Addis Ababa University

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

DESIGN AND SIMULATION OF FUZZY LOGY BASED FREQUENCY CONTROLLER FOR STANDALONE MICRO HYDRO POWER PLANT

A Thesis Submitted to the School of Graduate Studies, Addis Ababa Institute of Technology in Partial Fulfillment of the Requirements for the Degree of Master of Science in Electrical and Computer Engineering (Control Engineering)

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DECLARATION

I, the undersigned declare that this thesis is my original work, and has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged.

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Addis Ababa, Ethiopia MAY 30, 2017

Place Date of submission

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

Dr. Mengesha Mamo ______________

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ABSTRACT

Despite a long history of micro hydropower in Ethiopia, locally manufactured low cost frequency controllers are not well developed and are not available off-the-shelf in local market. The frequencies of micro hydropower plants are controlled by electronic load controllers. Unfortunately, these governors have harmonic effect on the system, waste more amounts of water and energy during low power demand.

In this thesis, simple, less cost and fast response fuzzy logic based frequency control system is modeled, designed and simulated. The frequency controller controls flow rate of water by acting on electric valves and keep the frequency of the micro hydropower system nearly constant. In addition to this when flow rate is minimum, the controller designed to prevent component from damage by isolating loads from the system. It is observed from the simulation results that the average overshoot for 35% load change is 0.9% and the settling time is 26.85 seconds. Moreover, even for 75% load change, overshoot is only 3.04% and the settling time is 27.65 seconds. It is further observed that energy wasted on the valve is always around zero at steady state conditions. In addition the proposed controller is less expensive, which cost 10-20 USD than ELC which cost 70-120 USD per kilo watt. Generally both the transient and steady state performances are improved with fuzzy controller and the controller works efficiently under all operating conditions. Therefore, this controller can play crucial role for low cost micro hydro power plant development in rural part of Ethiopia.

Key Words: Micro Hydropower, Fuzzy Logic Controller, Rural Electrification

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LIST OF SYMBOLS

f	Frequency
P_o	Number of poles
P_m	Mechanical Power
P_{th}	Theoretical output power
P_{act}	Actual output power
$P_{hydraulic}$	Hydraulic Potential
e	efficiency factor
g	Force of Gravity
T_w	Water starting time
ΔP_m	Change in mechanical power
ΔG_t	Change in gate position
V	Water velocity
a_g	Acceleration
V’	Volume Flow in (m^3/s)
P	Density in (kg/m^3)
Q	Flow Rate
G_t	Gate position
H_d	Hydraulic head
A	Pipe Area
L	Length of Conduit
G_{t0}	Initial gate position
Q_o	Initial Flow Rate
H_{d0}	Initial Hydraulic head
V_o	Initial Water velocity
ω_o	Initial Rated angular velocity
P_{m0}	Initial Mechanical Power
T_m	Mechanical torque

T_e	Electrical torque
K_u	a Constant of Proportionality
t	Time in Second
H	Inertia constant
G	Machine Rating
P_e	Electrical power generated
$\overline{P}_e$	Per unit electrical power generated
$\overline{w}_r$	Per unit angular velocity
δ	Angular position of the rotor
$\Delta\overline{w}_r$	Per unit change in rotor speed
$\Delta\overline{G}$	Per unit change in gate position
$\Delta\overline{P}_e$	per unit change in electrical load power
$\Delta\overline{P_D}$	Per unit change in demand power
D	Load damping constant
Δf	Change in frequency
$\Delta\overline{\omega}_r$	Per unit change in rotor speed
$\Delta\overline{G}_t$	Per unit change in gate position
$\Delta\overline{H}_d$	Per unit change in Hydraulic head
$\Delta\overline{Q}$	Per unit change in flow rate
$\Delta\overline{P}_D$	Per unit change in demand power
$\Delta\overline{P}_m$	Per unit change in mechanical power
$\Delta\omega_r$	Change in rotor speed
ΔG_t	Change in gate position
ΔH_d	Change in Hydraulic head
ΔQ	Change in flow rate
ΔP_D	Change in demand power
ΔP_m	Change in mechanical power
KE	Kinetic Energy
J	Rotor Moment of Inertia
M	Moment of Inertia in MJ-s

