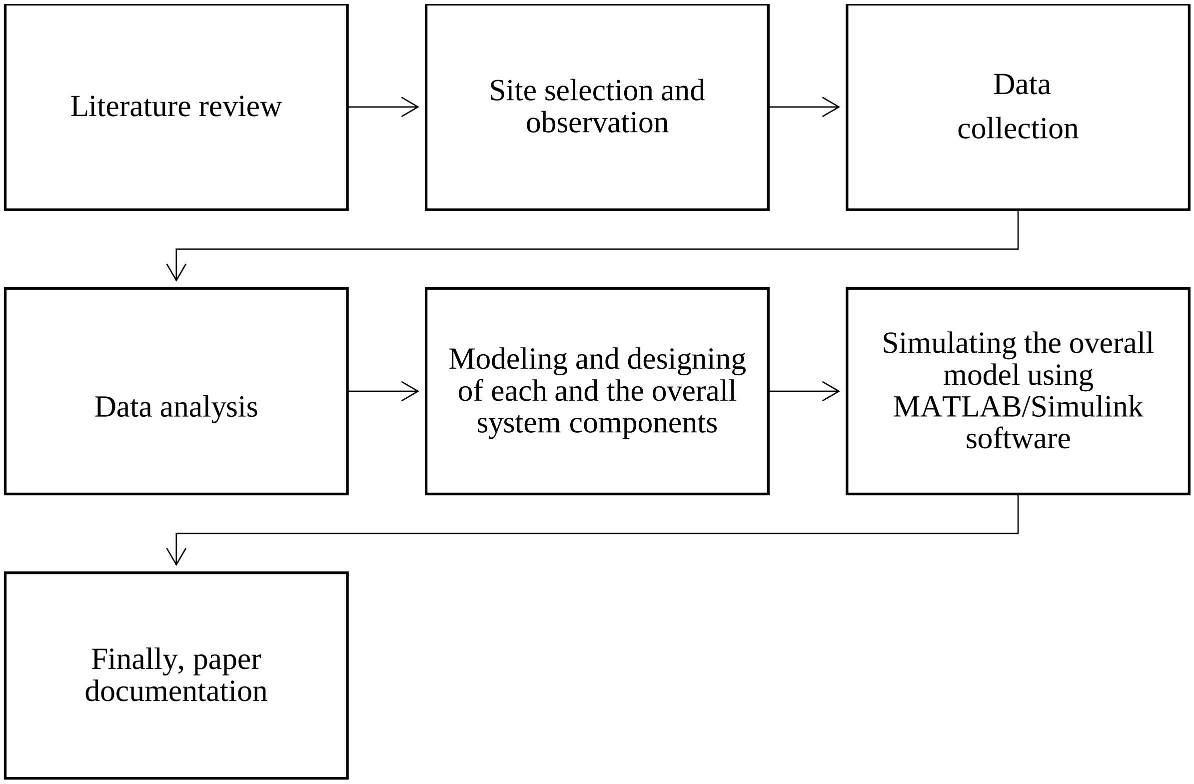


Figure 1.2. Block diagram of the overall methodologies to be followed for this thesis

1.7. Thesis Outlines

This thesis paper is mainly divided into six chapters.

CHAPTER TWO is a literature review part in which different kinds of literature are reviewed and the basic background theory briefly discussed related to the study.

CHAPTER THREE which is describe the mathematical model of MHPG is presented.

CHAPTER FOUR which is load estimation and design parameters of MHPG and also methods of head and flow measurement without sophisticated tools are briefly described.

CHAPTER FIVE which is a MATLAB simulation results and discussion parts are presented.

CHAPTER SIX which is the conclusion, recommendation, and future work have been discussed.

CHAPTER TWO

LITERATURE REVIEW

2.1. Introduction

Remote rural areas especially in developing countries are in great need of affordable and reliable electricity to achieve development. The issue of climate change, environmental degradation, population growth, and the non-stop need for electricity has made renewable energy sources [6]. Renewable energy systems are one of the most suitable and environment-friendly solutions to provide electricity within remote rural areas. The use of renewable sources of energy (RSE) has many advantages over conventional sources these are; minimizing the dependency on oil price fluctuations, reducing the transportation costs of fuels, improving health care, increasing economic productivity and creating local employment opportunities, fighting climate change, and poverty to allow better use of local natural resources [7]. The mini hydropower system is one of the best findings of renewable sources of energy. It is chosen because of their availability of water almost everywhere on earth compared to other renewable sources of energy such as solar, wind, and geothermal which occur in any place in the world.

Mini hydro power generation, the main components, and development of control systems of MHPG are presented in this chapter.

2.2. Mini Hydro Power Generation

Water is the cheapest non-conventional source of energy to generate electricity. The energy of water for hydropower generation may be kinetic or potential. The kinetic energy of water is its energy in motion and is a function of mass and velocity while the potential energy is a function of the difference in the level of water between two points called the head. In either case, continuous availability of water is a basic necessity [8]. Hydraulic turbines are used to change the potential energy of water into mechanical energy. The mechanical energy developed by the turbine is used in running the electrical generator which is directly coupled to the shaft of the turbine. The mini hydropower system is a small hydroelectric system that typically generates from 100 KW to 1 MW of electricity using the natural flow of water. This power system can provide power to an isolated home or small community, small factories, and supply an independent local mini-grid [9].

The simplest mini hydropower generation is depending on a run-of-river design which means it does not have water storage capability. It will produce power only when water is running or it might have relatively small water storage capability. For villages very far from the national grid where connection to it may not be economical and for which a constant stream flow is available, mini hydropower generation is the best option for electrification. The mini hydropower system is not that much different from large hydroelectric systems, except for its power rating. The principles of operation, types of material units, the mathematical equations used, and the design of system parameters are essentially the same as large hydro power systems [10].

2.3. The Main Components of Mini Hydro Power Generation

The main components of MHPG can be categorized into two civil work components and electromechanical components in figure 2.1. Each component is further classified into different parts which are presented in detail in the following subsections [11].

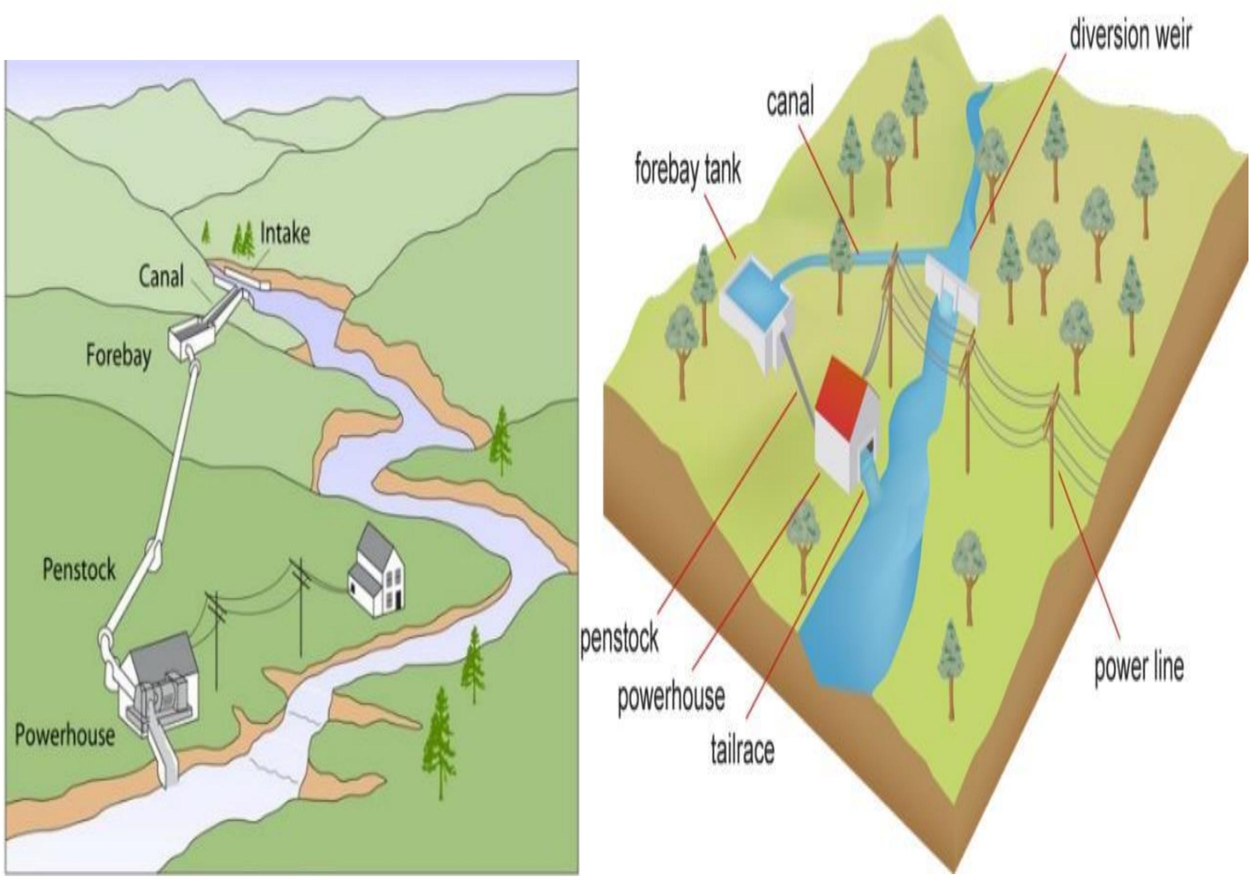


Figure 2.1. Typical layout of mini hydro power generation system [12]

2.3.1. Civil Work Components of Mini Hydro Power Generation

This section describes the most common civil work components such as the intake, inlet water ways, headrace canal, forebay tank, penstock pipe, and the tailrace of typical MHPG systems [13].

Intake

The intake would be well located to prevent debris and a high amount of flows of water from the source of water in the required quantity towards the waterways of the MHPG system [14]. The gates and valves control the rate of water flows entering the intake. Gates discharge excess amount of water during flood duration. There are various types of gates such as; crest gates, sluice gates, wheeled gates, plain sliding gates, radial gates, rolling or drum gates, etc. There are various kinds of valves from that needle valves and butterfly valves are used in the MHPG system [15].

Headrace Canal

The headrace canal is an excavated canal made of only soil, a mixture of stone and mud, a mixture of stone masonry with cement, concrete, metal sheet, or other different types of possible combinations which convey the water to the forebay. The materials are used in constructing the canal depend upon the geographical condition of the site and other obvious factors such as the availability of labor and materials [16].

Penstock pipe

This is a pipe that conveys water under high pressure to the turbine wire mesh of reasonable strength should be put in front of the penstock to sieve unsettled sand. It is slopping towards the power house and its grade is adjusted as per the topography. The trusted block, which is a mass of concrete fixed into the ground, is used to restrain the penstock from moving in undesirable directions [17].

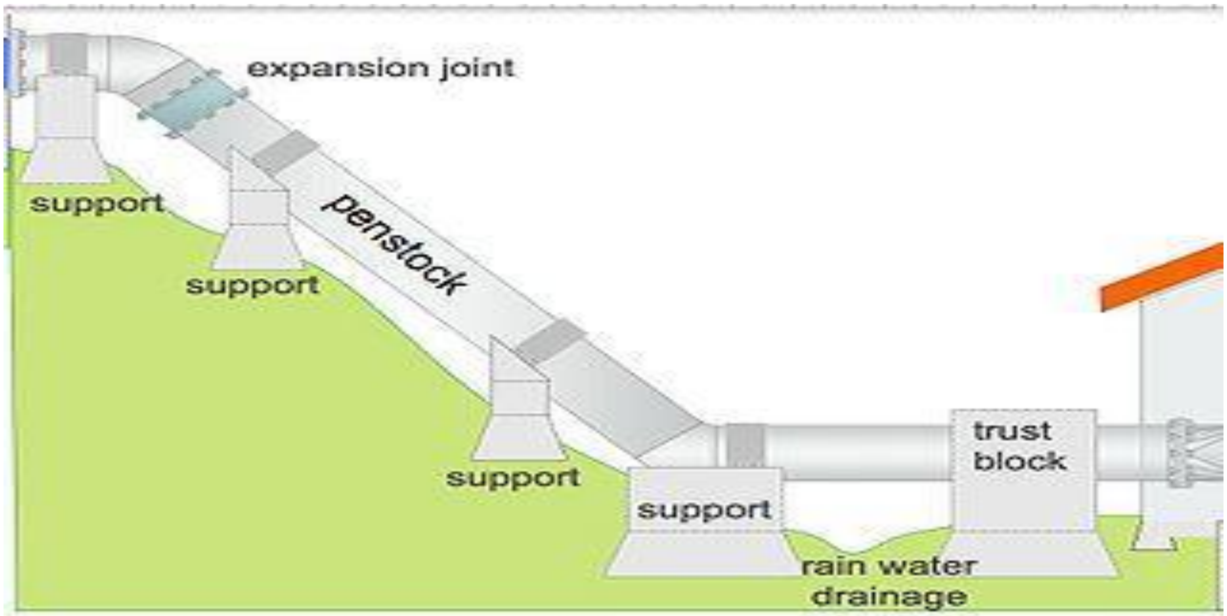


Figure 2.2. Components of penstock pipe in typical MHPG system [18]

Forebay Tank

The forebay is a basin located fast before the entrance to the penstock. It is a temporary storage of water made of reinforced concrete. The forebay tank is mainly a pool at the end of the headrace canal from which the penstock pipe draws the water. The basic advantage of the forebay tank is to minimize entry of air into the penstock pipe, which in turn can cause cavitation of both the penstock pipe and the turbine.

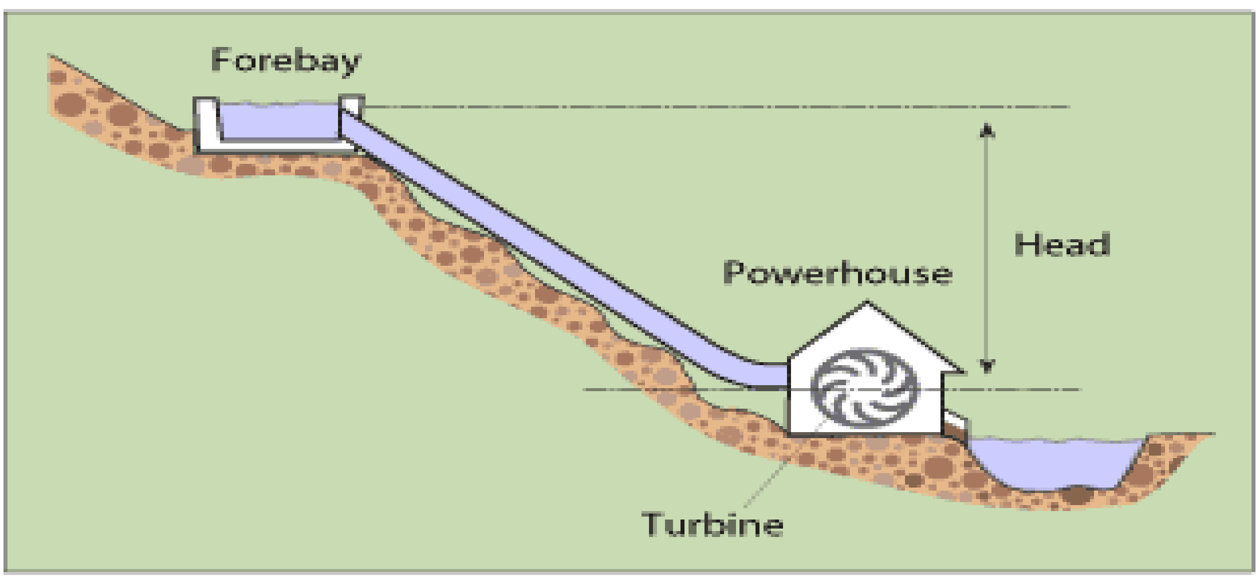


Figure 2.3. Design of a typical forebay tank in MHPG system [19]

Tailrace

Tailrace is a passage for discharging the water leaving the turbine into the river and in certain cases, the water from and it should be pumped back into the original reservoir. Water after doing work on the turbine runner passes through the draft tube to the tailrace. The water held in the tail race is called as tail race water level. The draft tube is an essential part of reaction turbine installation. It is a diverging passage from the point of runner exit down to the tail race [20].

2.3.2. Electromechanical Components of Mini Hydro Power Generation

Electromechanical components are the powerhouse components of a mini hydropower system and they are used to change the mechanical energy of water into electrical energy. The principal electromechanical components of mini hydropower systems are turbine, generator, and actuator [21].

Power House

The powerhouse is served as an engine room. It has prevented the turbine, generator, and other electrical or machinery equipment. The power house is a building in which the turbines, alternators, and auxiliary plants are housed [22]. Here conversion of the energy of water to electrical energy takes place. The powerhouse consists of two basic structures those are; a substructure to support the hydraulic and electrical equipment and a superstructure mostly is a building, housing, protecting, and operating these types of equipment [23].

There are so many principal electromechanical and hydraulic equipment's; some of the basic equipment's provided in the power house are:

- Prime movers or turbines coupled with generators
- Turbine governors
- Gate valves
- Water circulating pumps
- Flow measuring devices
- Oil circuit breakers
- Switch board equipment and instrument
- Low tension and high-tension bus bar etc.

Turbines

In mini hydropower generation, the hydraulic turbine is the rotary machine that converts kinetic energy and potential energy of the flowing water into mechanical energy through the rotation of the runner. The most popular and conventional classification of turbines is based on the pressure head available and the design flow for the proposed hydro power installation it can be divided as the high head, the medium head, or the low head under which it operates [24].

The hydraulic turbine selection criteria are based on the available water head and the available flow rate. All hydraulic turbines have their power-speed characteristics, this means they will operate effectively at a particular speed, head, and flow combination. Thus, the desired running speed of the generator or the devices being connected or loading on the turbine also influences the selection. There are many varieties of hydraulic turbines, each of them has its advantages and disadvantages. However, hydraulic turbines are classified depending on their hydraulic action into two main classes; impulse turbines and reaction turbines. Impulse turbines are generally used for high head rivers by changing the velocity of a water jet. These turbines are not well suited for Pico, micro, or mini hydro power generation due to their more complex structural requirements and their complexity. Reaction turbines are used for low head rivers and are also suited for Pico, micro, or mini hydro power generation.

Table 2.1. The basic classification of turbine types [25]

Head pressure			
Turbine Runner	High Head (above 100m/325ft)	Medium Head (30-100m/100- 325ft)	Low Head (less than 30m/100ft)
Impulse	Pelton Turgo	Pelton Crossflow Turgo	Water wheel Crossflow Screw
Reaction	Francis Propeller	Francis Propeller Kaplan	Kaplan

Kaplan turbine is a reaction turbine unlike impulse turbines, which is versatile and relatively simple to design in low and medium head plants. In addition, the Kaplan turbine can relatively simply be altered, only by changing the diameter and the width of the runner, to adjust it to different site characteristics or namely different head and flow characteristics [26].

Compared to other turbines, which generally require casting facilities, Kaplan turbines merely require simple fabrication techniques, are easier to maintain and they are usually cheaper. Considering these advantages, the Kaplan turbine is the most suitable for MHPG in Ethiopia where the remote rural community needs low cost of installation and maintenance.

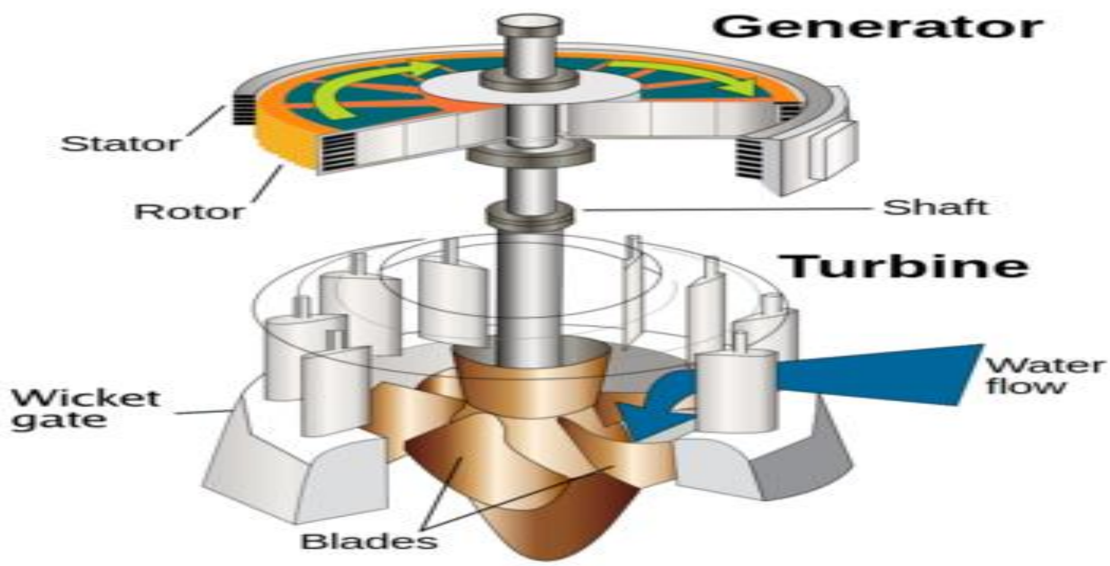


Figure 2.4. Kaplan turbine and electrical generator cut-away view [27]

Generator

Generator in power systems converts the mechanical power received from the turbine into electrical power and it is rotated by the turbine to generate electricity [28]. There are two types of generators used in hydro electricity generation. Those are synchronous generators and induction generators. Synchronous generators are used extensively in small-scale power generation when compared to induction generators. Induction generators are also the preferred type of generators in MHPG because they can operate at variable speeds with constant frequency, are available cheaply and rugged design that requires less maintenance than synchronous generators. In MHPG, the basic source of electric energy is the synchronous generator because it can establish its operating voltage and maintain frequency while it is operating in a remote rural location. Whereas when the power output levels are generally low i.e. less than 10 MW, synchronous generators are broadly used in most MHPG [29].

Actuator

An actuator is one of the principal electromechanical components responsible for moving and controlling a mechanism or a system. It needs the control signal and the source of energy to operate and convert into some kind of mechanical motion. The control signal might be electrical voltage or current, hydraulic, pneumatic, or human power [30].

2.4. Control Systems of Mini Hydro Power Generation

A controller must be designed to provide the overall system performance and stability for a nominal plant without uncertainty. The type of controller is dictated by the objective of control design. A controller can be linear or nonlinear but as always nonlinear controllers are much more difficult to design, analyze and ultimately certify for operation in real systems [31]. Like large hydro power systems, due to continuous variation in load demand and the presence of deferent types of loads with different characteristics, the voltage, and frequency of mini hydropower systems may not be constant. Therefore, similar to that of large hydro power systems, the voltage and frequency of mini hydro power should be kept at scheduled values [32]. To keep these parameters at the scheduled values, the mini hydro power system should be controlled. In the power system usually, voltage and frequency are controlled separately. The voltage is controlled by control of reactive power of the synchronous generator with the voltage regulator built in most of these synchronous generators, while the frequency is controlled by balancing generation and demand, i.e. by balancing generation and demand of active power. The balance between electrical generation and consumer demand is achieved in two different ways [33].

2.4.1. Automatic Generation Control

In the electrical power system, AGC is the system by adjusts the power output of many generators at various power plants, in response to changes in the load [34]. It is the major control function within a utility’s energy control center, whose function is the tracking of load variations while maintaining system frequency and optimal generation levels close to scheduled or specified values [35] [36].

2.4.2. Automatic Load Control

The purpose of ALC is to maintain optimum loading of the generator and to prevent wet stacking on the generator which might occur when the building load alone is low in comparison to generator capacity. Generally, electrical loads change randomly as a result of which frequency of the system is changed randomly. It is possible to compensate for the change in the electrical load, consequently the change in frequency using ballast loads [37].