LIST OF ABBREVIATIONS

NVS	Negative very small
NS	Negative small
NM	Negative medium
NL	Negative large
ZR	Zero
PVS	Positive very small
PS	Positive small
PM	Positive medium
PL	Positive large
V_{CO1}	Normally closed valve one
V_{CO2}	Normally closed valve two
V_{CO3}	Normally closed valve three
V_{CO4}	Normally closed valve four
V_{NO1}	Normally open valve one
V_{NO2}	Normally open valve two
V_{NO3}	Normally open valve three
V_{NO4}	Normally open valve four
FLC	Fuzzy Logic Controller
P.U	Per Unit
ELC	Electronic Load Controller
MHPP	Micro Hydro Power Plant
PI	Proportional Integral
EEP	Ethiopian Electric Power

CHAPTER 1

INTRODCTION

1.1 Background

Energy is a fundamental thing for society and economic growth of any country. The availability of energy system adds value to the lives of people in a society. It also allows a range of productive tasks that would not otherwise be possible. In developing countries lack of energy is often a constraint that holds people back from achieving a better life-style. For economic solvency, upgrading the standard of living and to support industrialization, energy is an essential need of developing countries like Ethiopia.

Energy generation involves both non-renewable and renewable energy sources. However, renewable energy is becoming more and more popular as it is a sustainable and environmentally friendly source of energy. In Ethiopia, available renewable energy resources are solar energy, wind power, biomass, geothermal and hydro power plants. Among them, hydro power is main resources for power generation. Ethiopia has a vast hydropower potential, which is estimated to be about 15,000 - 30,000 MW. So far very little percentage (less than 2%) of the vast potential has been harnessed, which is insufficient for fulfilling the increasing power demand now as well as in the future, and also a major barrier for foreign investment [1]. Moreover, a huge portion of the total population of our country still does not have the access to electricity. This is because, extension of the central electricity grid to such areas is either financially not viable or practically not feasible as these locations are geographically isolated, sparsely populated and have a very low power demand and insufficient EEP's power supply [1]. To overcome this problem using micro hydro energy resources is an appropriate choice for rural electrification where supplying grid electricity is not economical [1].

Hydropower plant is classified as large, medium, small, mini and micro according to their installed power generation capacity. Micro-hydro power plant (MHPP) was one of the earliest small scale renewable energy technologies to be developed and is still an important source of energy today [2]. Generation capacity of micro hydropower plants ranges from 0.2KW to 100KW and are thought to be ideal renewable resources to electrify isolated rural communities, particularly in developing countries [3]. Many micro-hydropower systems operate "run off river," which means that neither a large dam or water storage reservoir is built nor is land flooded. Only a fraction of the available stream flow at a given time is used to generate power and it has little environmental impact. The main problem in generating power from micro hydro power plant is to control power produced by the system. Large-scale hydro systems use mechanical governor that control the flow of water through the turbine to match the power produced to the demand from the grid. Mechanical control system is difficult to scale down and smaller versions tend to be as expensive as the larger ones, because the cost per kW rises sharply as the size is reduced.

1.2 Statement of the Problem

In order to prevent damage to the generator and loads connected with micro hydro power plant the frequency of output power must be constant. Therefore, load connected with MHPP or flow rate of water needs to be controlled to get an uninterrupted power at rated frequency. One of the challenges in developing micro hydropower plants is associated with developing low cost frequency controller, which can maintain an uninterrupted power at rated frequency. Since significant water resources are found in the rural areas, the frequency control system is intended to be cost-effective so that isolated rural communities can afford to develop their own micro hydropower plants [4]. Moreover, the frequency control system is expected to be less complex, which can be operated and maintained easily.

Large-scale hydro systems use mechanical governors that control the flow of water through the turbines to match the power produced to the demand from the grid. The frequency can be maintained constant by changing the gate opening position, thus by adjusting the water flow with mechanical governors to produce just the necessary power according to the load demand. These mechanical control systems are difficult to scale down and smaller versions tend to be as expensive as the larger ones so the cost per kW rises sharply as the size is reduced. In addition to this, they are complex and slow in response. Furthermore, electro-mechanical systems are produced, but these are still relatively expensive for micro hydro power systems. On the other hand, the electronic load controllers control the turbine speed by adjusting the electrical load on the generator. Thus, they maintain a constant electrical load on the generator in spite of changing user loads. Electronic load controllers are not expensive like electro-mechanical governor, but surplus electric power burned off on dump loads usually (resistance heater) and the peak or surge loads cannot exceed the output of the generator, which is determined by the steam available head and flow. This type of system needs to be large to meet peak electrical loads so it can often generate enough energy for all household needs, including dump load. Moreover, this controlling mechanism has harmonic effect because of heat resistor, and the life time of the component on the system is also affected since they are always running even though there is no customer load connected with the system.

Despite a long history of micro hydropower in Ethiopia, locally manufactured frequency controllers are not well developed and are not available off-the-shelf in local market. Therefore the objective of this thesis is to model, design and simulate a less expensive, less complex and fast frequency control system for standalone micro hydropower plants using electric valves. Thus, electric valves have different size and the numbers of valves used for different MHPP with different energy production capacity are different; more numbers of valves are used for MHPP with large energy production capacity.

The frequency controller controls flow rate of water by acting on this electric valves so that the flow of water and load connected to the system vary; consequently, keeping the frequency of the micro hydropower system nearly constant. Since the amount of power produce depend on number of electric valve used, it can handle all ranges of micro hydropower plants and also different ranges of loadings. In addition to this, when the flow rate of water is minimum and maximum customer loads are added, the controller is designed to prevent the components from damage because of frequency variation. Moreover, the proposed controller is less expensive compared with electric load controller since the controlling device (ELC) used for electric load controller is more expensive, than controlling devise that used in the proposed thesis.

1.3 Objectives of the Thesis

The general objective of this thesis is to model, design and simulate fuzzy logic based frequency controller for standalone micro hydropower plant. It is achieved by meeting the following specific objectives, and the specific objectives of the thesis are.

I. To model standalone micro hydropower plant for frequency control
II. To model electric valve for standalone MHPP
III. To design electric valve for standalone MHPP.
VI. To design a fuzzy controller and simulate on mat lab Simulink.

1.4 Methodology

The overall goal of this thesis is to electrify villages in remote areas of Ethiopia which are far-off from the existing national grid with reasonable cost. Different task are performed to accomplish the goal of this thesis. The statement of the problem was described and the objectives of the thesis was defined followed by reviewing literatures related to frequency control of MHPP systems and adopting different concepts and methodologies as required. A brief description on the fuzzy logic controller is also presented. Then MHPP mathematical modeling is described in detail. This is followed by the design of electric valve. Next, rule base is developed for fuzzy logic controller and rule tables are constructed with the development of membership functions for fuzzy logic controller. Using the rule base and membership functions a fuzzy logic controller is designed for both flow control and load control. Simulation studies are carried out for variable load and variable flow rate to show the advantages of the proposed fuzzy logic frequency controller compared to the mechanical frequency controller and electrical load controller. Finally the conclusion based on the thesis findings is presented.

1.5 Thesis Outline

This thesis is mainly divided into five chapters. The first chapter presents the introduction, statement of the problem, objectives, literature reviews and methodology of the thesis.

A general overview of micro hydropower plant and its development in Ethiopia is presented in chapter 2. This chapter also includes the detailed model of a micro hydropower plant. Modelling of the synchronous generator, turbine and electric valve are described in this chapter.

Chapter 3 deals with design of electromagnetic valve and design of fuzzy logic controller. The selection of membership functions and the construction of rule tables for fuzzy logic controller are presented in this chapter.

In chapter 4, the simulation results obtained using Matlab-Simulink and discussions of the results are presented. Chapter 5 includes the overall conclusion of the thesis work, recommendations and suggestions for future work.

CHAPTER 2

LITERATURE REVIEWS

2.1 Introduction

Micro-hydro power plant generation, development of micro hydropower in Ethiopia as well as classification of micro-hydropower plant based on different criteria is presented in this chapter. In addition to this, the principal components of MHPP, frequency control systems of MHPP and detailed model of a micro hydropower plant are discussed in this chapter.