2.5. Frequency Control

Frequency control is the ability to maintain the frequency band to its permissible limit. Frequency deviation or rise is the direct result of an imbalance between the electrical load and the power supplied by the connected generators, so, it provides a useful index to indicate the generation and the load imbalance [38]. A permanent out-of-range frequency may affect power system operation, security, reliability, and efficiency by damaging equipment, degrading load performance, overloading transmission lines, and triggering the protection devices. Increasing economic pressures for power system efficiency and reliability have led to a requirement for maintaining system frequency closer to scheduled values as much as possible [39]. The standard frequency deviation in any electric power system should not be greater than the nominal frequency. However, in mini hydro power systems frequency control is not as rigorous as that of large-scale hydro power systems. A frequency deviation up to $2.5Hz\ (0.05P.U)$ can be tolerated. The frequency limits in the EEP transmission system have been stated in table 2.2.

Table 2.2. Frequency limits in the EEP transmission system [40]

Operating condition	**Frequency limits**
Under normal operation	49.50 Hz to 50.50 Hz
Under system disturbance	49.00 Hz to 51.00 Hz
Maximum band under the fault system	48.75 Hz to 51.25 Hz
Under extreme system operation or fault condition	f<47.50 Hz or f>51.50 Hz for 20 sec.

2.6. Types of Controller

Controllers are a tool for regulating, collecting, receiving, executing, processing and performing so many tasks to achieve various controller architectures are available to obtain the desired behavior of the system. Several convectional and intelligent controllers can be used for controlling the system performance, those are PI, PD, PID, LQR, FLC, AFLC, ANFIS, MPC, SMC, etc. In this thesis, an intelligent AFLC and convectional PID controller are used to design load frequency control of mini hydro power generation to compare the control system stability.

2.6.1. Adaptive Control

Adaptive control is the control technique used by the controller which should be adapted to a controlled system when the parameters are vary or are initially uncertain [41]. An adaptive control system is a system that adjusts automatically the parameters of its controller, to maintain a satisfactory level of performance when the parameters of the system under control are unknown and/or time-varying.

In general speaking, the performance of a system is affected either by external perturbations or by parameter variations. In this case, the controller involves adjusting the parameters. Adaptive control schemes have been applied in the paper industries, rolling mills, power plants, motor drives, chemical reactors, cement mills, autopilots for aircraft, missiles, and ships, etc. The use of adaptive controllers may lead to improvement of product quality, increase in production rates, fault detection, and energy-saving [42].

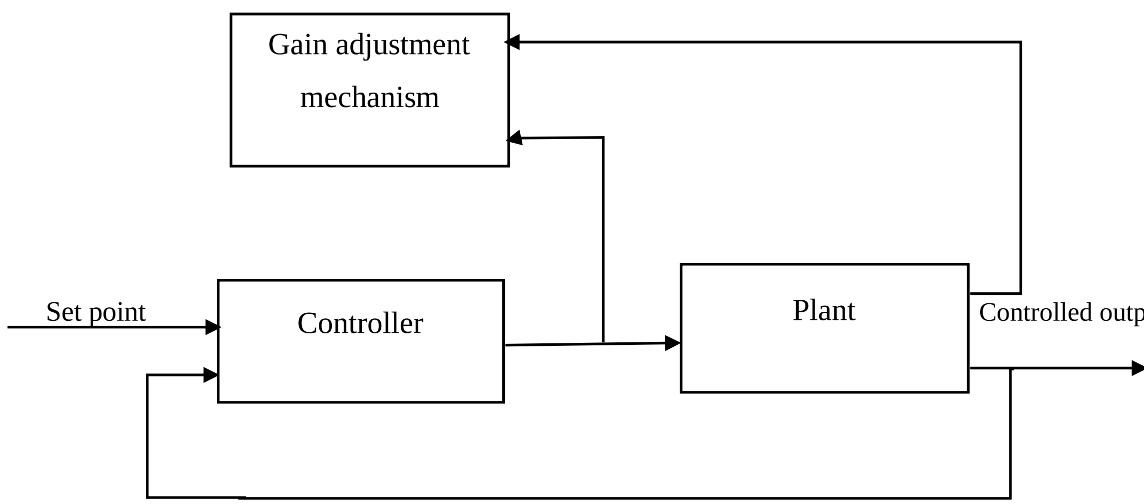


Figure 2.5. Block diagram of adaptive control [43]

2.6.2. Fuzzy Logic Controller

FLC is an attractive method when precise mathematical formulations are not possible. The reason is obvious, any control system maps the input space to the output space [44]. Generally, a desired set of outputs are calculated for a given set of inputs. Fuzzy logic provides a useful methodology to create a practical solution for controlling complex systems. It is not necessary to know the exact model of such complex systems to design FLC. It is sufficient to understand the general behavior of the system. When the variables are selected, the decision will be made through specific fuzzy logic functions [45] [46].
The basic configuration of FLC consists of four main parts such as fuzzification, rule base, fuzzy inference systems, and defuzzification [47]. To implement a fuzzy logic technique to a real application requires the following four main steps:

Fuzzification

Fuzzification is the process of converting the classical data or crisp data values of the control inputs into fuzzy data values with membership functions (MFs) in the form of a triangle, trapezoid, bell, or other appropriate forms expressed by the fuzzy linguistic variables so that they are compatible with the fuzzy set representation in the rule base [48].

Rule Base

The rule-based form uses linguistic variables as its antecedents and consequents. The antecedents express an inference or the inequality which should be satisfied. The consequents are those, which can infer and is the output if the antecedent inequality is satisfied. The fuzzy rule-based system uses an if-then rule-based system given by, if antecedent, then consequent [49].

Fuzzy Inference System

FIS is also known as fuzzy rule-based systems, fuzzy model, fuzzy expert system, and fuzzy associative memory. This is a major unit of a fuzzy logic system [50]. The FIS formulates suitable rules and based upon the rules the decision is made. This is mainly based on the concepts of the fuzzy set theory, fuzzy if-then rules, and fuzzy reasoning. FIS uses "if. . . then" statements and the connectors present in the rule statement are OR or AND to make the necessary decision rules [51]. The basic FIS can take either fuzzy inputs or crisp inputs, but the outputs it produces are almost always fuzzy sets. Combine membership functions with the control rules to derive the fuzzy output and arrange those outputs into a table called the lookup table.
The control rule is the core of the fuzzy inference system and those rules are directly related to a human being's intuition and feeling [52].

Defuzzification

Calculating each associated output and inputting them into a table is known as the lookup table. Pick up the output from the lookup table based on the current input and convert control output from the linguistic variable back to the crisp variable and output to the control operator. This can be achieved by using the defuzzification process [53]. The defuzzification can reduce a fuzzy to a crisp single-valued quantity or as a set or convert to the form in which fuzzy quantity is present.

There are several defuzzification methods are used such as the mean of the maximum method, the height method, center of gravity or centroid method, max-membership principle, weighted average method, the center of the largest area, and first of maxima or last of maxima to convert from the inference mechanism into the crisp values applied to the actual system. From this method, the centroid method is the most prevalent and physically appealing of all the defuzzification methods [54].

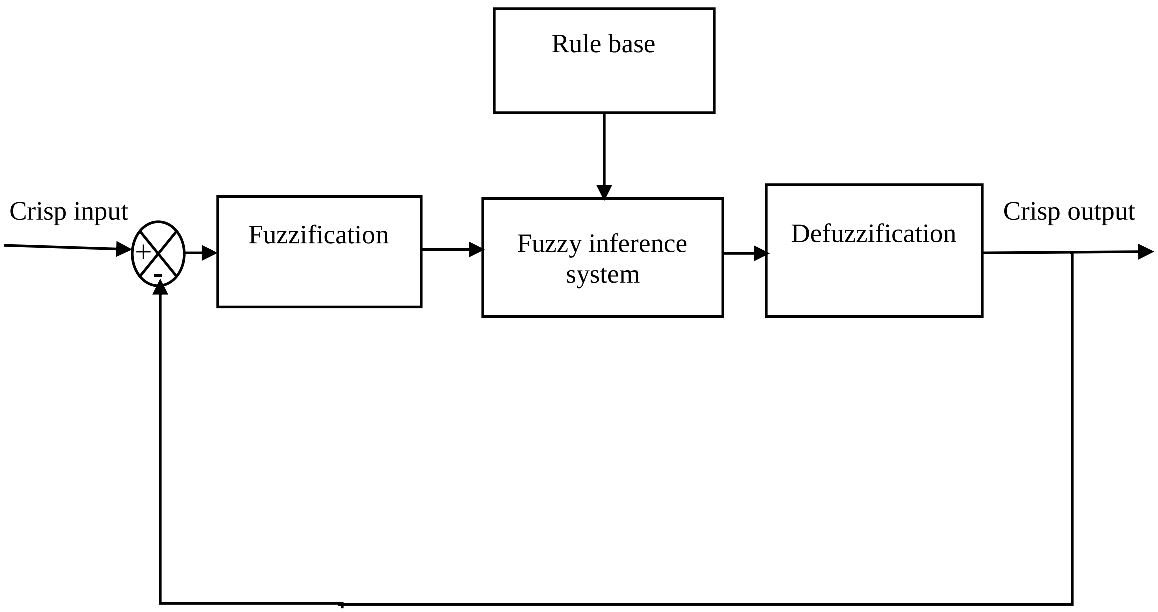


Figure 2.6. Block diagram of fuzzy logic controller [55]

2.6.3. Intelligent Adaptive Fuzzy Logic Controller

An adaptive fuzzy logic controller (AFLC) is used to regulate the unstable system to the origin and to control the overall system by changing the parameters of the fuzzy system. Gain scheduling control is the simplest version of an adaptive control system, uses the information about the process dynamics to adapt the parameters of proportional-integral (PI) or PID controllers to obtain good performance measuring variables at all operating conditions or regions. Parameters of adaptation are; the fuzzy set representing the meaning of linguistic variables, the scaling factors for each linguistic variable, and the if-then rules [56]. Just as fuzzy logic can be described as computing with words rather than numbers, fuzzy control can be described as control with sentences rather than equations. It is more natural to use sentences or rules, for instance, operator-controlled plants, with the control strategy written in terms of if-then clauses. If the controller furthermore adjusts the control strategy without human intervention it is adaptive. An adaptive fuzzy logic controller is a controller that can modify its behavior after changes in the controlled plant or the environment. Some objectives for using adaptive fuzzy logic control are: the character of the plant varies or the character of the disturbances varies. The gain scheduling parameters of the fuzzy logic controller are tuned with the load information. K_p and K_i are called as gain parameter output variables of the fuzzy logic controller and K_d is a gain parameter input variable feedback of the controller in figure 2.7. The input and output gain parameters in the fuzzy controllers are important for providing to fire of appropriate rules independent from the physical domain of the input and output signals. The gain parameters can be tuned to obtain maximum control performance stability of the system.

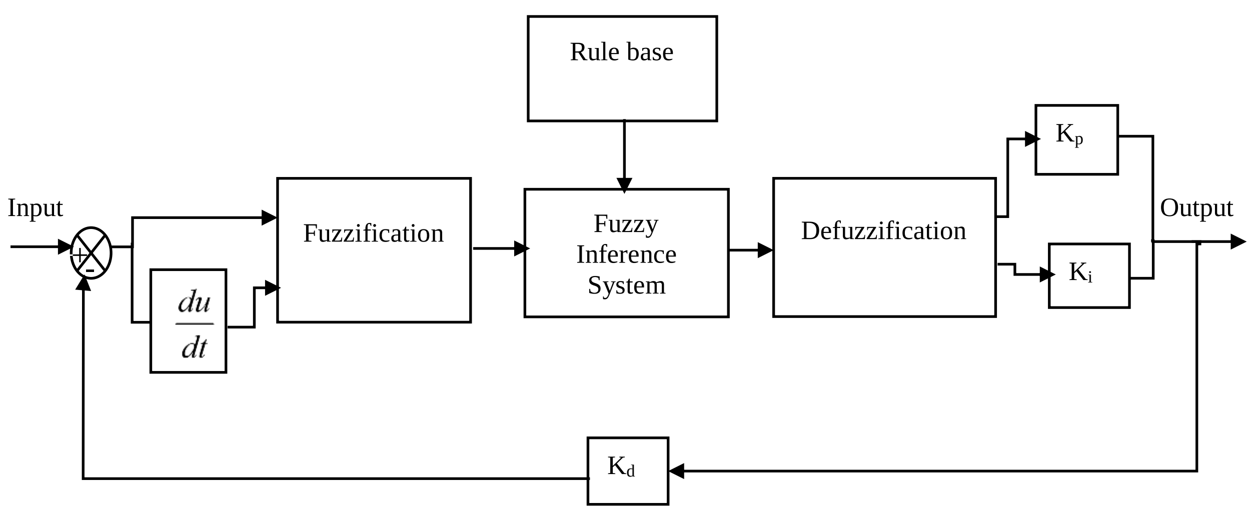


Figure 2.7. Block diagram of adaptive fuzzy logic controller [57]

2.6.4. Convectional PID Controller

The most common convectional controllers available commercially are the PI and PID controllers. The PI controllers are used to improve the dynamics response as well as to reduce or eliminate the steady-state error. The PID controller is made up of three main components i.e. proportional, integral, and derivative [58].

Proportional term

The Proportional term sometimes called 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, known as the proportional gain.

Integral term

The contribution from the integral term sometimes called reset is proportional to both the magnitude of the error and the duration of the error. The magnitude of the contribution from the integral term to the overall control action is determined by the integral gain, K_i.

Derivative term

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

Generally, a convectional PID controller is most broadly used in industry due to ease in design, inexpensive cost, and including zero steady-state error. The PID formulas are simple and can be easily adopted to correspond to different controlled plants but they cannot yield a good control performance if the controlled system is higher-order and nonlinear.

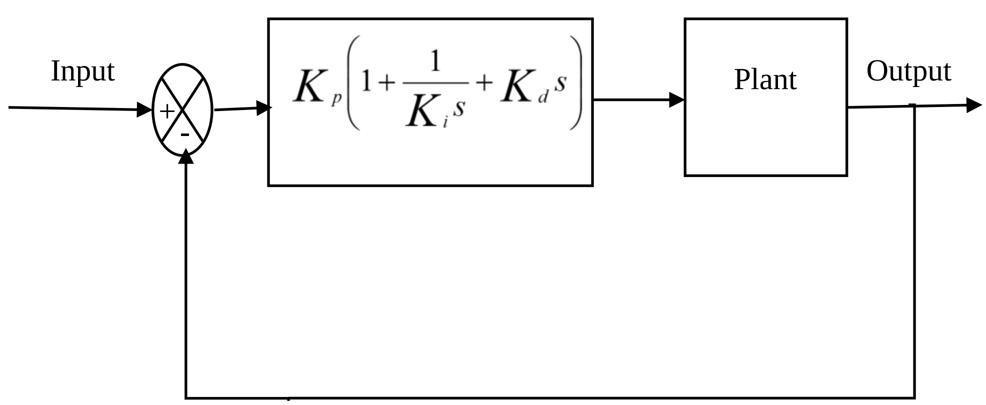


Figure 2.8. Block diagram PID controller [59]

2.7. Previous Works on Frequency Control of Hydro Power Generation

The scientific community is widely interested in modeling and controlling renewable sources of energy, specifically on hydro power plants (HPP). Different researches have been worked on the generation of power from HPP and the controlling mechanism of hydro power plants related to frequency control. Several scholars used different techniques and approaches to control load frequency of HPP. From those some of the approaches [60] up to [81] are reviewed in the following paragraphs.

The papers [60] [61] [62] automatic generation control have been purposed to control the frequency of micro hydropower plants by using convectional governors such as mechanical hydraulic governors, electro-hydraulic governors, purely mechanical and servo motor types. Mechanical hydraulic governors are sophisticated devices that are generally used in large hydro power plants. They require heavy maintenance and are expensive to install, making their usage in micro and mini hydro power systems complex and uneconomical. Electro-hydraulic governors are also complex and expensive devices that require precision design. Mechanical governors incorporate a massive fly ball arrangement and usually do not provide flow control. They require an elaborate set of complex guide vanes, inlet valves, and jet deflectors. The above three governing systems are types of convectional governing systems therefore, because of their uncertainty, nonlinearity, complexity, higher-order, and time-delay systems are not ideally suited for frequency control of mini hydro power generation systems where uncertain, nonlinear, complex, and higher-order systems are a sensitive issue in frequency control to balance supply and demand of the consumer.

The paper [63] automatic load control mode is developed for micro hydro power plant generation. In load control mode, a ballast load is controlled so that the total load connected to the synchronous generator is kept constant consequently, the frequency remains nearly constant. This method is simple, less cost and fast response. However, because of the presence of electronic switches, this technique introduces harmonics into the electrical system. The presence of these harmonics will cause overheating of electrical equipment connected to the system and the generator. In addition to this during minimum demand of power, a lot of energy is wasted on ballast load, which could have been utilized by the rural communities for different purposes and automatic load control is not suitable for nonlinear, uncertain, complex, higher-order, and time-delay hydro power systems for frequency control.

The papers [64] [65] [66] [67] proposed a PID controller to control the load frequency rule features of one or two power sources for hydro power systems. The suggested tuning PID controller has been displayed to improve load frequency control exists for the hydro power system model of second-order, linear, and usually under damping that coming later a stage variation in load and provides an improved achievement over other convectional controllers. The majority of present PID tuning methods by using manual tuning methods normally rely on being capable to check the system response manually and then regulate the PID values until an acceptable response has been found. These values would be adjusted manually to complete the required performance. These apply the identical methods in the manual methods, automating the operations to decrease the time required and to help increase standardization focus on over-damped operations, thus straight request for present PID tuning methods at load frequency control (LFC) has been never correct. The simulation results of the PID controller in this paper are high steady-state frequency error, high settling time, high rise time, high overshoot when the load varies from small to large values. Therefore, the PID controller is not suitable for nonlinear, uncertain, complex, higher-order, and time-delay hydro power systems for frequency control of one or two power sources.

The papers [68] [69] proposed self-tuning fuzzy PI controller system model for small hydro power plants, has been proposed to overcome the disadvantages of the traditional PI controller and evaluate the performance, such as the rise time, overshoot, settling time, etc. which is the combination of a convectional PI controller and a fuzzy controller in third-order is not use the hydraulic amplifier servo mechanism for concerning the stability to control load frequency of the system. The simulation results show that the system adjustment time and overshoot decrease significantly and control performance is gotten much improved after the fuzzy self-tuning algorithm is applied in conventional PI controller using 25 fuzzy rules. As seen from the results, steady-state frequency deviation goes to 0 to 1 p.u, when the load varies from 25 to 95% changes, as time goes from 0 to 400 sec and the rise time, overshoot, settling time is high, so, the actual base frequency is small relatively the nominal base frequency.

The papers [70] [71] [72] proposed modeling of a load frequency control for a hybrid power system by using a PID controller. LFC plays a very important role when a large amount of renewable power and non-renewable supplies which are hydro, thermal, and wind power generation. In this paper, LFC with considerable penetration of renewable has been analyzed in the presence of thermal, hydro, and wind systems with PID controllers.

In the electric power industry, there is an ongoing need for efficient and effective LFC techniques to counter the ever-increasing complexity of large-scale power systems and robustness against parameter uncertainties as well as plant or model mismatch and external load change. An interconnected thermal, hydro, and wind power system are considered at the first instance with convectional controllers like PI and PID, out of these PID controller provides the best solution. But the simulation results show that with the interconnection of the power system the response is large peak overshoot, large settling time, large peak time, large delay time, and large steady-state frequency error results in small actual base frequency.

The papers [73] [74] [75] proposed a fuzzy logic controller for small hydro power plants (SHPPs) to control a load frequency-based model using linear hydraulic turbine assuming inelastic water column was proposed for isolated SHPPs. The model consists of the governor, turbine, and generator i.e. the system is third-order. The fuzzy controller is used as a regulator because suitable for white-box problems, based on expert knowledge of the system. The controller regulates the wicket gate position according to the load variation. Because the water flows into the turbine is controlled by a guide vane which is changed the gate position depends on the governor control signal. But as seen the simulation results for a step load changes for different load values were used from 25 to 95%, the steady-state frequency deviation goes from 0 to 1 p.u as time goes from 0 to 500 sec, the rise time, overshoot, settling time is high, undershoot and fall time is zero, the actual base frequency is very small, so the system performance is low.

The papers [76] [77] proposed an improved design of a micro-hydroelectric power plant for the socio-economic development of the country. A micro-hydroelectric power plant is a type of hydroelectric power that generates a capacity of less than 100KW. Electromechanical components like turbines, generators, and actuators are converted renewable sources of energy i.e. water into use full electrical energy. The overall mathematical model and design are simulated using MATLAB/Simulink software, but this paper only considers the generating power without either frequency or voltage control by any controller. It observed the simulation results as the time approaches a large number, rotor speed goes to the large number, and the output power increases sinusoidal waveform. This result indicates the system performance is very low.

The papers [78] [79] [80] [81] automatic load frequency control for multi-source power systems using hybrid intelligent optimization techniques. For multi-source power systems, a new heuristic-based hybrid optimization technique is the method to regulate the frequency deviation in single-area or multi-areas. The proposed optimization technique uses the main features of three different optimization techniques, namely, Firefly Algorithm (FA), Particle Swarm Optimization (PSO), and the Gravitational Search Algorithm (GSA). The proposed algorithm was used to tune the parameters of a PID controller to achieve the automatic load frequency control in single-area, two-areas, and multi-areas power systems were designed using MATLAB/Simulink software consisting of three types of power sources such as hydro, thermal and gas-turbine power plant. It observed the simulation results in three optimization techniques using PID controller the settling time and peak overshoot were considered to measure the effect on the frequency deviation in different areas at different load variations from 0.01 to 0.03 p.u. POS technique is better than the other two techniques. But the simulation results in three algorithm techniques are large settling time and peak overshoot, this results in large frequency error and less system performance.

Therefore, in this thesis, an intelligent adaptive fuzzy logic controller is proposed that adapts to non-linear changing parameters of the systems with smooth gain adjustment to control load frequency by concerning system stability using hydraulic amplifier servo mechanism in the overall system performance. This controller is suitable for complex, nonlinear, uncertain, higher-order, and time-delay systems measuring variables. They are ideally suited for load frequency control of mini hydropower systems by acting simply tuning the gain parameters K_p, K_i, and K_d, where system performance measuring variables are a sensitive issue to obtain better system actual base frequency when the load varies from 0% to 65%.

CHAPTER THREE

Mathematical Model of Mini Hydro Power Generation

3.1. Introduction

For the design and analysis of the control system, the first step that has to be done is the mathematical modeling. It uses mathematical equations such as state-space, differential equation, and transfer function. In this thesis, accurate mathematical representation of power system parameters is significant for steady-state and transient stability studies [82]. State-space modeling is applied for both linear and non-linear systems. Solving differential equations is complicated and bulky, but transfer function modeling is quite easy when compared to differential equation modeling. The first step in modeling MHPG is to evaluate the water resource by measuring the head and flow rate of water [83]. Those two-parameter measurements are necessary to determine the output power of MHPG. The turbine type, rotational speed, penstock pipe size, and generator size are determined after the head and flow rate of the water is measured. Nothing can be done after measuring the head and flow rate of the water.

3.2. Mathematical Model of Linear Hydraulic Turbine

Hydraulic turbine derives mechanical energy which is changed into electrical energy from the force exerted by water as it falls. The hydraulic turbine dynamic model has a considerable influence on the dynamic or steady-state stability of the power system [84]. There are two types of hydraulic turbine models linear and nonlinear models from those linear hydraulic turbine models are used in this thesis. The developed output power by the turbine is a function of the water flow rate, the runner blade angle, and the net head. The flow through the turbine is a function of the net head, rotational speed, gate opening position valve, and runner blade angle. The effect of the runner blade angle of movement is not considered in the modeling of turbines with fixed blades, such as the Kaplan turbine. The turbine dynamics are related to the generator dynamics through mechanical power produced by the turbine.