2.2 Micro-Hydro Power Plant

A micro-hydropower system is a small system in the range of 0.2-100 KW, which can be used for small factories and to supply an independent local mini-grid [1]. The simplest micro-hydropower plant is based 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. These small units have been used for many years, especially for their mechanical power, but recent increases in the value of electrical energy and incentive programs have made the construction and development of micro-hydro power plants much more attractive. 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, micro hydropower plants are the best options for electrification [4]. Except their power rating, micro hydropower plants are not different from large or small hydro systems. For example, the principles of operation, types of material units, and the mathematical equations used in selection and design of system components are essentially the same as conventional/large hydro power plants [5].

The topography of Ethiopia, with mountainous areas coupled with numerous rivers and streams makes MHPP development suitable. The total potential for micro hydropower (of size less 100 kW) is estimated to be 100 MW. 85 % of Ethiopia’s population is living in rural areas while only 10 out of 100 households (HHs) have access to electricity. Extending the national grid to isolated rural communities seems technically and economically not feasible. Due to this, micro hydropower plants could play an important role to electrify off-grid rural areas [1].

2.3 Principal Components of Micro-Hydropower Plant

The principal components of MHPP can be grouped into civil work components and electromechanical components, as shown in Figure 2.1 below. Each component is further classified into different parts which are presented in detail in the following subsections.

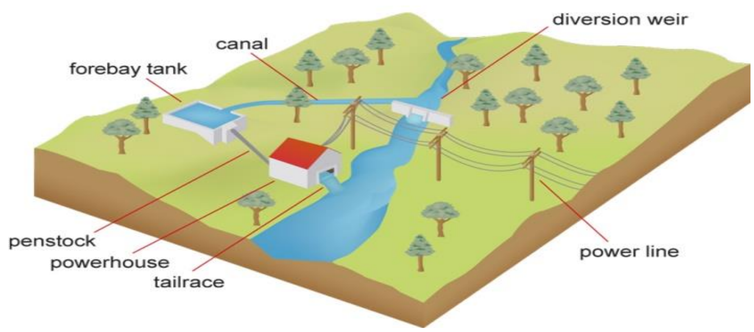


Figure 2.1: Typical layout of micro hydropower system [6]

2.3.1 Civil Work Components

This section describes the most common civil work components such as the intake, headrace canal, de- Sanding basin, spillway, forebay tank, penstock and tailrace of a typical MHPP [6].

Intake

Intake is the primary means of conveyance of water from the source of water in required quantity towards the waterways of MHPP [7]. Intake could be of side intake type or the bottom intake type. Usually, trash racks have to be placed at the intake which acts as the filter to prevent large water born objects to enter the waterway of the MHPP [8].

Headrace Canal

Once the water enters through the intake, the headrace canal conveys the water to the forebay. Sometimes, pipes can also be used in place of the canals. The materials to be used in constructing the canal depends upon the geographical condition of the site and other obvious factors such as the availability of labor and materials. Most usual types of canal are built from combination of cement and mortar, only soil, mixture of stone and mud, mixture of stone masonry with cement and other different types of possible combinations [9]. When pipes are used, they are generally of HDPE (High Density Polythene) types. The length of the headrace canal can be anywhere from few meters to over a kilometer long. The most important thing to consider while constructing head race canal is to make the slope of the canal only slightly elevated because higher slope can lead to higher velocity of water which can then cause erosion in the headrace canal surface.

Settling Basin

In order to reduce the sediment density, which has negative impact to other components of the MHPP de-sanding basins are used to capture sediments by letting the particles settle by reducing the speed of the water and clearing them out before they enter the canal. Therefore, they are usually built at the head of the canal. They are equipped with gate valves for flushing the settled undesirable sediments. De sanding basin is capable of settling particles above 0.2-0.3 mm of size [10]. Figure 2.2 shows the typical de-sanding basin.