The relation between the mechanical power (P_m) and the mechanical torque (T_m) expressed in per unit by linear and angular synchronous speed is given by [85],

$$P_m = \frac{n_s}{\omega_s} \cdot T_m \tag{3.1}$$

Assuming a simplifying made is that, $(n_s = \omega_s)$ [86], this is not the same as saying that the speed is constant, it assumes that speed changes are small and do not have a significant effect. Thus equation,

$$P_m = T_m \tag{3.2}$$

By considering the water flow rate through the turbine (Q) and the mechanical output power is dependent on these parameters, the hydraulic net head increment (H_d), the rotating speed increment (ω_r) and the turbine gate opening position valve increment (G) of the hydropower system can express as non-linear functions of these parameters as [87],

$$Q = Q(H_d, \omega_r, G) \tag{3.3}$$

$$P_m = P_m(H_d, \omega_r, G) \tag{3.4}$$

Through linearization equation 3.3 and 3.4, around the steady-state values expressed as,

$$\Delta Q = \frac{\partial Q}{\partial H_d}\Delta H_d + \frac{\partial Q}{\partial \omega_r}\Delta \omega_r + \frac{\partial Q}{\partial G}\Delta G \tag{3.5}$$

$$\Delta P_M = \frac{\partial P_m}{\partial H_d}\Delta H_d + \frac{\partial P_m}{\partial \omega_r}\Delta \omega_r + \frac{\partial P_m}{\partial G}\Delta G \tag{3.6}$$

Normalizing equation 3.5 and equation 3.6, based on rated values the following expressions that completely describe the hydraulic turbine features are obtained as [88],

$$\Delta\overline{Q} = a_{11}\Delta\overline{H_d} + a_{12}\Delta\overline{\omega_r} + a_{13}\Delta\overline{G} \tag{3.7}$$

$$\Delta\overline{P_m} = a_{21}\Delta\overline{H_d} + a_{22}\Delta\overline{\omega_r} + a_{23}\Delta\overline{G} \tag{3.8}$$

where the following notations were used:

$$\Delta\overline{Q} = \frac{\partial Q}{\partial Q_o}, \Delta\overline{P_m} = \frac{\partial P_m}{\partial P_{mo}}, \Delta\overline{H_d} = \frac{\partial H_d}{\partial H_{do}}, \Delta\overline{\omega_r} = \frac{\partial \omega_r}{\partial \omega_{ro}}, \Delta\overline{G} = \frac{\partial G}{\partial G_o}$$

Which represent the non-dimensional variations of the parameters around the steady-state variables.

$$a_{11} = \frac{\partial Q}{\partial H_d}, a_{12} = \frac{\partial Q}{\partial \omega_r}, a_{13} = \frac{\partial Q}{\partial G} \tag{3.7a}$$

$$a_{21} = \frac{\partial P_m}{\partial H_d}, a_{22} = \frac{\partial P_m}{\partial \omega_r}, a_{23} = \frac{\partial P_m}{\partial G} \tag{3.8a}$$

The partial derivatives of the flow rate of water and mechanical output power the turbine to the net head, rotational speed, and turbine gate position valve are called turbine coefficients. These coefficients stand for the non-linear characteristics of a hydraulic turbine. The partial derivative of mechanical output power concerning gate position is called turbine gain. The effect of the partial derivative of the flow rate of water through the turbine concerning rotational speed is usually considered to be negligible [89]. The partial derivative of mechanical power to rotational speed is known as turbine self-regulation. In an interconnected power system, the hydraulic units are synchronized with the system as a result rotational speed variation $\Delta\omega_r$ is nearly small and usually neglected. So that equation 3.7 and 3.8 is simplified to as,

$$\Delta\overline{Q} = a_{11}\Delta\overline{H_d} + a_{13}\Delta\overline{G} \tag{3.9}$$

$$\Delta\overline{P_m} = a_{21}\Delta\overline{H_d} + a_{23}\Delta\overline{G} \tag{3.10}$$

The flow rate of water through the turbine (Q_i) through each penstock pipe segment with the cross-sectional area (A_i) is identical and equal with the flow rate (Q) through the equivalent penstock pipe expressed mathematically as [89].

$$Q = V * A = Q_i = V_i * A_i \tag{3.11}$$

where,

- V is the water velocity in the equivalent penstock pipe
- V_i is the velocity in each segment of the real penstock pipe
- *for* $i = 1, 2, \ldots\ldots, n$

From the mass conservation law, it results:

$$V = \frac{Q}{A} = \frac{Q_i \sum L_i}{\sum L_i A_i} = \frac{\sum L_i}{\sum L_i A_i} * Q \tag{3.12}$$

Through linearization equation 3.12, around the operation point to obtain as,

$$\Delta Q = \frac{\partial Q}{\partial V}\Delta V = A\Delta V \tag{3.13}$$

Normalize equation 3.13, dividing both sides by $Q_o = AV_o$ which yields the rated values,

$$\frac{\Delta Q}{Q_o} = \frac{A\Delta V}{AV_o}, \Delta\overline{Q} = \Delta\overline{V} \tag{3.14}$$

The velocity of the water in the penstock pipe is given by the formula [90],

$$V = KG\sqrt{H_d} \tag{3.15}$$

where,

- V is the velocity of water
- G is the gate position valve
- H_d is the hydraulic net head
- K is proportionality constant

Through linearization equation 3.15, around the steady-state values to obtain as [90],

$$\Delta V = \frac{\partial V}{\partial H_d}\Delta H_d + \frac{\partial V}{\partial G}\Delta G = 0.5\Delta H_d + \Delta G \tag{3.16}$$

Normalize equation 3.16, dividing both sides by $V_o = KG_o\sqrt{H_{do}}$ which yields the rated values,

$$\frac{\Delta V}{V_o} = \frac{\Delta H_d}{2H_{do}} + \frac{\Delta G}{G_o}, \Delta\overline{V} = 0.5\Delta\overline{H_d} + \Delta\overline{G} \tag{3.17}$$

Where the subscript o denotes initial steady-state values, the prefix Δ denotes small deviations, and the super bar $''-''$ indicates normalized rated values based on steady-state operating values. Substituting equation 3.17, in an equation 3.14, to obtain as

$$\Delta\overline{Q} = \Delta\overline{V} = 0.5\Delta\overline{H_d} + \Delta\overline{G} \tag{3.18}$$

The acceleration of the water column due to a change in the net head at the turbine, characterized by Newton's second law of motion is expressed as [91],

$$\Delta H_d * A * \rho * a = -\rho AL\frac{d\Delta V}{dt} \tag{3.19}$$

where,

- L is the length of the penstock
- A is the cross-sectional area of the penstock
- ρ is the specific mass density
- a is the water acceleration in the equivalent penstock pipe
- ρAL is the mass of water in the penstock
- $\Delta H_d \rho a$ is the incremental change in pressure at the turbine gate
- t is time in seconds

Dividing both sides equation 3.19, by $A\rho a H_{do} V_o$ the acceleration equation in normalized form becomes,

$$\frac{\Delta H_d}{H_{do}} = -\frac{L\Delta V}{a H_{do}} \frac{d}{dt}\left(\frac{\Delta V}{V_o}\right), \Delta\overline{H_d} = -\frac{L\Delta V}{a H_{do}} \frac{d}{dt}\left(\Delta\overline{V}\right) = -T_w \frac{d}{dt}\left(\Delta\overline{V}\right) \qquad (3.20)$$

From the equation 3.20, to obtain the rated values in terms of water time constant expressed as,

$$\Delta\overline{H_d} = -T_w \frac{d}{dt}\left(\Delta\overline{V}\right), T_w = \frac{L\Delta V}{a H_{do}}$$

Equation 3.18, and equation 3.20, the relationship between change in velocity of water and change in gate position can be expressed as [90] [91],

$$\Delta\overline{H_d} = 2\left(\Delta\overline{V} - \Delta\overline{G}\right) = -T_w \frac{d}{dt}\left(\Delta\overline{V}\right)$$

Dividing both sides by negative sign to get,

$$T_w \frac{d}{dt}\left(\Delta\overline{V}\right) = 2\left(\Delta\overline{G} - \Delta\overline{V}\right) \qquad (3.21)$$

Both sides Laplace transforming and simplifying the equation 3.21, to obtain,

$$T_w s\Delta\overline{V}(s) = 2\Delta\overline{G}(s) - 2\Delta\overline{V}(s)$$

$$T_w s\Delta\overline{V}(s) + 2\Delta\overline{V}(s) = 2\Delta\overline{G}(s)$$

$$0.5T_w s\Delta\overline{V}(s) + \Delta\overline{V}(s) = \Delta\overline{G}(s)$$

$$\Delta\overline{V}(s)\left(0.5T_w s + 1\right) = \Delta\overline{G}(s)$$

$$\frac{\Delta\overline{V}(s)}{\Delta\overline{G}(s)} = \frac{1}{1 + 0.5T_w s}$$

Substituting this Laplace equation in an equation 3.14, to obtain,

$$\Delta\overline{Q}(s) = \Delta\overline{V}(s) = \frac{\Delta\overline{G}(s)}{1 + 0.5T_w s} \qquad (3.22)$$

For an ideal hydraulic turbine without losses the linear coefficients a_{ij}, resulting from the partial derivatives in equation 3.9, and equation 3.10, have the following values in table 3.1.

Table 3.1. Hydraulic turbine linearized coefficients [92]

Hydraulic turbine linear coefficients	Value of linear coefficients
a_{11}	0.5
a_{12}	0
a_{13}	1
a_{21}	1.5
a_{22}	0
a_{23}	1

After substituting this value in equation 3.9, and equation 3.10, to obtain,

$$\Delta\overline{Q}(s) = 0.5\Delta\overline{H_d}(s) + \Delta\overline{G}(s)$$

$$\Delta\overline{P_m}(s) = 1.5\Delta\overline{H_d}(s) + \Delta\overline{G}(s)$$

$$\Delta\overline{P_m}(s) = 1.5(2)\left(\Delta\overline{Q}(s) - \Delta\overline{G}(s)\right) + \Delta\overline{G}(s)$$

$$\Delta\overline{P_m}(s) = 3\Delta\overline{Q}(s) - 2\Delta\overline{G}(s) \tag{3.23}$$

Substituting equation 3.22, in an equation 3.23, the block diagram of hydraulic turbine around the steady-state point the transfer function is determined as [92],

$$\Delta\overline{Q}(s) = \frac{\Delta\overline{G}(s)}{1 + 0.5T_w s}$$

$$\Delta\overline{P_m}(s) = 3\Delta\overline{Q}(s) - 2\Delta\overline{G}(s)$$

$$\Delta\overline{P_m}(s) = 3\left(\frac{\Delta\overline{G}(s)}{1 + 0.5T_w s}\right) - 2\Delta\overline{G}(s)$$

$$\Delta\overline{P_m}(s) = \frac{3\Delta\overline{G}(s) - 2\Delta\overline{G}(s) - T_w s\Delta\overline{G}(s)}{1 + 0.5T_w s}$$

$$\Delta\overline{P_m}(s) = \frac{\Delta\overline{G}(s)(1 - T_w s)}{1 + 0.5T_w s}$$

Thus, the transfer function of a linear hydraulic turbine is obtained by dividing both sides $\Delta\overline{G}(s)$ as,

$$\frac{\Delta\overline{P}_m(s)}{\Delta\overline{G}(s)} = \frac{1-T_w s}{1+0.5T_w s} \tag{3.24}$$

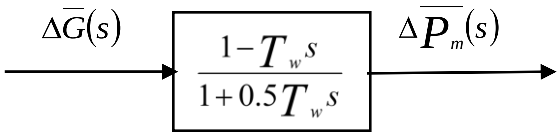


Figure 3.1. Block diagram of linear hydraulic turbine model

3.3. Mathematical Model of Synchronous Generator

The physical characteristics of the synchronous generators and their performance affect the system's stability. The complete mathematical modeling of the synchronous generator is a fairly complex system for the stability analysis of power systems. The following assumptions are made to develop the mathematical model of a synchronous generator [93].

The three-phase stator winding is symmetrically distributed, the capacitance of all the windings can be neglected, each of the distributed windings may be represented by a concentrated winding, the change in the inductance of the stator windings due to rotor position is sinusoidal and does not contain higher harmonics, hysteresis loss is negligible but the influence of eddy currents can be included in the model of the damper windings, in the transient and sub-transient states, the rotor speed is near the synchronous speed and the magnetic circuits are linear or not saturated and the inductance values do not depend on the current.

Therefore, the kinetic energy of the rotor at the synchronous generator is [94],

$$KE = \frac{1}{2} J \omega_s^2 * 10^{-6} MJ \tag{3.25}$$

The rotor speed of the synchronous generator is expressed as,

$$\omega_r = \frac{p_o}{2}\omega_s \tag{3.26}$$

where,

- J is the rotor moment of inertia in $kg \cdot m^2$
- ω_r is the rotor speed in $rad(elect)/s$
- ω_s is the synchronous speed in $rad(elect)/s$
- p_o is the number of machine poles

Substituting equation 3.26, in an equation 3.25, to obtain kinetic energy in terms of rotor speed and machine poles:

$$KE = \frac{1}{2} J \left(\frac{2}{p_o} \omega_r \right)^2 * 10^{-6} MJ$$

$$KE = \left(\frac{1}{2} J \omega_r \left(\frac{2}{p_o} \right)^2 * 10^{-6} MJ \right) \omega_r$$

$$KE = \mathrm{M} \omega_r \qquad (3.27)$$

$$\mathrm{M} = \frac{1}{2} J \omega_r \left(\frac{2}{p_o} \right)^2 * 10^{-6} MJ$$

where, M is the moment of inertia in $MJs/rad(elect)$.

The kinetic energy of the rotor at synchronous generator using inertia constant (H) is expressed as,

$$KE = \mathrm{M} \omega_r = G\mathrm{H} \qquad (3.28)$$

$$\mathrm{H} = \frac{1}{G} KE = \frac{1}{G} \mathrm{M} \omega_r$$

where,

- G is machine rating (base) in MVA (3-phase)
- H is inertia constant in MJ/MVA or MWs/MVA

It follows that, the moment of inertia in per unit expression,

$$\mathrm{M}(P.U) = \frac{2\mathrm{H}}{\omega_{ro}} \qquad (3.29)$$

Applying the Swing equation of a synchronous generator given by [94],

$$J\frac{d^2\theta_m}{dt^2} = (T_m - T_e)NM \tag{3.30}$$

where,

- θ_m is the angle in $rad(mech.)$
- T_m is mechanical turbine torque in NM, it acquires a negative value for a motoring machine
- T_e is electromagnetic torque developed in NM.

Multiplying both sides of the equation 3.30, by ω_s, it can be written as,

$$\omega_s\left(J\frac{d^2\theta_m}{dt^2}\right)*10^{-6} = \omega_s(T_m - T_e)*10^{-6}\,NM$$

$$\omega_s\left(J\frac{d^2\theta_m}{dt^2}\right)*10^{-6} = (P_m - P_e)MW$$

where,

- P_m is mechanical input power in MW
- P_e is electrical output power in MW, stator copper loss is assumed negligible [94].

Rewriting this equation as

$$\left(\frac{1}{2}J\,\omega_r\left(\frac{2}{p_o}\right)^2*10^{-6}\,MJ\right)\frac{d^2\theta_e}{dt^2} = (P_m - P_e)MW$$

$$\mathrm{M}\frac{d^2\theta_e}{dt^2} = (P_m - P_e)MW \tag{3.31}$$

where, θ_e is angle in $rad(elect.)$.

Let $\delta = \theta_e - \omega_s t$, rotor angular displacement or position from synchronously rotating reference frame, both sides first derivative to obtain,

$$\frac{d\delta}{dt} = \frac{d}{dt}(\theta_e - \omega_s t) = \frac{d\theta_e}{dt} - \omega_s$$

Both sides second derivative omit the constant term of the synchronous speed to obtain,

$$\frac{d^2\delta}{dt^2} = \frac{d^2\theta_e}{dt^2}$$

Hence equation 3.31 can be written in terms of δ as,

$$\mathrm{M}\frac{d^2\delta}{dt^2} = (P_m - P_e)MW$$

With M, as defined in an equation 3.28, it can be written as,

$$\frac{2\mathrm{GH}}{\omega_r}\frac{d^2\delta}{dt^2} = (P_m - P_e)MW$$

Dividing both sides by G, the rating (base) of the generator,

$$\frac{2\mathrm{H}}{\omega_{ro}}\frac{d^2\delta}{dt^2} = (\overline{P}_m - \overline{P}_e)P.U \tag{3.32}$$

By taking a small deviation (denoted by Δ) from initial values, the input mechanical power, the electrical power generated, and the rotor angle are given by [95],

$$\overline{P}_m = \overline{P}_{mo} + \Delta\overline{P}_m, \overline{P}_e = \overline{P}_{eo} + \Delta\overline{P}_e, \delta = \delta_o + \Delta\delta \tag{3.33}$$

Substituting equation 3.33, in an equation 3.32, to obtain,

$$\frac{2\mathrm{H}}{\omega_{ro}}\frac{d^2(\delta_o + \Delta\delta)}{dt^2} = \left((\overline{P}_{mo} + \Delta\overline{P}_m) - (\overline{P}_{eo} + \Delta\overline{P}_e)\right)P.U \tag{3.34}$$

At the steady-state point, the value of $\overline{P}_{mo} = \overline{P}_{eo}$ is one, an equation 3.34, can be simplified as,

$$\frac{2\mathrm{H}}{\omega_{ro}}\frac{d^2\delta}{dt^2} = (\Delta\overline{P}_m - \Delta\overline{P}_e)P.U \tag{3.35}$$

If δ is the angular position of the rotor in electrical radians to asynchronously rotating reference frame and δ_o is its value at $t = 0$,

$$\delta = \delta_o + (\omega_r - \omega_{ro})t$$

Taking the first derivative to obtain,

$$\frac{d\delta}{dt} = \frac{d\delta_o}{dt} + \frac{d(\omega_r - \omega_{ro})t}{dt} = \frac{d(\Delta\omega_r)t}{dt}$$

$$\frac{d\delta}{dt} = \omega_r - \omega_{ro} = \Delta\omega_r$$

And also, by taking the second derivative to obtain,

$$\frac{d^2\delta}{dt^2} = \frac{d(\omega_r - \omega_{ro})}{dt} = \frac{d\Delta\omega_r}{dt}$$

$$\frac{d^2\delta}{dt^2} = \frac{d\omega_r}{dt} = \frac{d\Delta\omega_r}{dt}$$

Multiplied both sides by ω_{ro} to obtain as

$$\omega_{ro}\frac{d\overline{\omega_r}}{dt} = \omega_{ro}\frac{d\Delta\overline{\omega_r}}{dt} \qquad (3.36)$$

$$\frac{d\omega_r}{dt} = \frac{d\Delta\omega_r}{dt} = \frac{d\omega_s}{dt}$$

Substituting equation 3.36, in an equation 3.35, to obtain,

$$\frac{2\mathrm{H}}{\omega_{ro}} * \omega_{ro}\frac{d\Delta\overline{\omega_r}}{dt} = \left(\Delta\overline{P_m} - \Delta\overline{P_e}\right)P.U$$

$$2\mathrm{H}\frac{d\Delta\overline{\omega_r}}{dt} = \left(\Delta\overline{P_m} - \Delta\overline{P_e}\right)P.U$$

$$\frac{d\Delta\overline{\omega_r}}{dt} = \frac{\left(\Delta\overline{P_m} - \Delta\overline{P_e}\right)P.U}{2\mathrm{H}}$$

Once a load power change occurs, the mechanical output power sent from the turbine will no longer match the electrical power generated by the generator. This error between the mechanical output power $\left(\Delta\overline{P_m}\right)$ and electrical output power $\left(\Delta\overline{P_e}\right)$ is integrated into the rotor speed deviation $\left(\Delta\overline{\omega_r}\right)$, which can be turned into the frequency bias (Δf) multiplying by 2π .

Taking both sides by Laplace transform to obtain the block diagram of synchronous generator [96],

$$\Delta\overline{\omega}_r(s)=\frac{\Delta\overline{P}_m(s)-\Delta\overline{P}_e(s)}{2Hs} \tag{3.37}$$

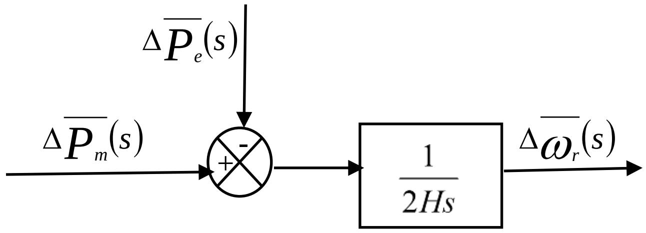


Figure 3.2. Block diagram of synchronous generator model

3.4. Mathematical Model of Load

Power system loads are consisting a variety of electrical devices people want to use in their home appliances, schools, historical church's, historical masjids, water pumps for daily uses, flour mills, and offices [97]. Electrical power loads can be classified into two those are; resistive loads such as lighting and heating loads the electrical power are independent of frequency which remain constant when the rotor speed is changing, and motor loads such as fans and pumps the electrical power changes with frequency due to changes in rotor speed. The overall frequency-dependent characteristics of electrical power load can be expressed as [98],

$$\Delta\overline{P}_e(s)=\Delta\overline{P}_D(s)=\Delta\overline{P}_{SL}(s)+D\Delta\overline{\omega}_r(s) \tag{3.38}$$

where,

- $\Delta\overline{P}_{SL}(s)$ are non-frequency sensitive consumer load changes and
- $D\Delta\overline{\omega}_r(s)$ are frequency sensitive consumer load changes

D is the generator load damping constant factor and expressed as percent change in load divided by percent change in frequency and its typical values of are 0.5 to 1 [99].

Substituting equation 3.38, in an equation 3.37, to obtain,

$$\Delta\overline{\omega}_r(s)=\frac{\Delta\overline{P}_m(s)-\left(\Delta\overline{P}_{SL}(s)+D\Delta\overline{\omega}_r(s)\right)}{2Hs}$$

$$\Delta\overline{\omega}_r(s)=\frac{\Delta\overline{P}_m(s)-\Delta\overline{P}_{SL}(s)-D\Delta\overline{\omega}_r(s)}{2Hs}$$

$$\Delta\overline{\omega_r}(s)*2Hs = \Delta\overline{P_m}(s) - \Delta\overline{P_{SL}}(s) - D\Delta\overline{\omega_r}(s)$$

$$\Delta\overline{\omega_r}(s)*2Hs + D\Delta\overline{\omega_r}(s) = \Delta\overline{P_m}(s) - \Delta\overline{P_{SL}}(s)$$

$$\Delta\overline{\omega_r}(s)(2Hs + D) = \Delta\overline{P_m}(s) - \Delta\overline{P_{SL}}(s)$$

$$\Delta\overline{\omega_r}(s) = \frac{\Delta\overline{P_m}(s) - \Delta\overline{P_{SL}}(s)}{2Hs + D} \tag{3.39}$$

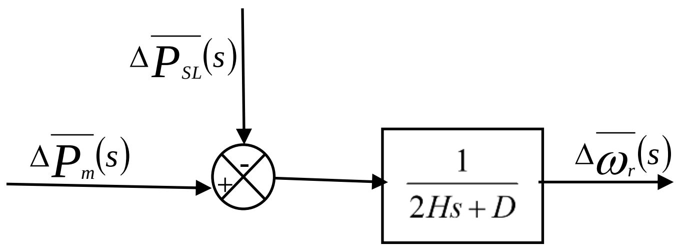


Figure 3.3. Block diagram of a load coupled with synchronous generator model

3.5. Mathematical Model of Governor

Governors are used in power systems to sense the frequency bias caused by the load change and cancel it by varying the inputs of the turbines, i.e. varying the flow rate of water. When the generator electrical load is suddenly increased, the electrical power exceeds the mechanical power input [100].

The function of the governor is to control the speed and/or load through the feedback signal to control the gate valve position to regulate the water flow through the penstock under any electrical load variations. Governors typically have a speed regulation of 5-6 percent from zero to full load.