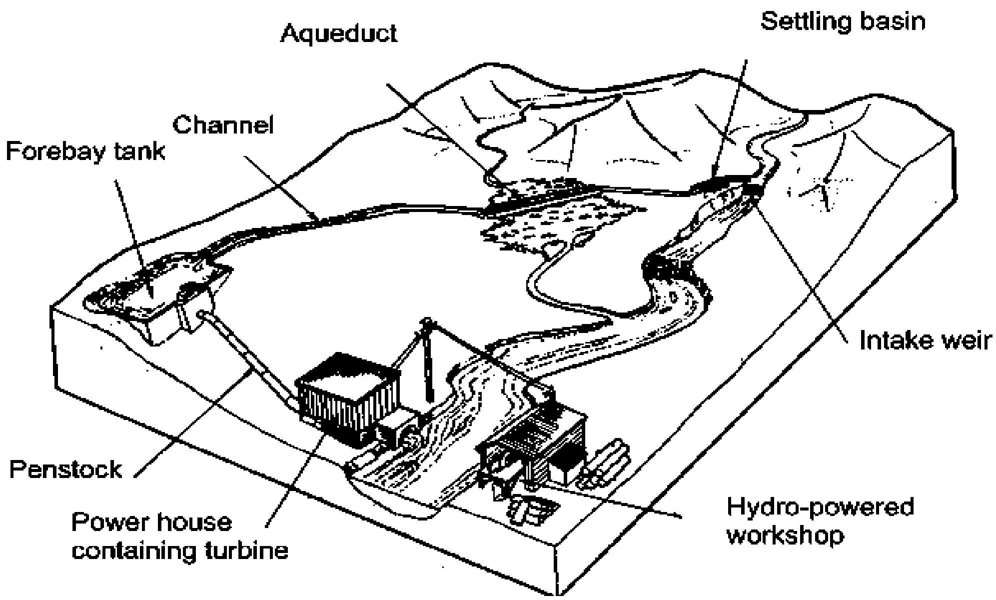


Figure 2.2: a Typical de-sanding basin[10]

Spillway

Spillways need to be designed to remove the excess water due to floods, in order to minimize the adverse effects to the other components of the MHPP. Spillways are often constructed in de-sanding basin and the forebay, from which the excess water is safely diverted to the water source.

Forebay Tank

Forebay tank is basically a pool at the end of headrace canal from which the penstock pipe draws the water. The main purpose of the forebay is to reduce entry of air into the penstock pipe, which in turn could cause cavitation (explosion of the trapped air bublles under high pressure) of both penstock pipes and the turbine [12]. It is also necessary to determine the water level at the forebay because operational head of the micro hydro power plant is determined through this factor. A forebay again requires two sets of additional construction. As the water speed is lowered at the forebay, it can cause sedimentation of particles, which requires the construction of spillway. Similarly, installation of trash racks to filter the fine sediments might be required before the water from the forebay gets inside the penstock pipes. Figure 2.3 illustrates a typical forebay tank in MHPP.

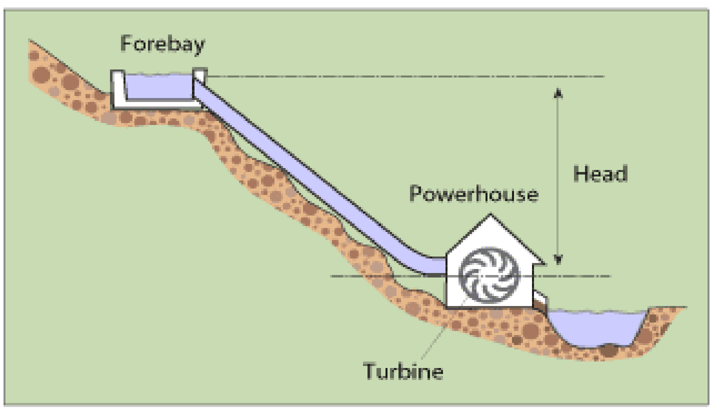


Figure 2.3: Design of a typical forebay in MHPP[13]

Penstock pipes

Penstock pipes are basically close conduct pipes that helps to convey the water from the forebay tank to the turbine. The materials used in penstock are usually steel, HDPE (High Density Polythene) and increasingly PVC (Poly Vinyl Chlo-ride). It is one of the most important components of the MHPP because it is at this point that the potential energy of the water is converted into kinetic energy. The velocity of water at the penstock is typically 3m/s and is often located at a slope over 45 degrees [13]. Due to the risk of contraction and expansion of penstock pipes due to fluctuation in seasonal temperature, sliding type of expansion joints are placed between two consecutive pipe lengths. Anchor block, which is basically a mass of concrete fixed into the ground, is used to restrain the penstock from movement in undesirable directions. Figure 2.4 shows the configuration of penstock pipes in typical MHPP [9].