The speed governor mechanism acts as a comparator whose output change in per unit governor angular frequency is the difference between the change in per unit reference set angular frequency, and the speed regulator multiplied by change in per unit system actual angular frequency can be expressed as [101],

$$\Delta\overline{\omega_g}(s) = \Delta\overline{\omega_{ref}}(s) - \frac{1}{R}\Delta\overline{\omega_r}(s) \tag{3.40}$$

The command $\Delta\overline{\omega_g}(s)$ is transformed through the hydraulic amplifier to the valve position command i.e. per unit change gate transient droop compensator $\Delta\overline{G_{TDC}}(s)$. Assuming a linear relationship and considering a simple time constant T_g, have the following s-domain relation,

$$\frac{\Delta\overline{G_{TDC}}(s)}{\Delta\overline{\omega_g}(s)} = \frac{1}{1+T_g s} \tag{3.41}$$

For stability concerns, a hydraulic amplifier servo mechanism in the governor is needed for the hydraulic turbine. A hydraulic amplifier is a device that increases the power of a signal in a hydraulic servo mechanism through the use of a fixed and variable hydraulic intensifier. A hydraulic intensifier is very important in the case of hydraulic turbines, mainly hydraulic presses, which require water or hydraulic fluid at very high pressure which cannot be obtained from the main supply directly [102]. There are three main parts in the hydraulic intensifiers to be noted, those are:

- Fixed ram
- Hollow inverted sliding cylinder
- Fixed inverted cylinder

The transfer function of hydraulic amplifier servo mechanism when, the transient droop compensation $\Delta\overline{G_{TDC}}(s)$ as an input and the gate position valve $\Delta\overline{G}(s)$ as an output part is given by [103],

$$\frac{\Delta\overline{G}(s)}{\Delta\overline{G_{TDC}}(s)} = \left(\frac{1+T_R s}{1+T_R\left(R_T/R\right)s}\right) \tag{3.42}$$

$$\frac{\Delta\overline{G}(s)}{\Delta\overline{G_{TDC}}(s)} = \left(\frac{1+T_R s}{1+T_R T_T s}\right) \tag{3.43}$$

$$T_T = R_T/R$$

where T_T is the transient droop compensation time, R_T is temporary droop, and R is permanent droop characteristics of the hydraulic amplifier.

The working mechanism of the hydropower generation unit is the same as the working operation of the thermal plant. The speed governor incorporated with the hydraulic amplifier is given by [101] [103],

$$\Delta\overline{G_{TDC}}(s) = \left(\frac{1}{1+T_g s}\right)\left(\frac{1+T_R s}{1+T_R T_T s}\right)\Delta\overline{\omega_{ref}}(s) - \frac{1}{R}\Delta\overline{\omega_r}(s) \tag{3.44}$$

3.6. Adaptive Fuzzy Logic Controller Modelling

The principal work of a controller is to balance a generator load towards the main load changes. Therefore, the output of the generator will be stable even though changes on the main load occur. Different types of controllers can be used to balance generator load and main load and consequently, to control the frequency of output power. The AFLC is proposed in this thesis because this controller is suitable for complex, nonlinear, uncertain, higher-order, and time-delay systems [104].

The input variables of the fuzzy logic controller are frequency deviation and change in frequency deviation. The controller output variables are the gain parameters of K_p and Ki, those are useful tools to regulate the system provided that the system dynamics vary non-linearly with set conditions.

It is expected that its working mechanism is better if the correlation between the dynamics of the systems and the conditions under which they operate are already known and the linear time-invariant model is not sufficient to consider.

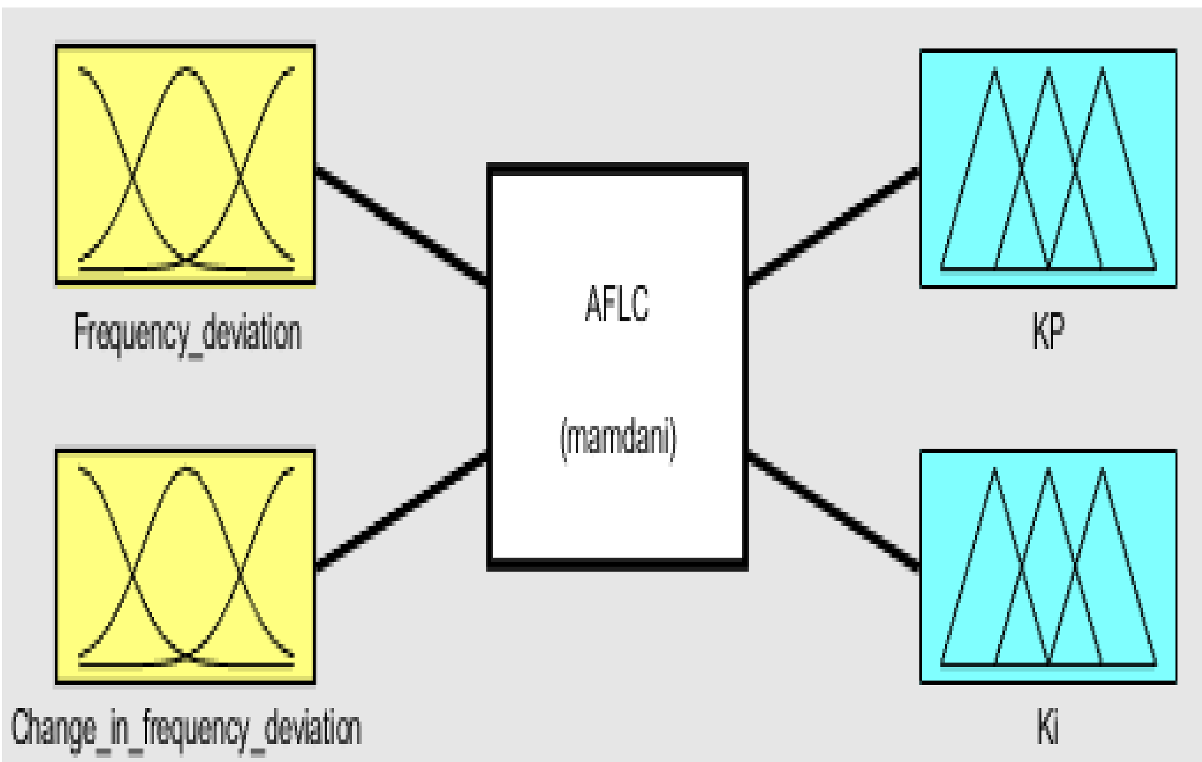


Figure 3.4. Adaptive fuzzy logic controller model

3.7. The Overall Model of Mini Hydro Power Generation

All the different electromechanical components of mini hydro power generation have been modeled in the previous sections. Putting together all the transfer functions obtained results in the block diagram of the proposed model of MHPG is shown in figure 3.5. The model consists of a speed governor, hydraulic amplifier, hydraulic turbine, synchronous generator, speed regulator, and adaptive fuzzy logic controller.

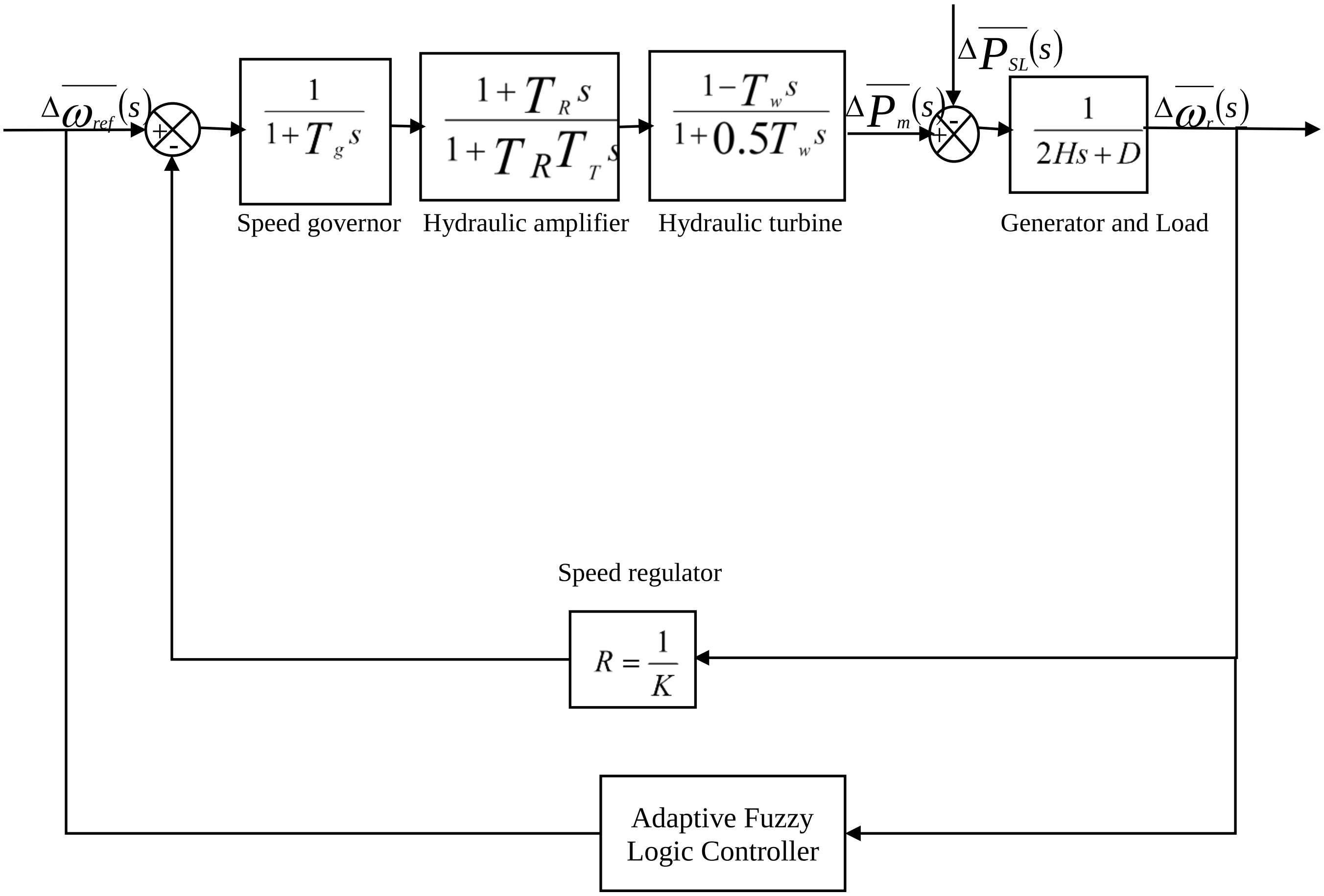


Figure 3.5. The overall model of the proposed load frequency control of MHPG

3.8. The Overall Model of MHPG Control System Stability

The tendency of a power system to develop restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium is known as stability (see Appendix A.1).

In this thesis, the overall model control system stability depends and to analyze the stability of systems using Routh-Hurwitz's stability criteria (see Appendix A.1.1). Consider a simple open-loop control system as shown in the figure 3.5, where the rated change in frequency deviation, $\Delta\overline{\omega_{ref}}(s)$ and rated change in non-frequency sensitive load power, $-\Delta\overline{P_{SL}}(s)$ as the s-domain reference inputs and also the rated change in frequency deviation, $\Delta\overline{\omega_r}(s)$ as the s-domain controlled output.

The open-loop transfer function of the overall model control system is expressed as,

$$G(s)H(s)=\frac{1}{R}\frac{(1+T_R s)(1-T_w s)}{(2Hs+D)(1+T_g s)(1+T_R T_T s)(1+0.5T_w s)} \tag{3.45}$$

And the closed-loop transfer function where, $\Delta\overline{\omega_{ref}}(s)$ as the reference input and $\Delta\overline{\omega_r}(s)$ as the controlled output to obtain as,

$$\frac{\Delta\overline{\omega_r}(s)}{\Delta\overline{\omega_{ref}}(s)}=T_1(s)=\frac{(1+T_R s)(1-T_w s)}{(2Hs+D)(1+T_g s)(1+T_R T_T s)(1+0.5T_w s)+\frac{1}{R}(1+T_R s)(1-T_w s)} \tag{3.46}$$

where, $-\Delta\overline{P_{SL}}(s)$ as the reference input and $\Delta\overline{\omega_r}(s)$ as the controlled output the closed-loop transfer function obtain as,

$$\frac{\Delta\overline{\omega_r}(s)}{-\Delta\overline{P_{SL}}(s)}=T_2(s)=\frac{(1+T_g s)(1+T_R T_T s)(1+0.5T_w s)}{(2Hs+D)(1+T_g s)(1+T_R T_T s)(1+0.5T_w s)+\frac{1}{R}(1+T_R s)(1-T_w s)} \tag{3.47}$$

By using the superposition principle, the overall model closed-loop transfer function obtained as,

$$T(s)=\frac{[(1+T_R s)(1-T_w s)]+[(1+T_g s)(1+T_R T_T s)(1+0.5T_w s)]}{(2Hs+D)(1+T_g s)(1+T_R T_T s)(1+0.5T_w s)+\frac{1}{R}(1+T_R s)(1-T_w s)} \tag{3.48}$$

or the s-domain response is

$$\Delta\overline{\omega_r}(s)=\left(\frac{-\Delta\overline{P_{SL}}(s)*\Delta\overline{\omega_{ref}}(s)}{\Delta\overline{\omega_{ref}}(s)-\Delta\overline{P_{SL}}(s)}\right)*T(s) \tag{3.49}$$

The two reference inputs are a step input, i.e. $\Delta\overline{\omega_{ref}}(s)=\Delta\overline{\omega_{ref}}/s$ and $\Delta\overline{P_{SL}}(s)=\Delta\overline{P_{SL}}/s$. Utilizing the final value theorem, the steady-state value of $\Delta\overline{\omega_r}$ is,

$$\Delta\overline{\omega_{ss}}=\lim_{s\to 0} s\Delta\overline{\omega_r}(s)=\left(\frac{-\Delta\overline{P_{SL}}*\Delta\overline{\omega_{ref}}}{\Delta\overline{\omega_{ref}}-\Delta\overline{P_{SL}}}\right)*\frac{1}{D+1/R} \tag{3.50}$$

It is clear that for the case with no frequency sensitive load i.e. $D=0$, the steady-state deviation in frequency is determined by the governor speed regulation is,

$$\Delta\overline{\omega_{ss}}=\lim_{s\to 0} s\Delta\overline{\omega_r}(s)=\left(\frac{-\Delta\overline{P_{SL}}*\Delta\overline{\omega_{ref}}}{\Delta\overline{\omega_{ref}}-\Delta\overline{P_{SL}}}\right)*R \tag{3.51}$$

Where, the values of hydraulic amplifier transient droop time (T_T), speed governor time constant (T_g), hydraulic amplifier reset time (T_R), hydraulic turbine water starting time (T_w), generator inertia constant (H), generator load damping factor constant (D) is expressed in table 3.2. and $K=1/R$.

Table 3.2. Typical parameter values of mini-hydro power generation system [105]

Parameter type	**Parameter value**
Speed governor time constant (T_g)	0.2sec.
Hydraulic amplifier reset time (T_R)	1sec.
Hydraulic amplifier transient droop time (T_T)	0.5sec.
Hydraulic turbine water starting time (T_w)	1sec.
Generator inertia constant (H)	5sec.
Generator load damping factor constant (D)	0.8

The open-loop transfer function of the overall model of the system shown in the figure 3.5, as equation 3.45,

$$G(s)H(s) = \frac{K(1+s)(1-s)}{(10s+0.8)(1+0.2s)(1+0.5s)(1+0.5s)}$$

$$G(s)H(s) = \frac{K(1-s^2)}{0.5s^4 + 4.54s^3 + 12.36s^2 + 10.96s + 0.8}$$

The characteristic equation is given by,

$$1 + G(s)H(s) = 1 + \frac{K(1-s^2)}{0.5s^4 + 4.54s^3 + 12.36s^2 + 10.96s + 0.8} = 0$$

which results in the characteristic polynomial equation obtained,

$$0.5s^4 + 4.54s^3 + (12.36 - K)s^2 + 10.96s + (0.8 + K) = 0$$

The criterion is applied through the use of a Routh-Hurwitz table for this polynomial is then (see Appendix A.1.1). There is no change of sign in the first column, hence the system is stable. Therefore,

$$11.1529 - K > 0$$

$$\frac{118.603784 - 15.5K}{11.1529 - K} > 0$$

$$0.8 + K > 0$$

From the s^2 row, we see that for control system stability, K must be less than 11.1529, the s^1 row, K must be less than 7.6518, and also from the s^0 row, K must be greater than -0.8. Thus, select the intersection of the two, and with a positive value of K, for control system stability

$$0 < K < 7.6518$$

Since $R = 1/K$ for control system stability, the governor speed regulation must be

$$0 < R > \frac{1}{7.6518} \quad \text{or} \quad 0 < R > 0.1307$$

For $K = 7.6518$, the auxiliary equation from the s^2 row is

$$3.5011s^2 + 8.4518 = 0$$

or $s = \pm j1.5537$, that is for $R = 0.1307$, it has a pair of conjugate poles on the $j\omega$ axis therefore, the overall model control system is marginally stable.

CHAPTER FOUR

LOAD ESTIMATION AND DESIGN PARAMETERS OF MHPG

4.1. Load Estimation

The term load refers to a demand for electric energy. The load estimation is mainly concerned with calculating the power and energy demand of the community [106]. To estimate the theoretical and actual output power demand of the community, first to know the full information of the selected area. So, Debre Zeit kebele is one of the selected remote rural areas which have no access to electricity. By asking the kebele leader of Debre Zeit kebele's information "Debre Zeit kebele is one of the 17 Kebele's in Sinan woreda and including nine different villages" which is found in East Gojjam Zone around Debre Markos town. The full information of the nine different villages lists and expressed in the bar graph in figure 4.1.

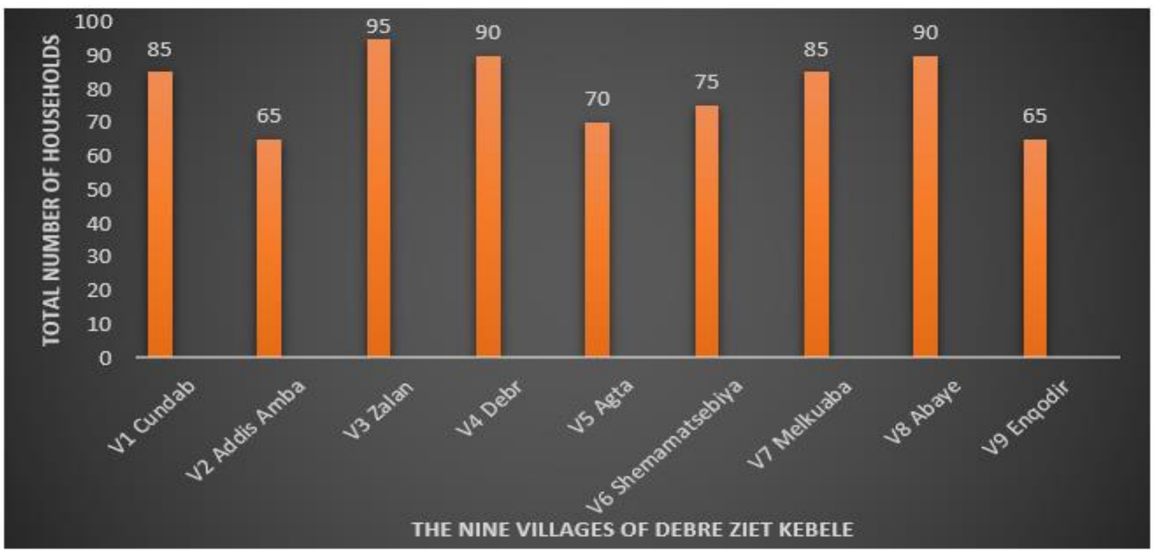


Figure 4.1. Total number of households for the nine different villages of the selected area

According to the collecting data from the kebele leader, there is 3,155 total number of populations with 720 total number of households living in nine different villages. The total number of females and males are 1,893 (i.e. 60%) and 1,262 (i.e. 40%) respectively have been living in this kebele. Due to this reason assuming, four types of consumer loads can be considered in this thesis. Those are primary, secondary, tertiary and other extra loads so, these load estimations are performed for the villages with 720 total number of households by considering the basic needs of the communities at the Debre Zeit kebele area.

Primary load is electrical demand that the power system must meet at a specific time. Electrical demand associated with lights, radio, TV, household appliances, computers, and industrial processes is typically modeled as primary load. According to [107], electric load in the remote rural villages of Ethiopia can be assumed to be composed of lighting, radio, television, water pumps, health care center, and primary schools load. In this thesis, electricity for cooking food, refrigerator, and flour mills is added. Secondary and tertiary loads are electrical demands that can be met anytime within a certain time, which exact timing is not important. If the renewable power supply ever exceeds the primary load, the surplus can serve the secondary and tertiary loads rather than going to waste. In this thesis, flour mills are considered as secondary loads, water pumps for daily use, and primary school loads are considered as tertiary loads while the others as primary loads [108].

4.1.1. Energy Demand Assessment and Scheduling of the Villages at Debre Zeit kebele

The basic energy requirements of the villages at Debre Zeit kebele can also be classified into two categories of loads. These are domestic loads and community loads. Domestic loads are loads used for the applications of lighting, cooking food, refrigerator, television, and radio in each household.

The community loads are also the types of loads that include primary school loads, health care center loads, flour mills, and water pumps for daily use. All primary, secondary, tertiary, and other extra loads found at Debre Zeit kebele with it shown in the next section.

a. Primary load profile of the villages

It is a fact that all the people of the villages do have not the same economic status i.e. some of the households are relatively rich and most of them are comparatively poor. For instance, the majority of the households may not offer the electricity cost if they use the electric oven or Injera Mitad and refrigerator. Hence out of the 720-total number of households of the villages 216 (i.e. 30%) of them are categorized as relatively rich and the rest 504 (i.e. 70%) of households are assumed as comparatively poor. Assuming the planning electrical loads for each poor household includes three 13W compact fluorescent light (CFL) bulbs to be used for between 13:00 and 18:00 during every night days, a 10W radio receiver operated for 6 hours during working days and 11 hours during weekends, a 110W rated 19’’- 36’’ color television (TV) working between 13:00 and 18:00 during working days and 9:00-19:00 during weekends and also 1.5KW rating electric stove operated for 2 hours per day.

Similarly, the electrical loads for each rich household assumed to have three 13W compact fluorescent light (CFL) bulbs, a 10W radio receiver, a 110W rated 19''- 36'' color television (TV), 1.5KW rated electric stove, 3KW rated electric oven working for two hours every day and 300W rated refrigerator working for every day. Likewise, the following electrical loads are considered for the health care center. Six 13W CFL bulbs for rooms and external lighting working between 13:00 and 24:00 per day, a 300W rated refrigerator working for 24 hours, a 50W capacity microscope operated for four hours per day, and a 1.5KW rated water heater operated for four hours per day [109].

b. Secondary load profile of the villages

Flour mills are considered secondary loads and assuming there are two flour mills in Debre Zeit kebele. The power rating for each flour mill is 2.5KW and milling capacity of 350 kg/hour is considered for the community, then the total flour mills rating 5KW (i.e. 2*2.5KW) assumed if it operates for 6 hours per day the total energy required per day is (2*2.5KW*6h =30KWh).

Because of the religious concern of the people, it assumed that the flour mill is not also operational during weekends.

c. Tertiary load profile of the villages

Water pumps for daily use and primary school loads are considered tertiary loads. A water pumping system is required for households, schools, and health care centers.

Assuming a minimum of 100 L of water per day per family and 6,000 L per day for each pair of one health care center and two primary schools are suggested. Assuming the community needs has 3 water pumps for daily uses for each village and 27 (i.e. 3*9) water pumps for the total villages enough to supply the households as well as services to the community sufficiently. So, 27 water pumps for all households as well as the service centers which deliver public service to the community. Assume the type of water pump is HR-14 which is taken from the Lorenz PS600 series with a 300W power rating and pumping capacity of 40L/m (i.e.2,400L/h) [109]. This can pump water at this rate from a depth of 15m. As mentioned, above the average daily water consumption of the community per household is assumed to be 100L/day and 6,000L/day for all the service centers (i.e., both of the primary schools and health care centers). The total daily water consumption of the community is then 72,000L/day (i.e. 720*100L/day). This indicates that the overall water needed by the villages in a day is 78,000L/day (i.e. 72,000L/day + 6,000L/day).

Therefore, the water pumps of the over mentioned types with a peak load of 1.5 kW rated are used to supply the water demand of the community. The water storage tank is assumed to have a capacity of storing water for four days 312,000L (i.e. 78,000L*4) of water.

To determine the number of hours required to fill the daily consumption of the community, the daily water consumption is divided by the total pumping rate of the 27 water pumps which is 64,800L/h (i.e.2,400L/h*27), then the number of hours needed to supply the daily water consumption of the community is then obtained to be approximately 1.204 hours, which is 78,000L/64,800L/h. Hence, the daily tertiary load will be 1.806KWh (i.e. 1.5kw*1.204hrs). This load is constant for all months approximately except for June, July, and August which are the months of the rainy season of the areas, and their water consumption is assumed to reduce by 30% [110]. The other tertiary load is primary school loads. There are two primary schools at Debre Zeit kebele namely, Shola and Debre Zeit primary schools, the schools will need 200W load for office loads such as 2 and 3 respectively computer printer to be operated between 9:00 and 4:00 per day.

d. Other extra load profiles of the villages

The electrical energy requirements of the villages vary from season to season and weekend to working days. Another extra load is for unknown loads in each category such as cell phone charging, historical church's, historical masjid's prediction is necessary.

Table 4.1. Summary of all load profiles of the total energy required at Debre Zeit kebele community [109] [110]

Type of loads	**The total amount of energy required in (KWh)**
Primary loads	
Home appliance	6,462
Health care center	14.258
Secondary loads	
Flour making mills	30
Tertiary loads	
Water pumps for daily use	1.806
Primary school loads	7
Other extra loads	400
Total overall	$6{,}915.064 \approx 864.381KW$

The theoretical amount of output power (P_{th}) available from any hydro power system is directly related to the flow rate of water (Q), the net head (H_d) and the force of gravity (g) given as [111],

$$P_{th} = Q * H_d * g \tag{4.1}$$

To calculate the actual power output (P_{act}) from any hydropower system, it is required to consider friction losses in the penstock pipe and the efficiency of the turbine and generator. Typically, overall efficiencies for small hydropower generating systems can vary from 50 to 75% with higher overall efficiencies occurring in high head systems. Therefore, to determine the actual power output, the theoretical power must be multiplied by an efficiency factor of 0.5 to 0.75 depending on the capacity and type of system given as [111],

$$P_{act} = P_{th} * \eta = Q * H_d * g * \eta \tag{4.2}$$

Where, η is efficiency conversion of potential energy into kinetic energy or efficiency factor of turbine and generator.

Using equation 4.2, and the theoretical amount of output power available from table 4.1 of the load estimation, the selected river the net head of water is slightly medium assumed to be $(10m)$ at a medium efficiency factor of turbine and generator (0.6), the actual power output obtain,

$$P_{act} = 864.381KW * 0.6 = 518.6286KW$$

4.2. Methods of head and flow measurement of Chemoga river without sophisticated tools

Head and flow are the two most important facts of the selected hydropower potential river. Inaccurate measurements result in low efficiency, high cost, and scarcity of power.

Measuring Head: - The head is defined as the vertical height in meters from the level where, the water enters the penstock to the level where the water leaves the turbine housing, i.e. the vertical distance between the intake and the turbine. Estimation of height can be done easiest if there is a steep slope or waterfall by rope [112]. So, the net head of the selected river is slightly medium assumed to be $(10m)$.

Measuring Flow rate: - Flow rate of the water is the quantity of water available flowing or how much water comes down the stream, past a point at a given time in a stream or river and may vary widely for a day, week, month and year. The purpose of a hydrology study is to predict the variation in the flow rate during the year. It is important to know the mean streamflow and the extremely high flow rates.

Environmental and climatic factors and human activities in the watershed determine the amount and characteristics of streamflow on a day-to-day and seasonal basis. Generally, unless considering a storage reservoir, it should be used the lowest mean annual flow is the basis for the system design. There are several techniques for measuring water flow rate, the most commonly used including the bucket or container method, the velocity-area float method, the weir method, the salt dilution method, and the current meter method [112]. However, in this thesis, the velocity-area float method is the best and most common one determining the flow rate of water. Estimation of flow rate is very difficult without measurement but, a quick and easy way to measure is the velocity-area float method:

First, measure the water speed at a steady flowing part of the river. Therefore, drop some items and stop the time it needs for a certain distance to float.

$$V = \frac{s}{t} \tag{4.3}$$

where V is the water speed in m/s and s is the distance in m

Assume a stone drop in the water at $10m$ in $55\sec$, the water speed obtained using equation 4.3,

$$V = 10m/55\sec = 0.1818\ m/s$$

Second, sketch the selected river cross-sectional area by measuring its length and its depth then come up with a grid showing the river profile from side to side.

$$A = L * W \tag{4.4}$$

where A is the cross-sectional area in m^2, L is the length in m and W is the width in m.

Assume the length, $5m$ and the width, $10m$ of the selected river so, with this data its cross-sectional area can be calculated easily using equation 4.4,

$$A = 5m * 10m = 50\ m^2$$

Finally, the flow rate of water (Q) results from the product of water speed and the cross-sectional area.

$$Q = V * A \tag{4.5}$$

$$Q = 0.1818\ m/s * 50\ m^2 = 9.0909\ m^3/s$$

Therefore, for the selected hydropower potential river the maximum theoretical output power generating capacity is calculated by using equation 4.1,

$$P_{thout} = 9.0909\, m^3/s * 10m * 9.81\, m/s^2 = 891.8182\, KW$$

The actual output power generating capacity is calculated by using an equation 4.2, at a medium efficiency factor of turbine and generator (0.6),

$$P_{actout} = 9.0909\, m^3/s * 10m * 9.81\, m/s^2 * 0.6 = 535.0904\, KW$$

The output power generation capacity from the selected river differs from season to season depending on the amount of rainfalls. So, to meet steady-state performance in this system, the valve is mandatory to control the flow rate of water by closing and opening depending on the amount of water.

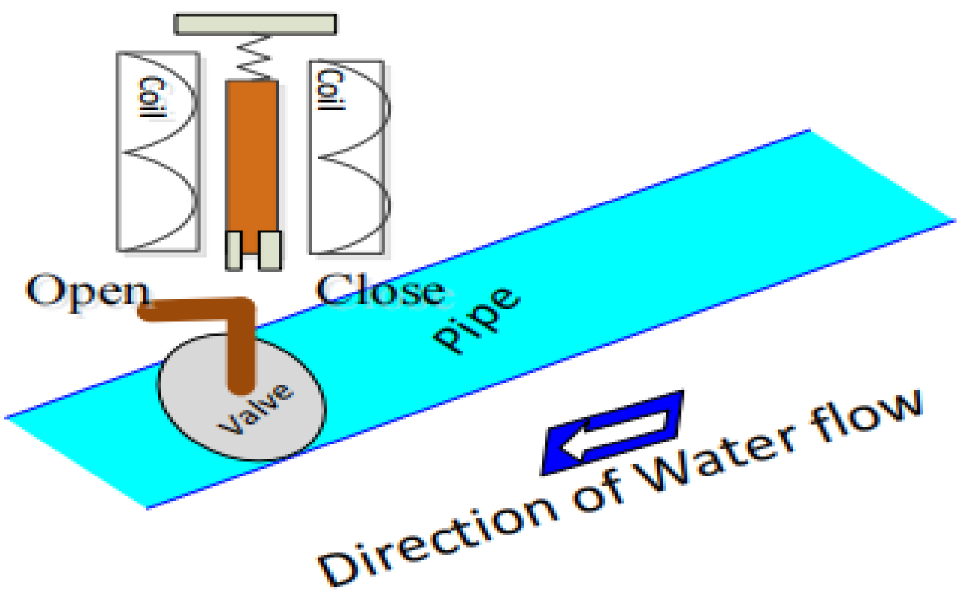


Figure 4.2. The basic component of the valve [112]

To open the valve electromagnetic force, push the plunger in the right direction and push the main valve clockwise indirectly, to close the valve electromagnetic force push the plunger to the left direction and push the main valve anticlockwise indirectly.

The total torque needed to close the valve (T_{ct}) and the total torque to open the valve (T_{ot}) are expressed in an equation 4.6 and equation 4.7 respectively.

$$T_{ct} = T_h + T_{bf} + T_{ss} + T_{su} \tag{4.6}$$

where,

- T_h is hydrostatic torque
- T_{bf} is bearing friction torque
- T_{ss} is stem seal friction torque
- T_{su} is a seating and unseating torque

$$T_{ot} = T_{bf} + T_{ss} + T_d \tag{4.7}$$

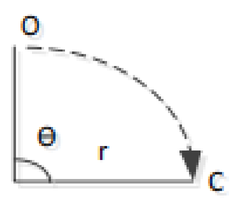
where T_d is dynamic torque

Bray has developed closing and opening torque charts for valves with standard discs (rated for full pressure) and for valves with reduced diameter discs (rated for 50PSI / 3.5 bar.) [Resilient Seated Butterfly Valves Technical Manual] and the torque for the proposed valve is taken from this manual. The total electromagnetic force needed to close the valve (F_{ct}) and the total electromagnetic force to open the valve (F_{ot}) are expressed mathematically in an equation 4.8 and equation 4.9 as,

$$F_{ct} = \frac{T_{ct}}{d} \tag{4.8}$$

$$F_{ot} = \frac{T_{ot}}{d} \tag{4.9}$$

where, d is the distance moved by the plunger,



$$d = r * \sin\theta \tag{4.10}$$

In the summer season which is characterized by heavy rainfalls in all areas and the selected areas due to this the flow rate of water is very high and the net head of the water is high, the generating output power is also high, all the required loads are fulfilled then the valve is normally open and the water is applicable for another purpose.

In the spring and autumn seasons which are characterized by less rain falls in all areas and the selected areas due to this the flow rate of water is relatively medium and the net head of the water is slightly medium, the generating output power is also medium, then the valve is normally open and normally closed at some angle θ and all the required loads are maybe fulfilled.

In the winter season which is characterized by very less or no rain falls in all areas and the selected areas due to this the flow rate of water is relatively low and the net head of the water is slightly low, the generating output power is also low, then the valve is normally closed, the water will be stored and all the required loads are maybe or may not be fulfilled.

4.3. Adaptive Fuzzy Logic Controller Design

This thesis describes an adaptive fuzzy logic control system for mini hydropower generation is proposed to get better system performance. Take the frequency deviation and change in frequency deviation as the input variables and the gain parameters K_P and K_i are output variables for the fuzzy inference system. The following steps are applied to design the adaptive fuzzy logic controller:

- First, all the information about the system is collected.
- The control elements are identified to apply adaptive fuzzy logic.
- Input and output variables for the fuzzy logic controller are identified.
- To know the gain scheduling output variables of the adaptive control.
- The universe of discourse is defined for 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 adaptive fuzzy logic controller under different load operations.

4.3.1. Fuzzification Design

The first step in fuzzification is to determine input and output variables which, have two input variables frequency deviation and change in frequency deviation, and two output variables gain parameters K_P and K_i.

The Controller Input Variables

Frequency deviation and change in frequency deviation are the two input variables of the controller. The type of membership function used in this thesis is triangular because of easy to understand, then the following seven triangular membership functions have been identified and applied. The fuzzy linguistic variables were assigned to be the Mamdani-type fuzzy inference system.

Table 4.2. Membership function of adaptive fuzzy logic controller

NEGATIVE BIG	NB
NEGATIVE MEDIUM	NM
NEGATIVE SMALL	NS
ZERO	ZE
POSOTIVE SMALL	PS
POSITIVE MEDIUM	PM
POSITIVE BIG	PB

I. Membership function of frequency deviation

The limits of the power system frequency deviation were decided based on the variation of the system frequency of the generating power system.

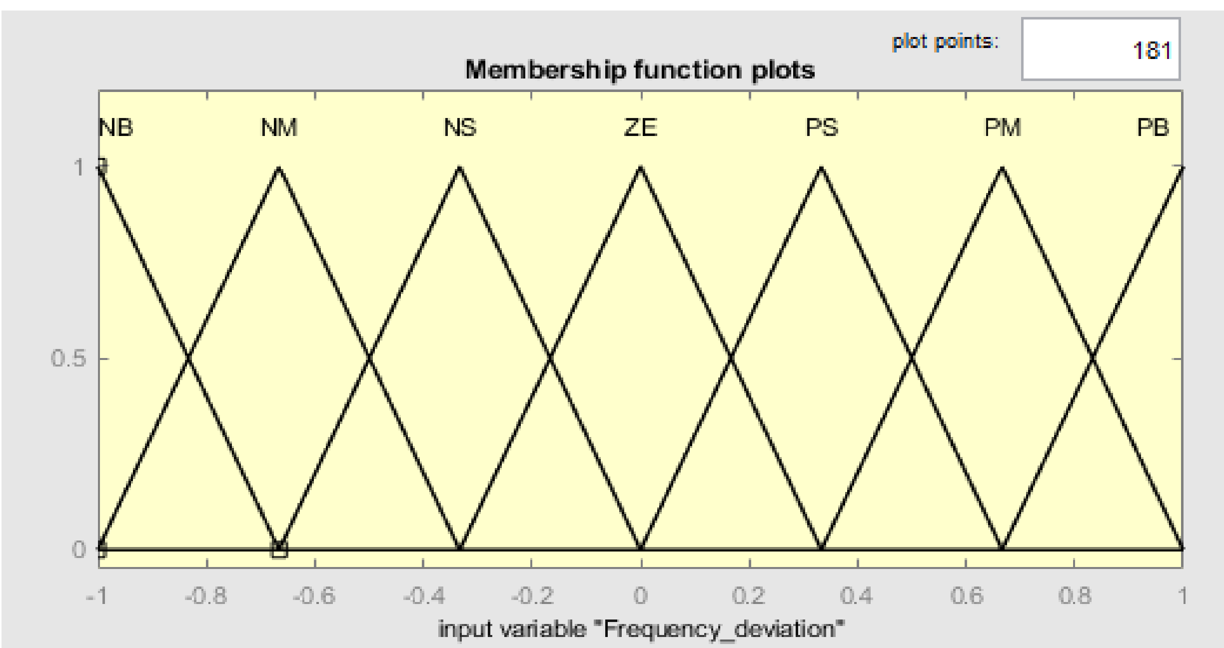


Figure 4.3. The controller input variable membership function for frequency deviation

II. Membership function of change in frequency deviation

Here, a derivative has to be used to predict the frequency deviation in the future, based on the current slope of the frequency deviation. The limits of membership values are used to reflect the frequency deviation exactly.

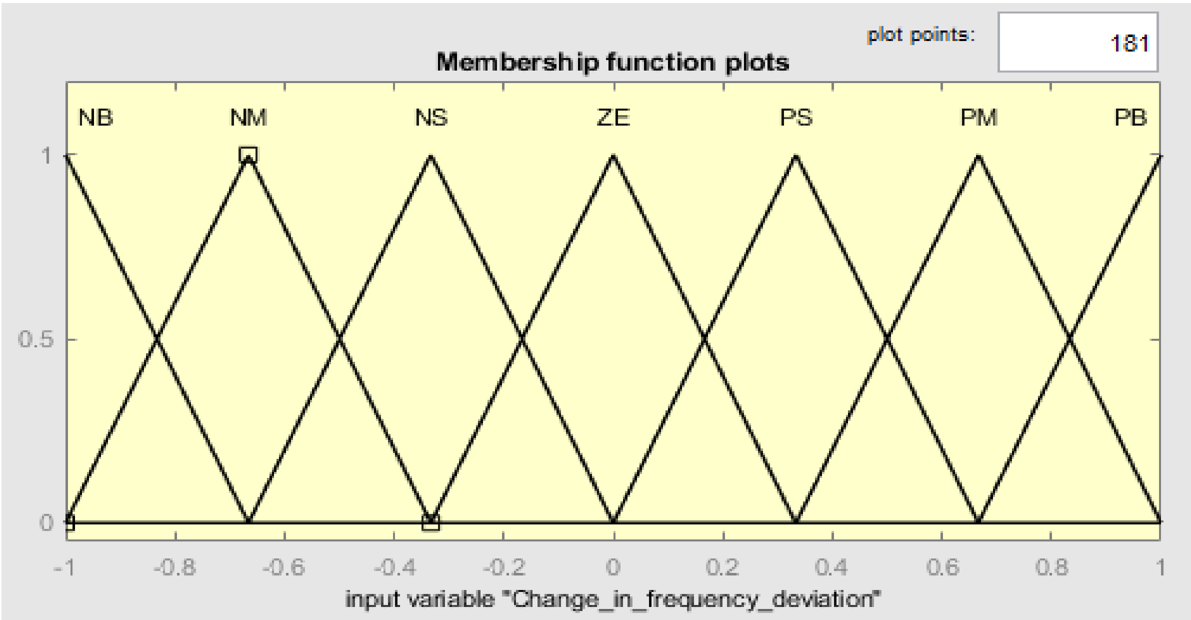


Figure 4.4. The controller input membership function for change in frequency deviation

Seven fuzzy linguistic variables Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), and Positive Big (PB) are chosen for the input variables frequency deviation and change in frequency deviation. The universe of discourse of each membership function is shown in figure 4.3 and 4.4 respectively. The frequency deviation and change in frequency deviation are normalized to [-1, 1] and the membership functions for frequency deviation and change in frequency deviation are made more in number to activate only the required governor and to minimize error.

III. Gain adjustment function of input scaling factor K_d for adaptive control

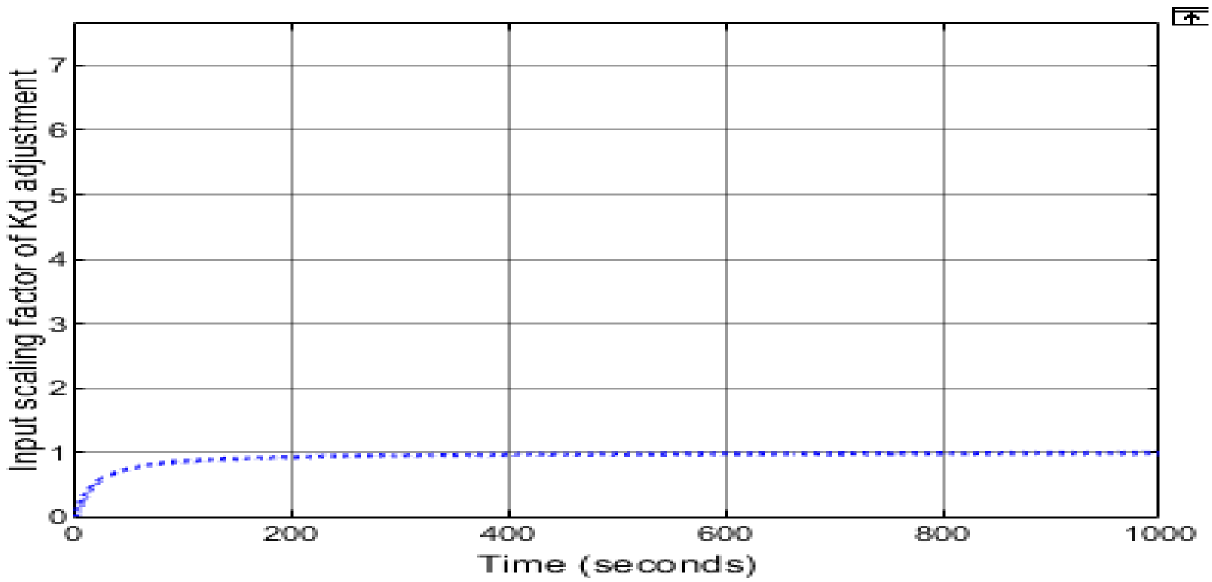


Figure 4.5. Gain adjustment function of input scaling factor K_d

The Controller Output Variables

The controller output variables identified here are the gain parameters K_p and K_i. These output variables can be positive or negative like the input variables, the frequency deviation, and the change in frequency deviation since the load on the system are not constant.

IV. Membership function of output variable K_p

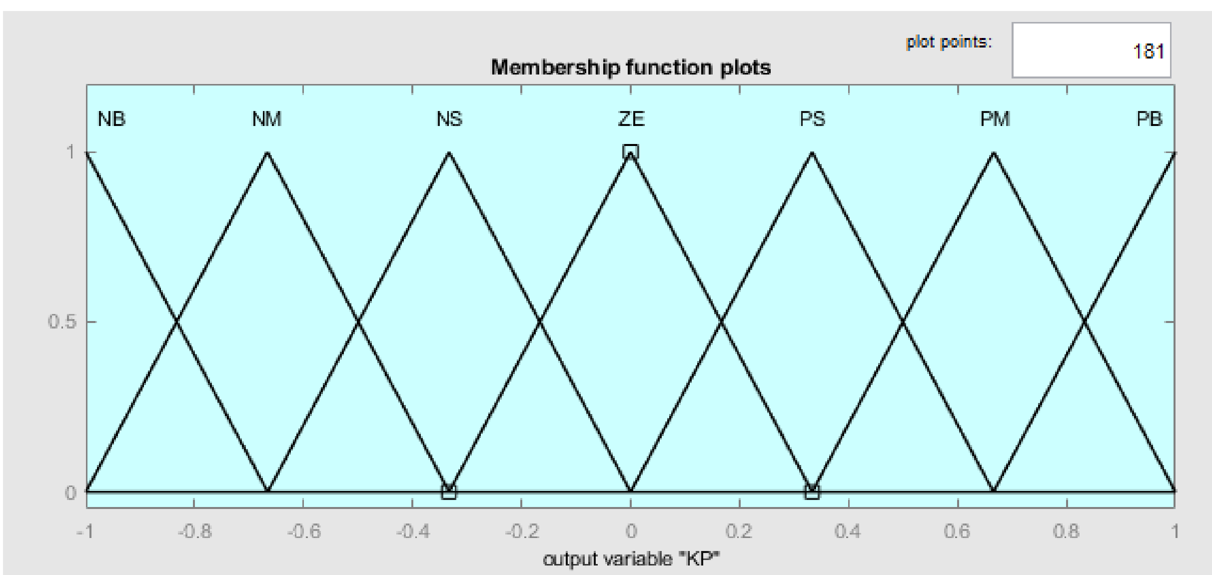


Figure 4.6. The controller output membership function for K_p

V. Membership function of output variable K_i

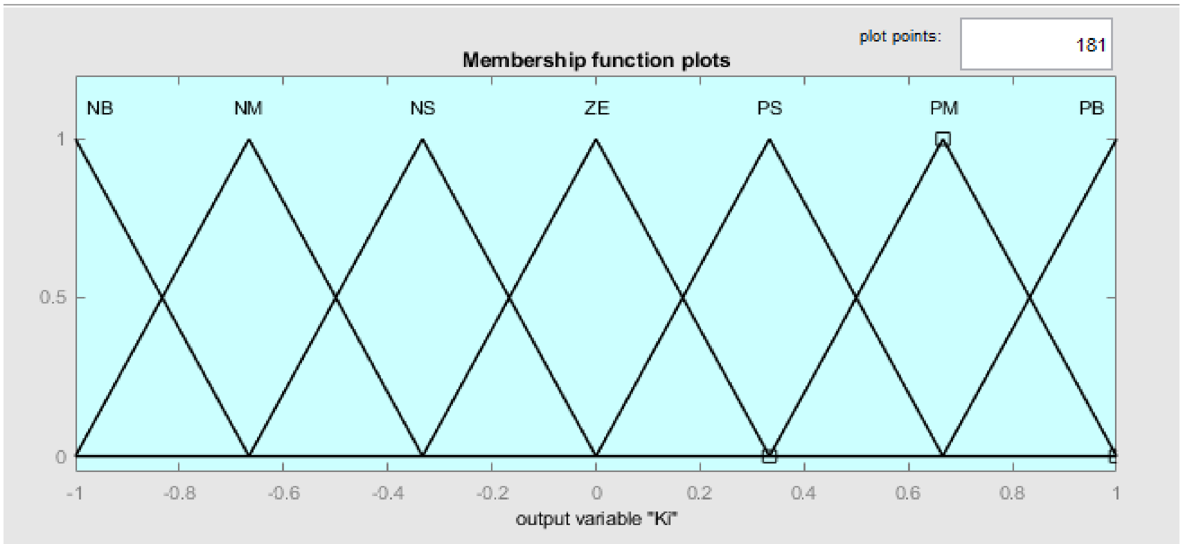


Figure 4.7. The controller output membership function for K_i

Seven fuzzy linguistic variables Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), and Positive Big (PB) are chosen for the adaptive gain scheduling output variables are normalized to in fuzzy universe discourse of each membership function range from [-1 1] and shown in figure 4.6 and 4.7 respectively.