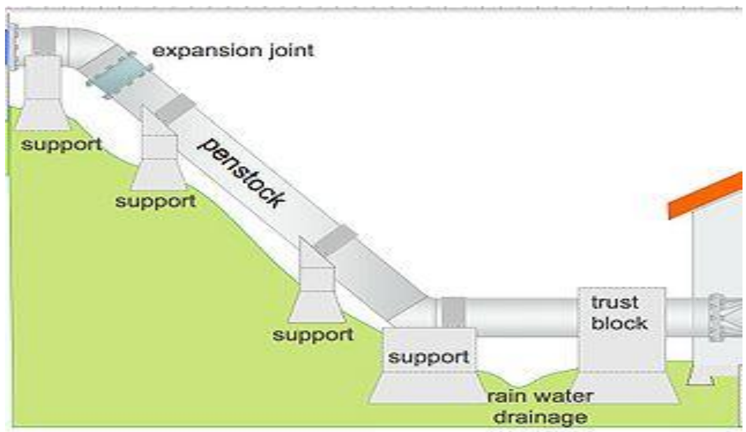


Figure 2.4: Components of the penstock assembly[9]

Tailrace

Tailrace is very similar to headrace canal described previously in this section. The only difference with that of the headrace canal is that it is situated at the end of the civil components and is used to convey the water back to the source after use in the micro hydro plant.

2.3.2 Electro Mechanical Components

Electro Mechanical Components are the powerhouse components of Micro-Hydropower and they are used to convert mechanical energy of water into electrical energy. The principal electro mechanical components of a micro hydro plant are the turbine, valve, generator and drive systems.

Turbines

In a MHPP hydraulic turbine is the primary component which converts the energy of the flowing water into mechanical energy through the rotation of the runner**.** Turbines can be classified as high head, medium head or low head machines based on the head under which it operates. They are also typified by the operating principle and can be either impulse or reaction turbines. The basic turbine classification is given in the Table 2.1[14].

Table 2.1: Group of turbines [14]

Turbine Runner	High Head (more than 100m/325ft)	Medium Head (20- 100m/60-325ft)	Low Head (5- 20m /16- 60ft)	Ultra Low Head (less than 5 /16ft)
Impulse	Pelton Turgo	Cross flow Turgo Multi Jet Pelton	Cross flow Multi-Jet Pelton	Water Wheel
Reaction	_	Francis Pump-as-turbine	Propeller Kaplan	Propeller Kaplan

The rotating part (called 'runner') of a reaction turbine is completely submerged in water and is enclosed in a pressure casing. The runner blades are designed in a manner such that the pressure difference across their surface imposes lift forces (similar to the principle used for airplane wings), which cause the runner to turn/rotate. The impulse turbine (as the name suggests) on the other hand is never immersed in water, but operates in air, driven by a jet (or jets) of water striking its blades. The nozzle of the penstock converts the head of the water (from forebay tank) into a high speed jet that hits the turbine runner blades that deflect the jet so as to utilize the change of momentum of the water and converting this as the force on the blades – enabling it to rotate. Impulse turbines are usually cheaper than reaction turbines because there is no need for a pressure casing or for carefully engineering clearances, but they are also only suitable for relatively higher heads [15].