VI. Gain adjustment functions of output scaling factor K_P and K_i for adaptive control

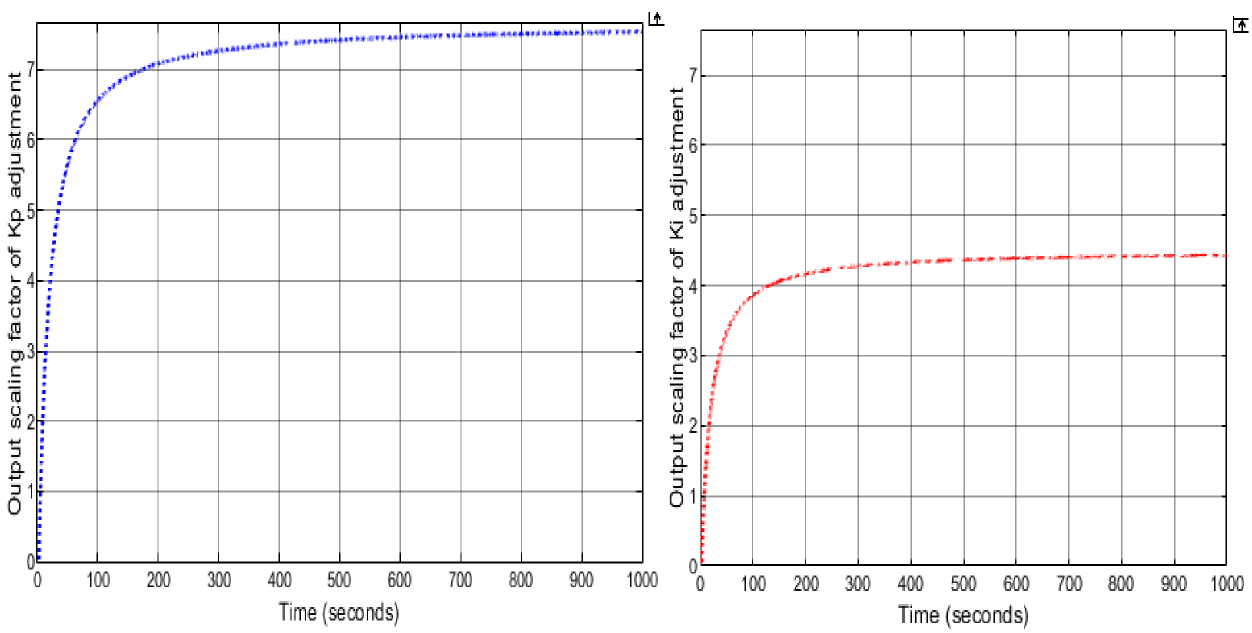


Figure 4.8. Gain adjustment functions of output scaling factor K_P and K_i

4.3.2. Fuzzy Control Rule Base Construction and Rule Evaluation

A fuzzy control rule base 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. In the case of the adaptive fuzzy logic frequency controller, the desired effect is to keep the output frequency of the generator at its rated value under varying load operating conditions. From this desired goal, rules are made for every combination of frequency deviation and change in frequency deviation on what the output variables of the gain parameters should be to stabilize the frequency. It is convenient when dealing with a large number of combinations of inputs, to put the rules in the form of a rule table. The complete rule base for this controller is shown in table 4.3. After rule base construction, rule evaluation which focuses on operation in the antecedent of the fuzzy rules is done. AND/OR fuzzy operation is used in the antecedent part which AND operation is used in this design.

Table 4.3. Rule base of fuzzy membership function

Frequency deviation	Change in frequency deviation						
	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NM	NB	NM	NS	ZE
NM	NB	NB	NM	NM	NS	ZE	PS
NS	NB	NM	NM	NS	ZE	PS	PM
ZE	NM	NM	NS	ZE	PS	PM	PM
PS	NM	NS	ZE	PS	PM	PM	PB
PM	NS	ZE	PS	PM	PM	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

4.3.3. Aggregation (Fuzzy Inference) Rule Output for the Proposed Controller

After construction and evaluation of all rule-base of the system, the overall consequent is obtained from the individual consequent contributed by each rule in the rule-base by using a minimum correlation inference technique. This means that the logic operation of AND will return the minimum of all inputs and outputs of membership functions are the same and seven-segment triangular membership functions are used as stated earlier. For the fuzzy linguistic rule stated earlier, the output variables of gain scheduling parameters would receive a membership function that was equal to the minimum of the two inputs, frequency deviation, and change in frequency deviation. Since each input has seven membership functions, the number of fuzzy-based rules is forty-nine and they are presented in table 4.3, it consists of 49 rules, working of the adaptive fuzzy logic controller is based on 49 rules.

4.3.4. Defuzzification Design

After the rules are evaluated, each output membership function will contain a corresponding membership. From these memberships, a numerical or crisp value was produced. It is impossible to convert a fuzzy set into a numeric value without losing some information. Many different methods exist to accomplish defuzzification. A 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. The defuzzification method used in this proposed model is the center of gravity or centroid method.

CHAPTER FIVE

MATLAB SIMULATION RESULTS AND DISCUSSION

5.1. Introduction

This chapter presents simulation results got from tests performed on the mini hydro power generation model is established, it is simulated and studied with a convectional PID controller and an intelligent AFLC by using MATLAB/Simulink software. The Simulink model is used to carry out simulation studies and analysis the performance measuring variables of the system by using PID controller and AFLC under different operating load conditions.

5.2. Overall Simulink Model of Mini Hydro Power Generation System

All electromechanical components of MHPG are modeled to design the controller and to analyze the simulation results. The Simulink model of AFLC and the overall Simulink model of MHPG for a frequency control system with PID controller and AFLC is shown in figure 5.1, 5.2, and 5.3 respectively.

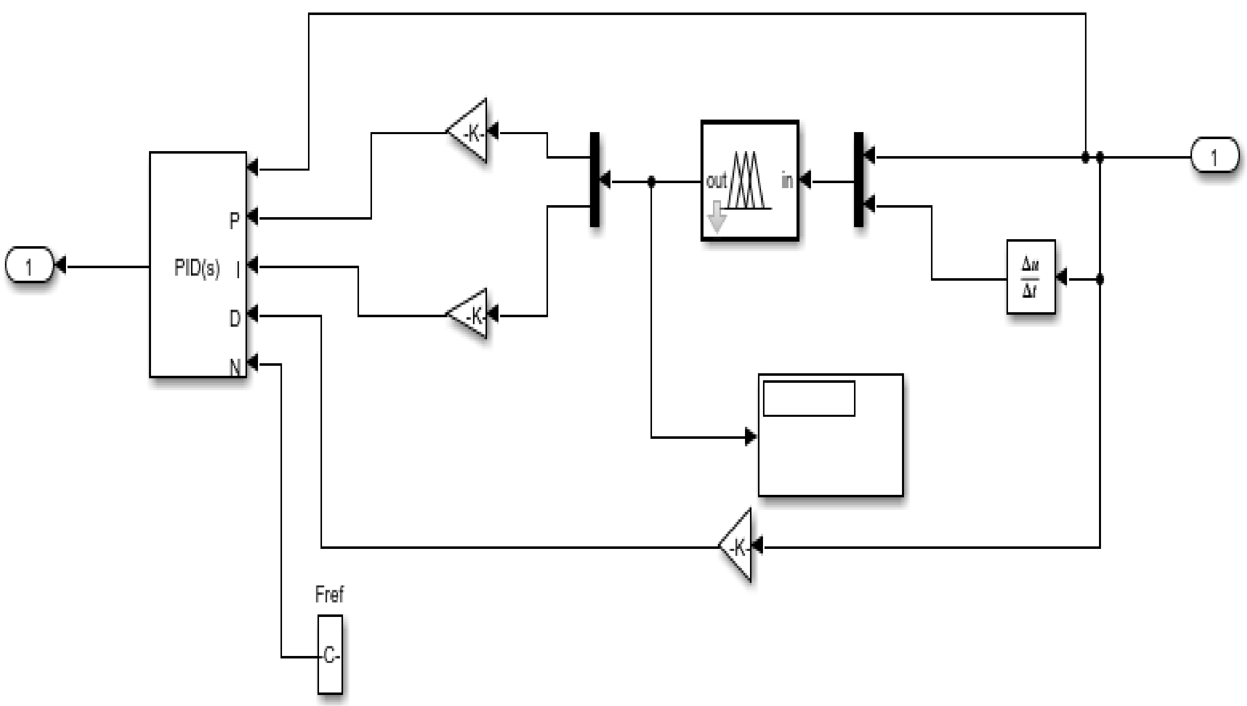


Figure 5.1. Simulink model of adaptive fuzzy logic controller

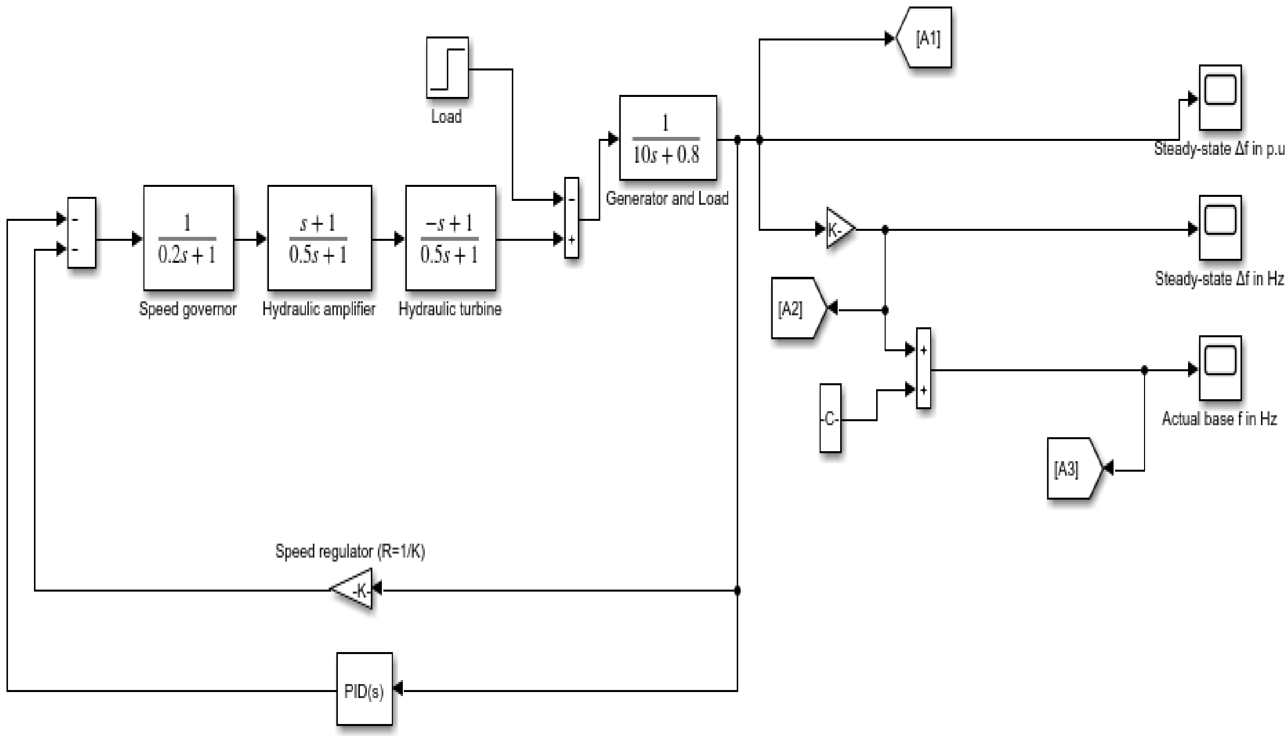


Figure 5.2. The overall Simulink model of MHPG with PID controller

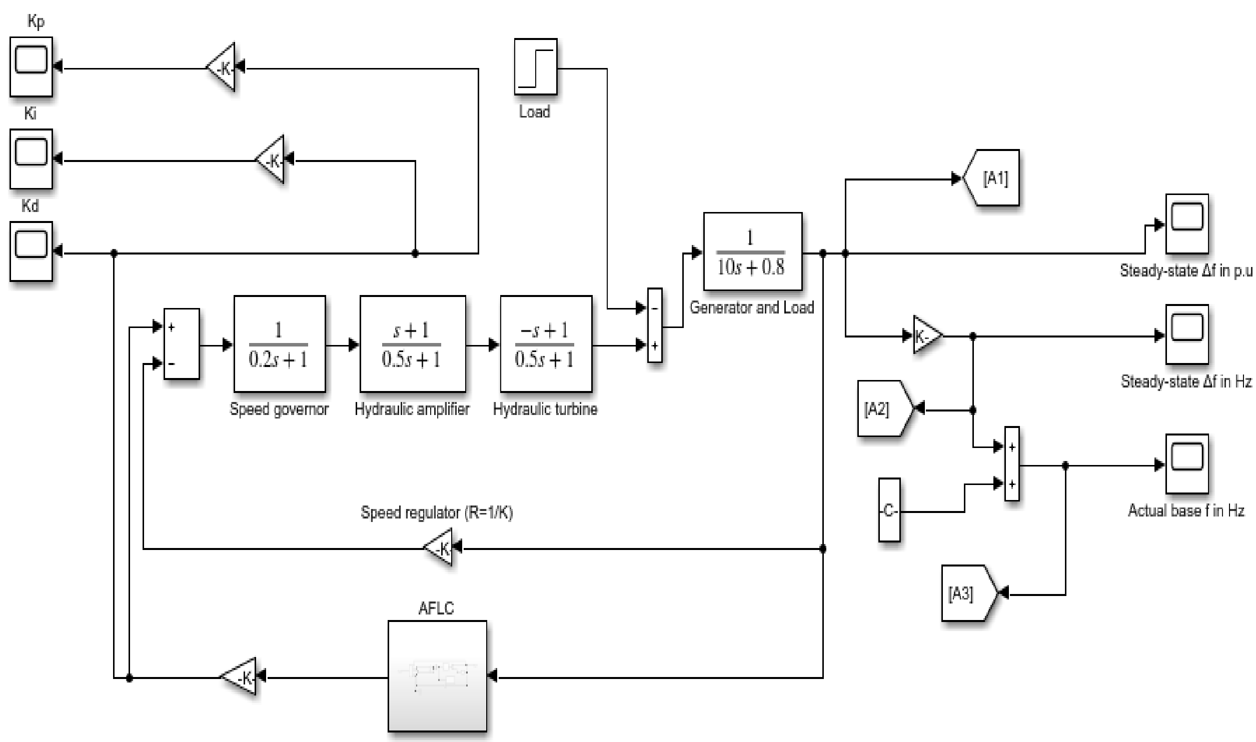


Figure 5.3. The overall Simulink model of MHPG with AFLC

5.3. MATLAB Simulation Results

The response of the system is tested for different sudden load power changes. The simulation results show both the p.u and Hz value of steady-state frequency deviation and system actual base frequency. The selected river the maximum theoretical output power generating capacity is 891.8182 KW relatively the same as the theoretical output power demand obtained from the load estimation of the consumer in that kebele area, from this, the actual output power generating capacity of 535.0904 KW is assumed to be used by constant load power, the load power which is always running and the remaining 356.7278 KW is assumed to be used by variable load power, the load power which is not always running. This means the output power which supplies the variable demand power can vary from 0-356.7278 KW according to the power needed by the consumer. Therefore, to see the effect of load variation on the system in MATLAB simulation results, the response of the system is tested for a load variation of 0%, 20%, 50%, 60%, and 65% within PID controller and AFLC by considering the maximum theoretical output power generating capacity of the selected river.

The simulation result of steady-state Δf in p.u by using PID controller and AFLC when the actual output power generating capacity is 535.0904 KW at a sudden load power change of 0.0 KW occurred. Therefore, the value for step input function will become 0.0 p.u (i.e. for 0% load).

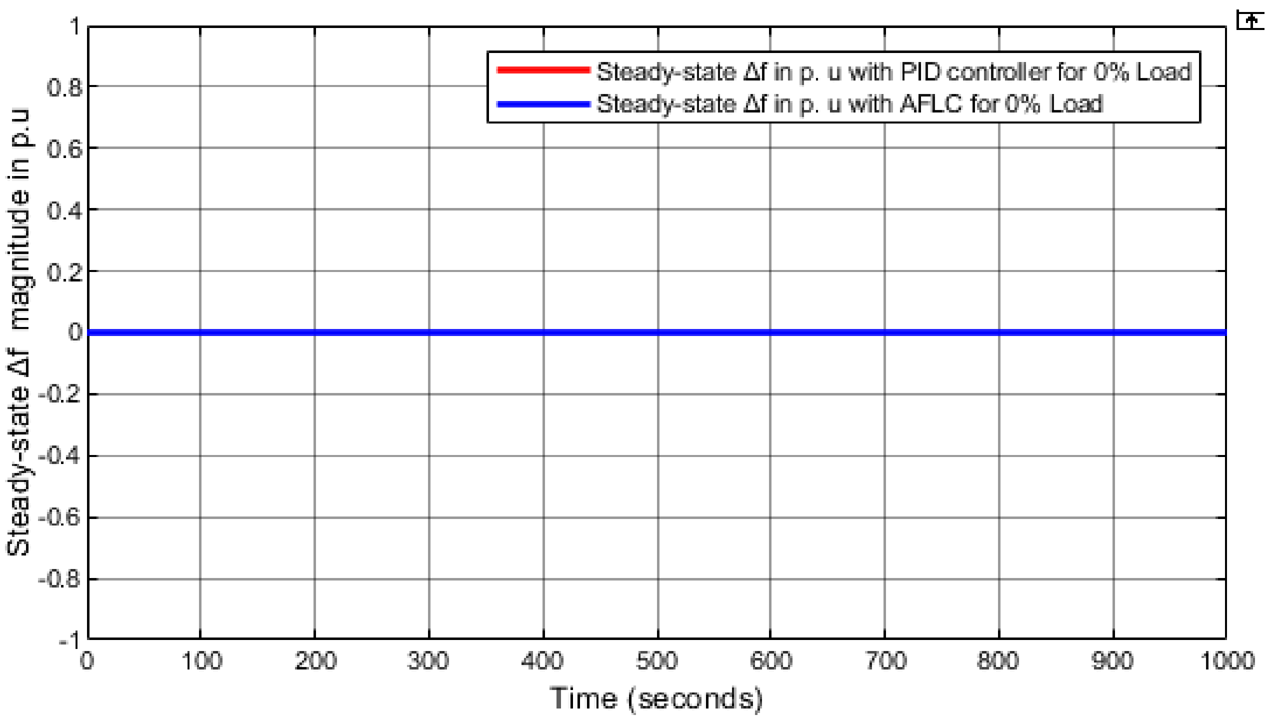


Figure 5.4. Simulation response of steady-state frequency deviation for 0% load with PID and AFLC in p.u

The simulation result of steady-state Δf in p.u by using PID controller and AFLC when the actual output power generating capacity is 535.0904 KW at a sudden load power change of 107.01808 KW occurred. Therefore, the value for step input function will become 0.2 p.u (i.e. for 20% load).

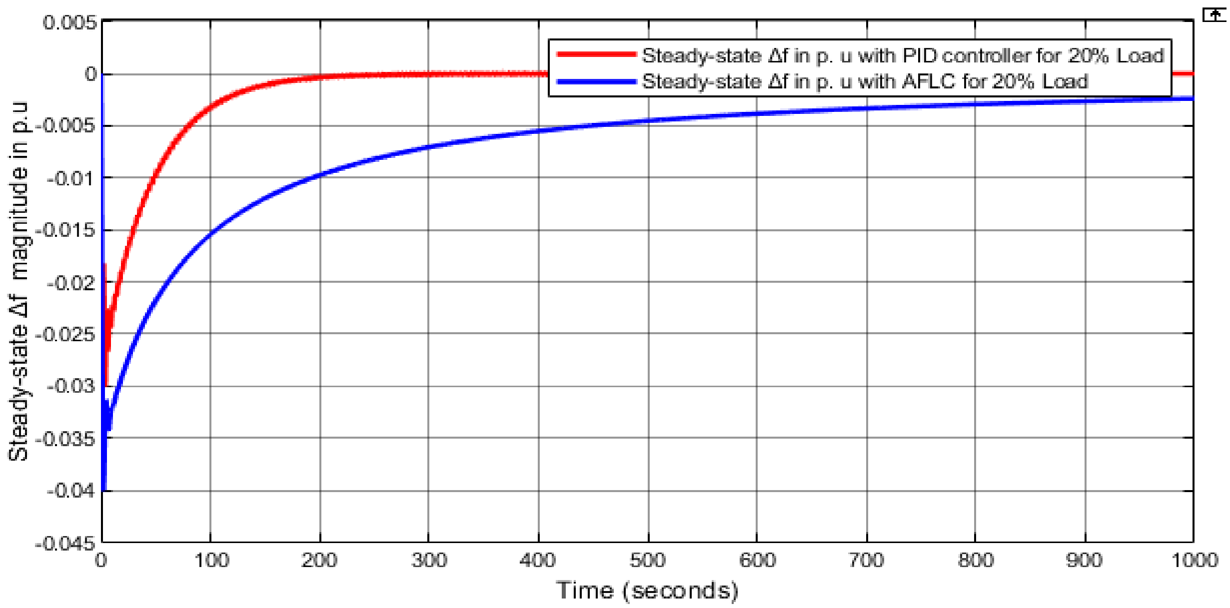


Figure 5.5. Simulation response of steady-state frequency deviation for 20% load with PID and AFLC in p.u

The simulation result of steady-state Δf in p.u by using PID controller and AFLC when the actual output power generating capacity is 535.0904 KW at a sudden load power change of 267.5452 KW occurred. Therefore, the value for step input function will become 0.5 p.u (i.e. for 50% load).

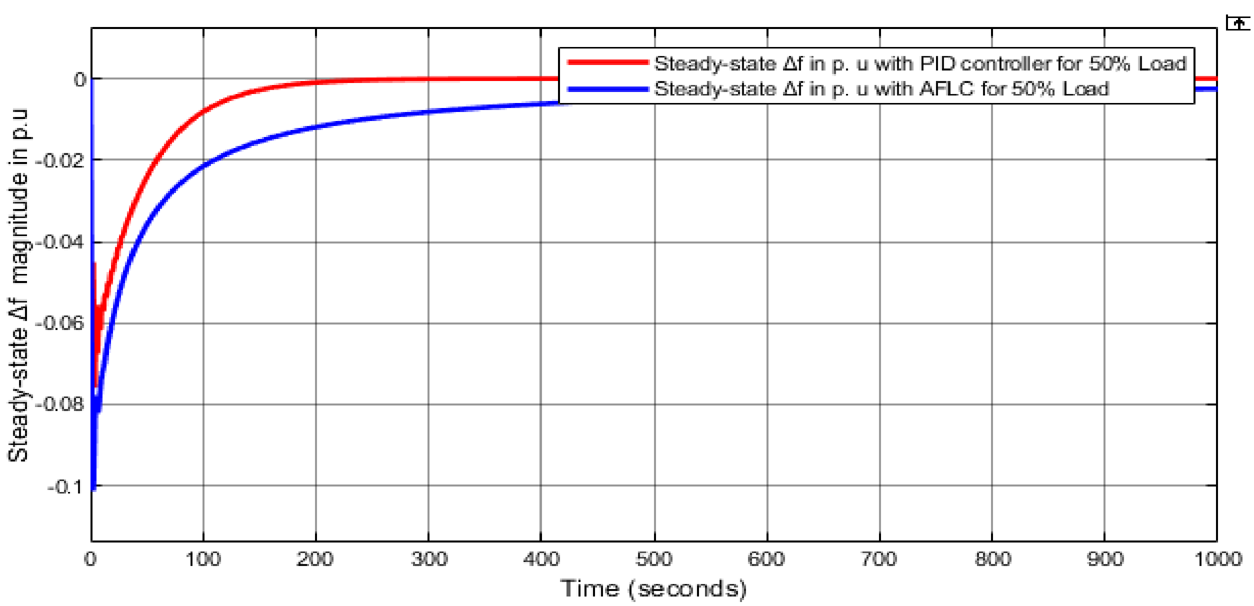


Figure 5.6. Simulation response of steady-state frequency deviation for 50% load with PID and AFLC in p.u

The simulation result of steady-state Δf in p.u by using PID controller and AFLC when the actual output power generating capacity is 535.0904 KW at a sudden load power change of 321.05424 KW occurred. Therefore, the value for step input function will become 0.6 p.u (i.e. for 60% load).

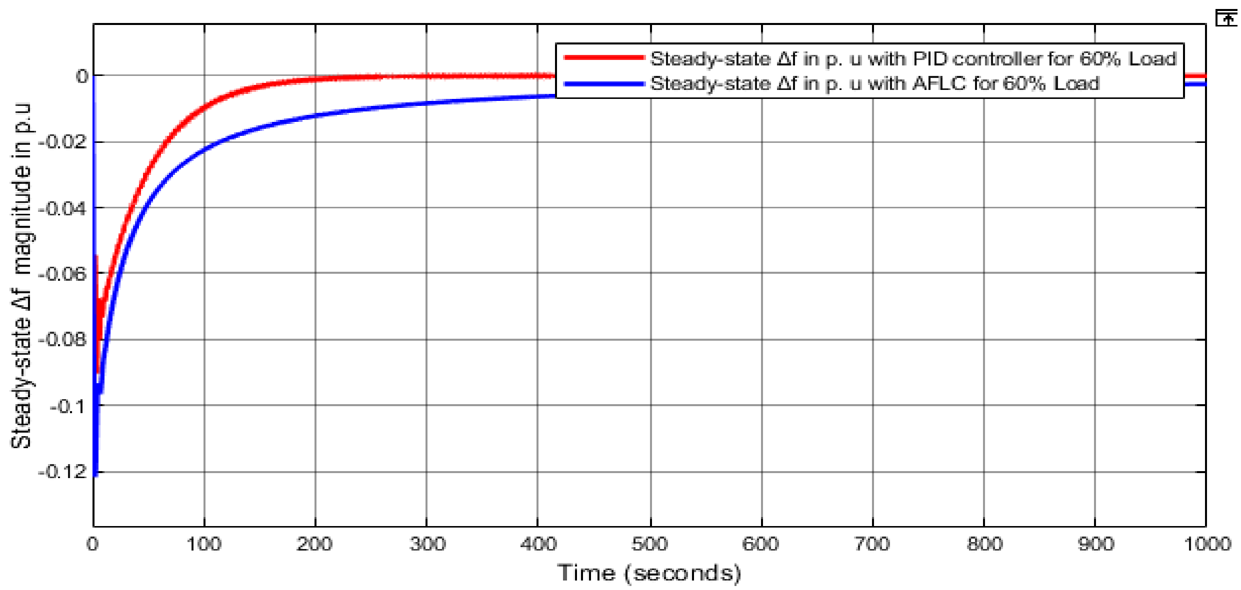


Figure 5.7. Simulation response of steady-state frequency deviation for 60% load with PID and AFLC in p.u

The simulation result of steady-state Δf in p.u by using PID controller and AFLC when the actual output power generating capacity is 535.0904 KW at a sudden load power change of 347.80876 KW occurred. Therefore, the value for step input function will become 0.65 p.u (i.e. for 65% load).

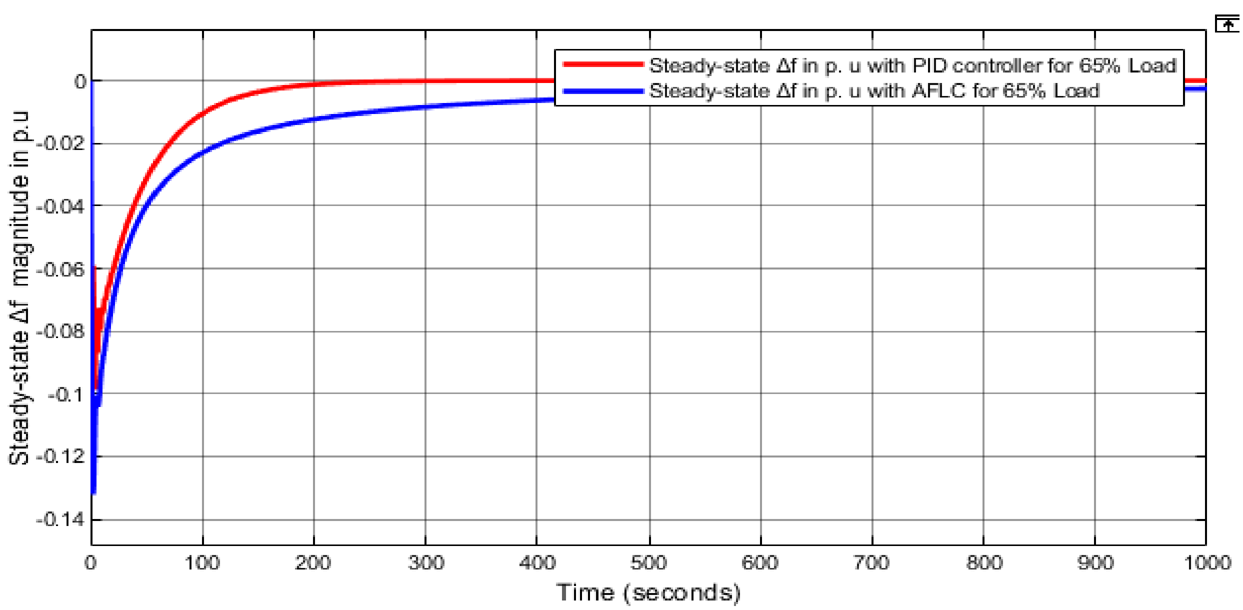


Figure 5.8. Simulation response of steady-state frequency deviation for 65% load with PID and AFLC in p.u

Summary of transient and steady-state system performance measuring variables of the proposed load frequency control of mini hydro power generation for sudden 0%, 20%, 50%, 60%, and 65% load power changes with PID controller and AFLC when steady-state Δf expressed in p.u value.

Table 5.1. Summary of transient and steady-state system performance for steady-state frequency deviation in p.u

Variation of Change in Load Power (ΔPL) in p.u	**Rise time (sec.)**	**(+) Overshoot (%)**	**(-) Overshoot (%)**	**Steady-state frequency error (p.u)**
ΔPL = 0.0 with PID	---	---	---	0.0
with AFLC	---	---	---	0.0
ΔPL = 0.2 with PID	97.882	0.735	12.508	0.0001904
with AFLC	--	---	0.404	0.003632
ΔPL = 0.5 with PID	97.850	0.735	12.549	0.0004181
with AFLC	--	---	2.632	0.003805
ΔPL = 0.6 with PID	100.530	0.733	12.394	0.0008941
with AFLC	162.959	0.795	0.695	0.003841
ΔPL = 0.65 with PID	100.530	0.733	12.394	0.001277
with AFLC	133.105	-0.009	0.111	0.003863

The simulation result of steady-state Δf in Hz by using PID controller and AFLC when the actual output power generating capacity is 535.0904 KW at a sudden load power change of 0.0 KW occurred. Therefore, the value for step input function will become 0.0 p.u (i.e. for 0% load).

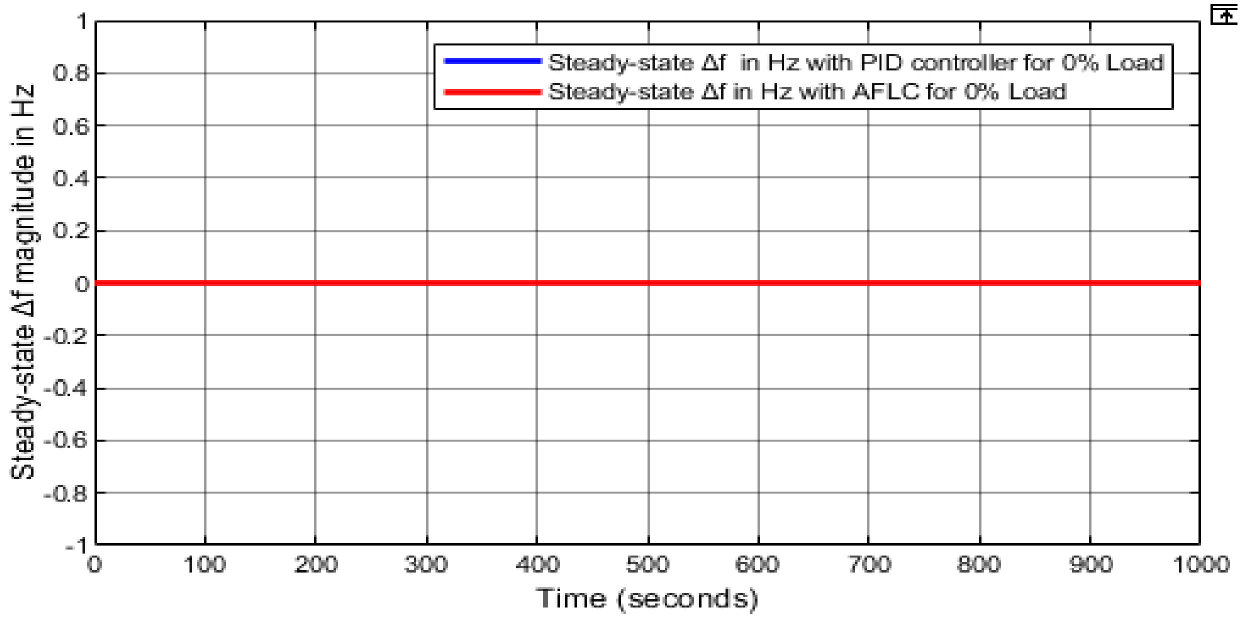


Figure 5.9. Simulation response of steady-state frequency deviation for 0% load with PID and AFLC in Hz

The simulation result of steady-state Δf in Hz by using PID controller and AFLC when the actual output power generating capacity is 535.0904 KW at a sudden load power change of 107.01808 KW occurred. Therefore, the value for step input function will become 0.2 p.u (i.e. for 20% load).

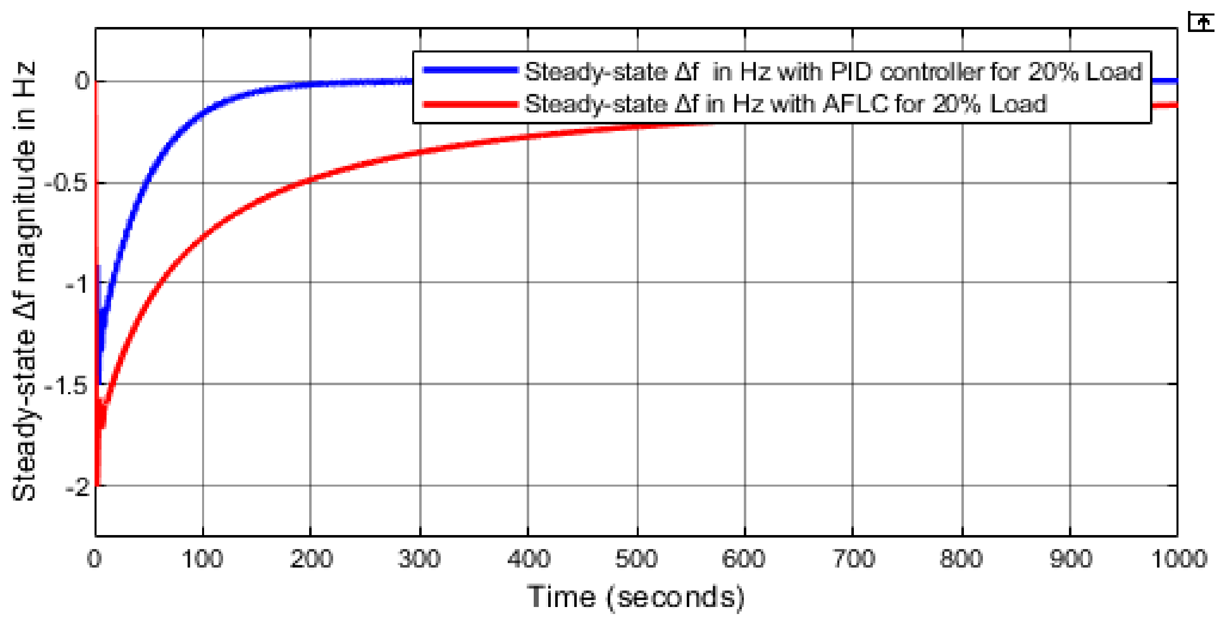


Figure 5.10. Simulation response of steady-state frequency deviation for 20% load with PID and AFLC in Hz

The simulation result of steady-state Δf in Hz by using PID controller and AFLC when the actual output power generating capacity is 535.0904 KW at a sudden load power change of 267.5452 KW occurred. Therefore, the value for step input function will become 0.5 p.u (i.e. for 50% load).

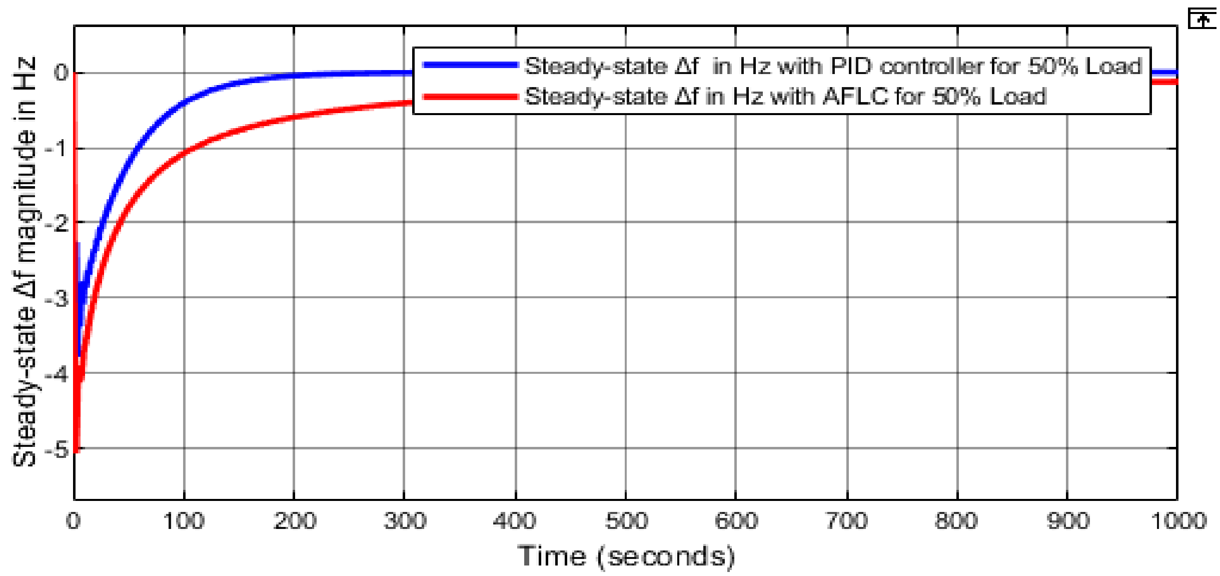


Figure 5.11. Simulation response of steady-state frequency deviation for 50% load with PID and AFLC in Hz

The simulation result of steady-state Δf in Hz by using PID controller and AFLC when the actual output power generating capacity is 535.0904 KW at a sudden load power change of 321.05424 KW occurred. Therefore, the value for step input function will become 0.6 p.u (i.e. for 60% load).

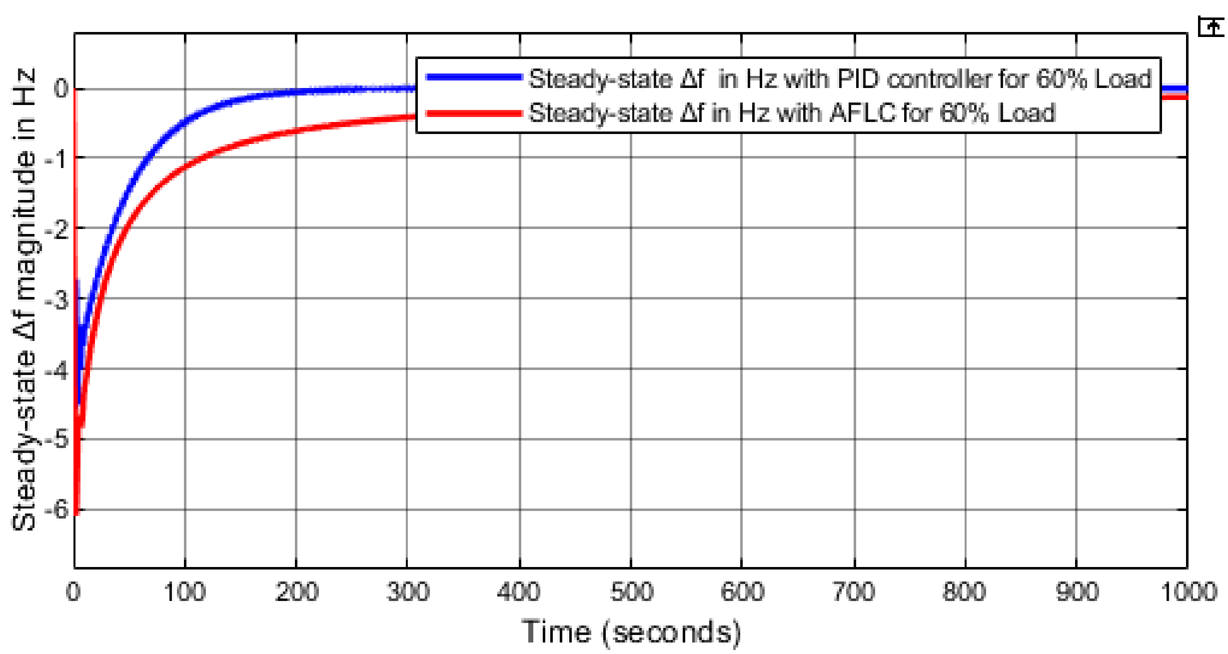


Figure 5.12. Simulation response of steady-state frequency deviation for 60% load with PID and AFLC in Hz

The simulation result of steady-state Δf in Hz by using PID controller and AFLC when the actual output power generating capacity is 535.0904 KW at a sudden load power change of 347.80876 KW occurred. Therefore, the value for step input function will become 0.65 p.u (i.e. for 65% load).

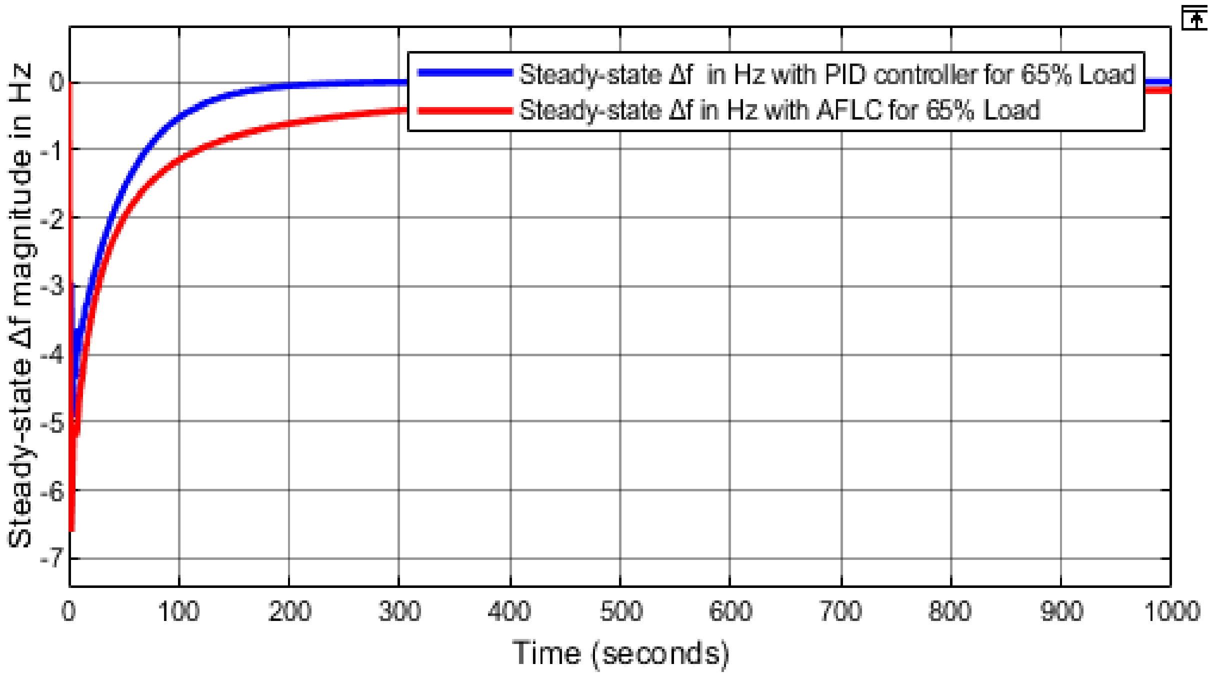


Figure 5.13. Simulation response of steady-state frequency deviation for 65% load with PID and AFLC in Hz

Summary of transient and steady-state system performance measuring variables of the proposed load frequency control of mini hydro power generation for sudden 0%, 20%, 50%, 60%, and 65% load power changes with PID controller and AFLC when steady-state Δf expressed in Hz values.

Table 5.2. Summary of transient and steady-state system performance for steady-state frequency deviation in Hz

Variation of Change in Load Power (ΔPL) in p.u	Rise time (sec.)	(+) Overshoot (%)	(-) Overshoot (%)	Steady-state frequency error (Hz)
ΔPL = 0.0 with PID	---	---	---	0.0
with AFLC	---	---	---	0.0
ΔPL = 0.2 with PID	97.882	0.735	12.508	0.00952
with AFLC	--	---	0.404	0.1816
ΔPL = 0.5 with PID	97.850	0.735	12.549	0.020905
with AFLC	--	---	2.632	0.19025
ΔPL = 0.6 with PID	100.530	0.733	12.394	0.044705
with AFLC	162.959	0.795	0.695	0.19205
ΔPL = 0.65 with PID	100.530	0.733	12.394	0.06385
with AFLC	133.105	-0.009	0.111	0.19315

The simulation result of system actual base frequency by using PID controller and AFLC when the actual output power generating capacity is 535.0904 KW at a sudden load power change of 0.0 KW occurred. Therefore, the value for step input function will become 0.0 p.u (i.e. for 0% load).

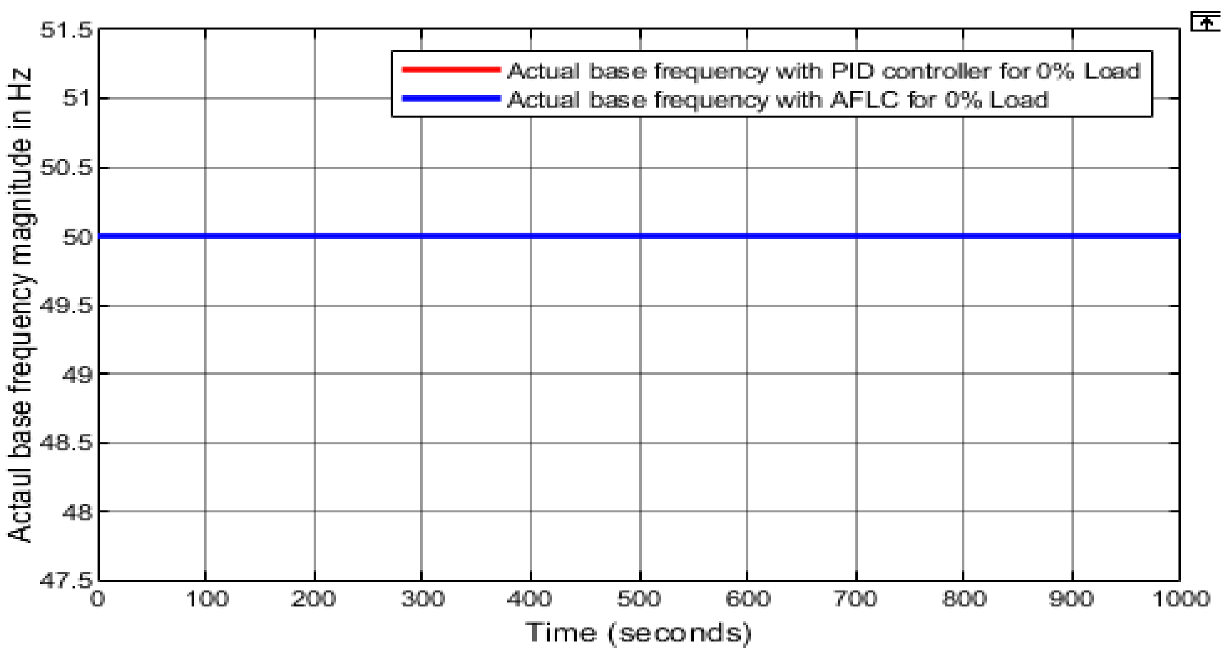


Figure 5.14. Simulation response of actual base frequency for 0% load with PID and AFLC in Hz

The simulation result of system actual base frequency by using PID controller and AFLC when the actual output power generating capacity is 535.0904 KW at a sudden load power change of 107.01808 KW occurred. Therefore, the value for step input function will become 0.2 p.u (i.e. for 20% load).

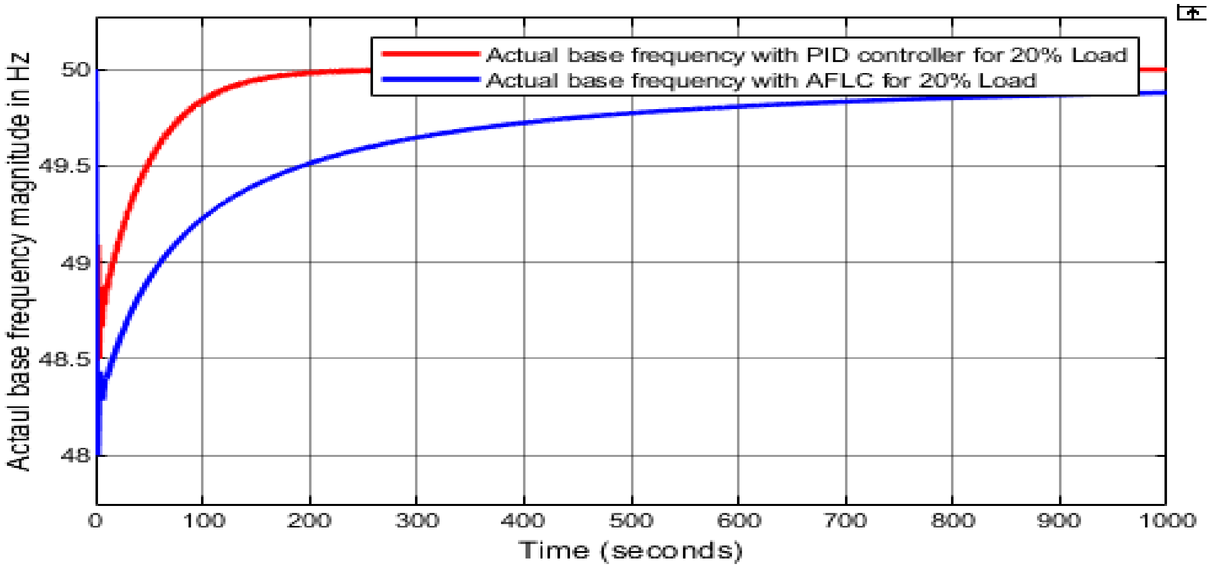


Figure 5.15. Simulation response of actual base frequency for 20% load with PID and AFLC in Hz

The simulation result of system actual base frequency by using PID controller and AFLC when the actual output power generating capacity is 535.0904 KW at a sudden load power change of 267.5452 KW occurred. Therefore, the value for step input function will become 0.5 p.u (i.e. for 50% load).

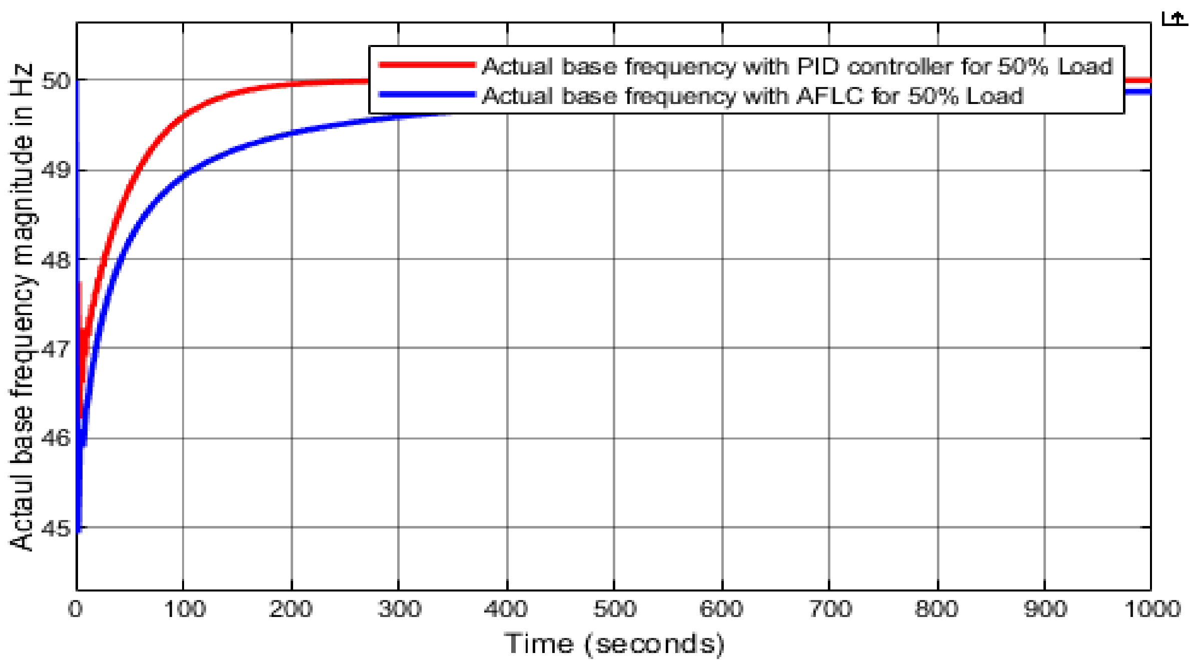


Figure 5.16. Simulation response of actual base frequency for 50% load with PID and AFLC in Hz

The simulation result of system actual base frequency by using PID controller and AFLC when the actual output power generating capacity is 535.0904 KW at a sudden load power change of 321.05424 KW occurred. Therefore, the value for step input function will become 0.6 p.u (i.e. for 60% load).

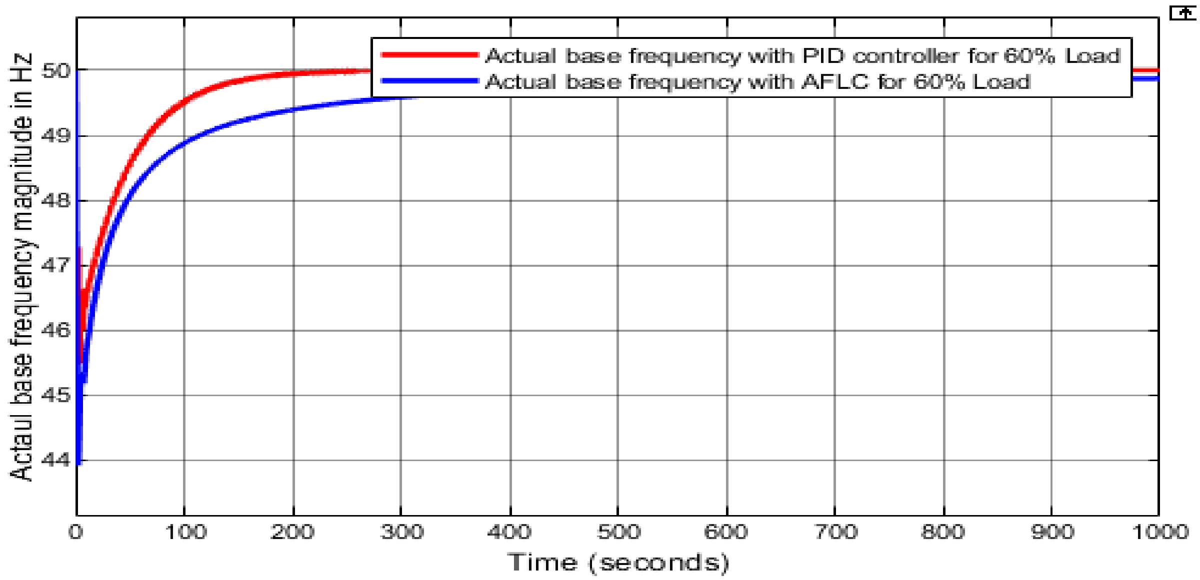


Figure 5.17. Simulation response of actual base frequency for 60% load with PID and AFLC in Hz

The simulation result of system actual base frequency by using PID controller and AFLC when the actual output power generating capacity is 535.0904 KW at a sudden load power change of 347.80876 KW occurred. Therefore, the value for step input function will become 0.65 p.u (i.e. for 65% load).

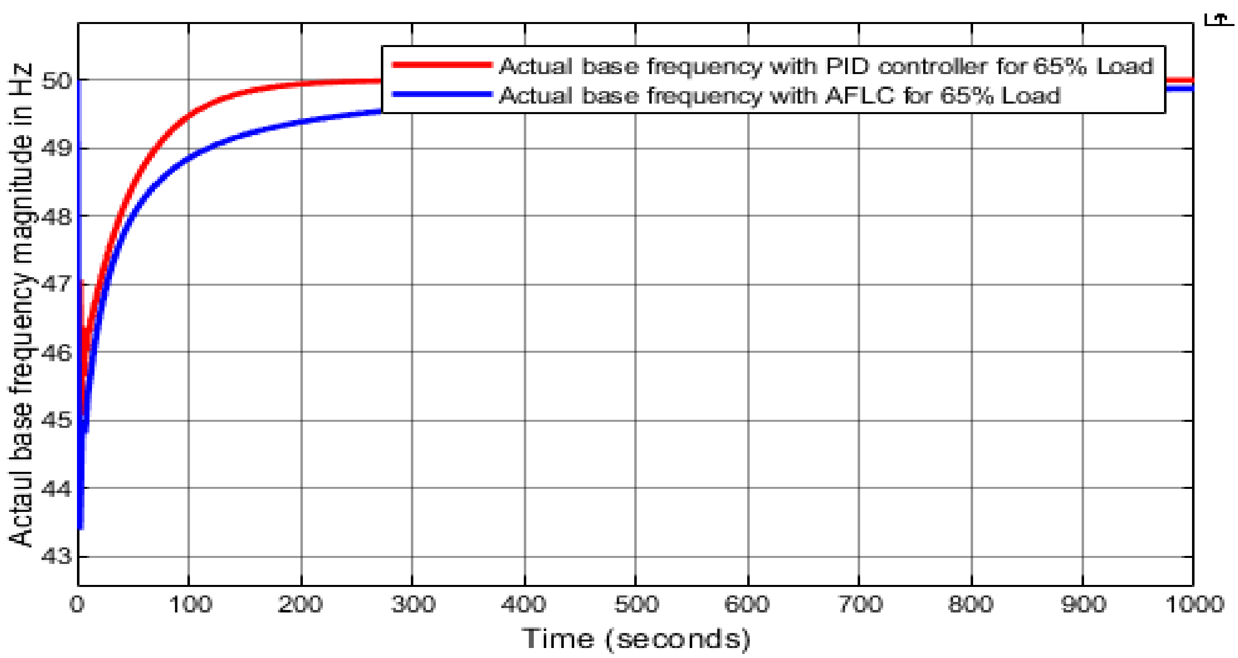


Figure 5.18. Simulation response of actual base frequency for 65% load with PID and AFLC in Hz

Summary of transient and steady-state system performance measuring variables of the proposed load frequency control of mini hydro power generation for sudden 0%, 20%, 50%, 60%, and 65% load power changes with PID controller and AFLC when system actual base frequency expressed in Hz.

Table 5.3. Summary of transient and steady-state system performance for actual base frequency in Hz

Variation of Change in Load Power (ΔPL) in p.u	Rise time (sec.)	(+) Overshoot (%)	(-) Overshoot (%)	Steady-state frequency error (p.u)	Actual base frequency (Hz)
ΔPL = 0.0 with PID	---	---	---	0	50.0
with AFLC	---	---	---	0	50.0
ΔPL = 0.2 with PID	97.882	0.735	12.508	0.0001904	49.99048
with AFLC	--	---	0.404	0.003632	49.8181
ΔPL = 0.5 with PID	97.850	0.735	12.549	0.0004181	49.979095
with AFLC	--	---	2.632	0.003805	49.80975
ΔPL = 0.6 with PID	100.530	0.733	12.394	0.0008941	49.955295
with AFLC	162.959	0.795	0.695	0.003841	49.80795
ΔPL = 0.65 with PID	100.530	0.733	12.394	0.001277	49.93615
with AFLC	133.105	-0.009	0.111	0.003863	49.80685

5.4. Discussion

The main goal of a control system is to get a better-desired output value by stable the system performance measuring variables and to minimize or diminish the steady-state frequency deviation between the reference set point given to the controller and the system actual output in the above, all MATLAB simulation results in the different graph at the different set point or different load power changes. As it was mentioned in the previous section the first objective of the tests performed on the MHPG was to analyze its system performance measuring variables for large load power changes as well as for small load power changes. As it can be seen from figure 5.4 to figure 5.18 and from table 5.1 to table 5.3, for any change in load power, the steady-state frequency deviation is very small or approaches to zero and the system actual base frequency is better nearest to the nominal base frequency in both PID controller and Adaptive fuzzy logic controller. But PID controller is poor system performance measuring variables than AFLC. So, the simulation results show that AFLC is more robust and better transient and steady-state response at very small overshoot, zero settling time, less fall time, very small steady-state frequency error, and obtain maximum actual base frequency nearest to the nominal frequency at various load conditions.

Therefore, the proposed adaptive fuzzy logic controller illustrates a good capability and effectiveness for load frequency control of mini hydro power generation systems in uncertain, nonlinear, complex, and higher-order systems by considering system performance measuring variables.

CHAPTER SIX

CONCLUSION, RECOMMENDATION AND FUTURE WORK

6.1. Introduction

In this chapter writing the conclusion from the result got and writing the recommendations and also future works about the mini hydro power generation in the remote rural area of Debre Zeit kebele area. MHPG is one of the earliest known renewable sources of energy has a significant role in the social-economic development of the countries. It has much importance due to its relatively low administrative and executive costs and short construction time compared to LHPG. The mathematical model of the MHPG system is the fundamental importance to understanding the physical system.

6.2. Conclusion

Many studies are using different control methods for load frequency control in literature. Considering the situation in our country Ethiopia where many villages still live without electricity especially, those in the remote rural areas, this thesis was aimed to develop a simple and cost-effective solution to bring basic energy services to the remote rural area of Debre Zeit kebele by using available hydro power resources of Chemoga river. The energy-related issues have been discussed and renewable sources of energy are introduced as an alternative solution to minimize the environmental effects of current sources of energy and achieve a cost-effective system configuration that is supposed to supply electricity to model the community of 720 households. This study is equipped with home appliances, a health care center, flour mills, a water pump for daily use, and primary school loads to improve the lifestyle of people living at Debre Zeit kebele area where electricity from the main grid has not reached yet. The proposed adaptive fuzzy logic controller was easily adapted to different load values to improve the output steady-state frequency deviation of MHPG system. The proposed controller can be used for load frequency control of mini hydro power generation with good transient and steady-state responses for different load conditions can be achieved by increasing the number of membership functions. The mathematical model and design of mini hydro power generation were developed and tested through simulation by using MATLAB/Simulink software.

It is observed from the MATLAB simulation results, the effects of system performance measuring variables by using PID controller are tested for different load variations of 0%, 20%, 50%, 60% and 65%, the rise time are 0 sec, 97.882 sec, 97.850 sec, 100.530 sec and 100.530 sec, the overshoot are 0%, 12.508%, 12.549%, 12.394% and 12.394%, and also the steady-state frequency error are 0 p.u, 0.0001904 p.u, 0.0004181 p.u, 0.0008941 p.u and 0.001277 p.u are obtained respectively. The effects of system performance measuring variables by using AFLC are tested for different load variations of 0%, 20%, 50%, 60% and 65%, the rise time are 0 sec, 0 sec, 0 sec, 162.959 sec and 133.105 sec, the overshoot are 0%, 0.404%, 2.632%, 0.695% and 0.111%, and also the steady-state frequency error are 0 p.u, 0.003632 p.u, 0.003805 p.u, 0.003841 p.u and 0.003863 p.u are obtained respectively.

When the change in load power increases, then the steady-state frequency deviation also increases as a result, the system actual base frequency will be decrease in very small values and vice versa in both convectional PID and intelligent adaptive fuzzy logic controllers.

Finally, I conclude that convectional PID controller is not suitable for system performance measuring variables, only considering the steady-state frequency error approaches to zero at various load changes, therefore, the proposed intelligent AFLC can be recommended to control the frequency of mini hydropower system by considering system performance measuring variables because, this controller is suitable for nonlinear, uncertain, complex and higher-order systems.

6.3. Recommendation

As it is shown in the simulation result discussion part, the designed intelligent adaptive fuzzy logic controller for load frequency control of mini hydro power generation unit has shown a better system performance measuring variable. In this thesis, the MHPG load frequency control system is modeled by assuming a linear hydraulic turbine model however, the performance of the plant can be investigated with a non-linear hydraulic turbine model. The controller can be modified to engage a genetic algorithm for further improvements in the performance of the large hydropower generation systems. This is already validated by MATLAB simulation only so, anyone can take this design and it can be implemented by prototypes in that area.

6.4. Future work

There are so many renewable sources of energy such as solar, wind, biogas, and water which may be relevant for remote rural electrification, only MHPG using AFLC is considered in this thesis. Therefore, as the future work, change the controller by integrating intelligent AFLC with linear quadratic regulator (LQR), sliding mode control (SMC), model predictive control (MPC), artificial neural fuzzy inference system (ANFS), artificial neural network (ANN), radial basis function neural network (RBFNN), probabilistic neural network (PNN) for further improvements in the system performance measuring variables of the large hydro power generation systems for large uncertain, large higher-order, more complex, more nonlinear and time-delay systems by considering control system stability.

The control system stability of hydro power system is depending on active power and reactive power, by considering frequency and voltage respectively at the admissible range, active power is controlled in this thesis, the mini hydropower system can be made more accurate and attractive by introducing voltage control in the excitation system for the future work. Moreover, this thesis presents a mini hydropower energy system only at the selected remote rural area but, other remote rural areas live without electric access. Therefore, as the future work, I suggest that somebody interested to see the feasibility of this mini hydropower system to forecast and implement for other remote rural areas in our country Ethiopia.

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APPENDIX

A.1. Stability

The tendency of a power system to develop restoring forces equal to or greater than the disturbing forces to maintain the state of equilibrium is known as stability. Every system has to pass through a transient stage for a small period before reaching a steady state. The stability problem is concerned with the behavior of a synchronous generator after a disturbance. For the convenience of analysis, stability problems are generally divided into two major categories; steady-state stability and transient stability. Steady-state stability refers to the ability of the power system to regain synchronism after small and slow disturbances, such as gradual power changes.

Transient stability deals with the effects of large, sudden disturbances such as the occurrence of a fault, the sudden outage of a line, or the sudden application or removal of loads.

Consider the block diagram of a simple closed-loop control system as shown in the figure A.1 where, $R(s)$ is the s-domain reference input, and $C(s)$ is the s-domain controlled output. $G(s)$ is the plant transfer function, K are a simple gain controller and the feedback elements $H(s)$ represent the sensor transfer function.

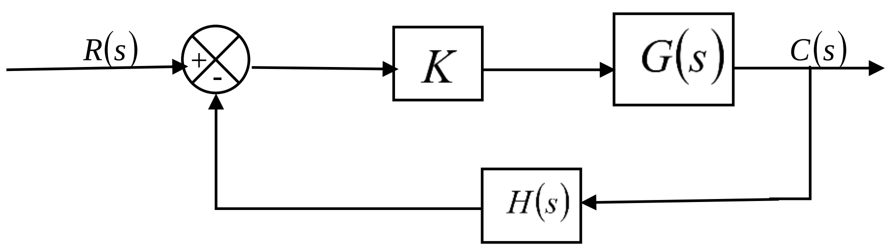

Figure A.1. Block diagram of a simple closed-loop control system

The closed-loop transfer function is,

$$\frac{C(s)}{R(s)} = T(s) = \frac{KG(s)}{1 + KG(s)H(s)} \tag{A.1}$$

or the s-domain response is

$$C(s) = T(s)R(s) \tag{A.2}$$

The gain $KG(s)H(s)$ is commonly referred to as the open-loop transfer function. For a system to be unstable, it must be stable. A linear time-invariant system is stable if every bounded input produces a bounded output. We call this characteristic stability.

The denominator polynomial of the closed-loop transfer function set equal to zero is the system characteristic equation. That is, the characteristic equation is given by

$$1 + KG(s)H(s) = 0 \tag{A.3}$$

The roots of the characteristic equation are known as the poles of the closed-loop transfer function. The response is bounded if the poles of the closed-loop system are in the left-hand portion of the s-plane. Thus, a necessary and sufficient condition for a feedback system to be stable is that all the poles of the system transfer function have negative real parts. The stability of a linear time-invariant system may be checked by using the Control System Toolbox function **impulse** to obtain the impulse response of the system. The system is stable if its impulse response approaches zero as the time approaches to infinity. One way to determine the stability of a system is by simulation. The function **lsim** can be used to observe the output for typical inputs. This is particularly useful for nonlinear systems. Alternatively, the MATLAB function **roots** can be utilized to obtain the roots of the characteristic equations. In the classical control theory, several techniques have been developed requiring little computation for stability analysis. One of these techniques is the Routh-Hurwitz criterion. Consideration of the degree of stability of a system often provides valuable information about its behavior. That is if it is stable, how close is it to being unstable? This is the concept of relative stability. Usually, relative stability is expressed in terms of speed response and overshoot. Other methods frequently used for stability studies are the Bode diagram, Root-locus plot, Nyquist criterion, and Lyapunov's stability criterion.

A.1.1. The Routh-Hurwitz stability criterion

The Routh-Hurwitz stability criterion provides a quick method for determining absolute stability that can be applied to an n^{th} order characteristic equation of the form

$$a_n s^n + a_{n-1} s^{n-1} + \ldots + a_1 s + a_0 = 0 \tag{A.4}$$

The criterion is applied through the use of a Routh-Hurwitz table defined as

s^n	a_n	a_{n-2}	a_{n-4}	$\cdots$
s^{n-1}	a_{n-1}	a_{n-3}	a_{n-5}	$\cdots$
s^{n-2}	b_1	b_2	b_3	$\cdots$
s^{n-3}	c_1	c_2	c_3	$\cdots$
$\cdots$	$\cdots$	$\cdots$	$\cdots$	$\cdots$

$a_n, a_{n-1}, \ldots, a_1, a_0$ are the coefficients of the characteristic equation and

$$b_1 = \frac{a_{n-1}a_{n-2} - a_n a_{n-3}}{a_{n-1}}, \quad b_2 = \frac{a_{n-1}a_{n-4} - a_n a_{n-5}}{a_{n-1}}, \text{ etc.}$$

$$c_1 = \frac{b_1 a_{n-3} - a_{n-1} b_2}{b_1}, \quad c_2 = \frac{b_1 a_{n-5} - a_{n-1} b_3}{b_1}, \text{ etc.}$$

Calculations in each row are continued until only zero elements remain. The necessary and sufficient condition that all roots of (A.4) lie in the left half of the s-plane is that the elements of the first column of the Routh-Hurwitz array have the same sign. If there are changes of signs in the elements of the first column, the number of sign changes indicates the number of roots with positive real parts.

A function called **routh(a)** is written that forms the Routh-Hurwitz array and determines if any roots have positive real parts. **a** is a row vector containing the coefficients of the characteristic equation. If the first element in a row is zero, it is replaced by a very small positive number ε, and the calculation of the array is completed. If all elements in a row are zero, the system has poles on the imaginary axis, pairs of complex conjugate roots forming symmetry about the origin of the s-plane, or pairs of real roots with opposite signs. In this case, an auxiliary equation is formed from the preceding row. The all-zero row is then replaced with coefficients obtained by differentiating the auxiliary equation.