Selection of an appropriate turbine to a large extent is dependent upon the available water head and to a lesser extent on the available flow rate. All turbines have a power-speed characteristic. This means they will operate most efficiently at a particular speed, head and flow combination. Thus the desired running speed of the generator or the devices being connected/ loading on the turbine also influence selection [15]. There are many varieties of turbine, each with its own benefits and drawbacks. However, hydraulic turbines are divided according to their hydraulic action into two main classes: impulse turbines and reaction turbines. Impulse turbines are generally not well suited for Pico or micro hydropower plants due to their more complex structural requirements and their complexity [16]. Cross flow turbine is a reaction turbine unlike impulse turbines, which is versatile and relatively simple to design. In addition, the cross flow design is suitable for a wide range of heads and power ratings, since one proper and reliable design of a cross-flow turbine can relatively simply be altered, only by changing the diameter and the width of the runner, to adjust it to different site characteristics (namely different head and flow characteristics) [17]. Under the given conditions in Ethiopia which mostly provide low to high heads, cross flow, pelton and to some extent francis turbines are most suitable because they are tolerant of sand and other particles in the water, they allow better access to working parts, they are easier to fabricate and maintain; cross flow turbines up to about 250kW can be fabricated locally, and they are usually cheaper than reaction turbines because pressure casing and carefully engineered clearances are not needed. In addition to this, they are less subject to cavitation, although at high heads, high velocities can cause cavitation in nozzles or on the blades or buckets and they offer flatter efficiency curves, especially if additional flow control devices are built in like, for example, variable cross section nozzles, spear valves, guide vanes, and devices to vary the number of jets or partition the flow [18].

Compared to pelton turbines, which generally require casting facilities, cross flow turbines merely require simple fabrication techniques. Considering these advantage, the cross flow turbine is the most suitable for MHPP in Ethiopia where the rural community need low cost of installation and maintenance [19].

Generator

There are basically two types of generators in use for hydroelectricity generation; either synchronous or induction generators. Synchronous generators are the primary types of generators which are used extensively in large scale power generation. When the power output levels are generally low (less than10 MW), induction generators are extensively used. Induction generators are also the preferred type of generators in MHPP because they can operate at variable speeds with constant frequency, are available cheaply and requires less maintenance than the synchronous generators. However, Synchronous generators are used in most MHPP because it has the ability to establish its own operating voltage and maintain frequency while it is operating in a remote location. Both of these generators have the possibility to be used connected to the grid or just standalone operation [20].

Drive Systems

The main purpose of the drive systems is to transmit the power from turbine to the generators at a stable voltage and frequency at a required direction and speed. Like any normal drive systems, in a MHPP also, drive systems comprise of generator shaft, turbine shaft, bearings, couplings, gearboxes, belts and pulleys. The different types of drive systems common in MHPP are direct drive, "V" or wedge belts and pulleys, timing belt and sprocket pulley and gearbox drive systems. A direct drive system is one in which the turbine shaft is connected directly to the generator shaft. In contrast, "V" or wedge belts and pulleys are the most commonly used type of drive systems in MHPP. However, in very small systems (less than 3 kW) where efficiency is critical, timing belt and sprocket pulley are commonly used. Gearboxes are suitable in large machine where drive belts are not efficient. Due to high maintenance and alignment costs of gearboxes, they are less frequently used in MHPP.

2.4 Design Parameters of Micro Hydro Power Plant

The first step in designing MHPP is to evaluate the water resource by measuring the head and flow of the stream. These two measurements are necessary to determine the power output of MHPP. Pipe line size, turbine type, rotational speed and generator size are determined after head and flow are measured. Nothing can be done until measuring head and flow.

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. Altimeter is used to calculate the "head" during the field survey [21]. Flow is defined as the quantity of water flowing past a point at a given time. There are several methods available to measure water flow rate such as salt dilution method, bucket method and weir method. However, in mountainous region salt-dilution method of determining the flow is the most common one [21].

With net head and flow rate measurement, one can determine the power output of steam engine. The theoretical amount of power available from a micro hydropower system is directly related to the flow rate (Q), head (H) and the force of gravity (g) as given below [22].

$$P_{th} = Q * H * g \tag{2.1}$$

To calculate the actual power output (P_{act}) from micro-hydro power plant, it is required to consider friction losses in the penstock pipes and the efficiency of the turbine and generator. Typically overall efficiencies for electrical generating systems can vary from 50 to 70 % with higher overall efficiencies occurring in high head systems. Therefore, to determine a realistic power output the theoretical power must be multiplied by an efficiency factor of 0.5 to 0.7 depending on the capacity and type of system as given below [22].

$$P_{act} = Q * H_d * g * e \tag{2.2}$$

Where e = efficiency factor (0.5 to 0.7).

$$P_{Hydraulic} = V' * \rho * g * H_d \tag{2.3}$$

Where $P_{Hydraulic}$ = hydraulic potential in [W]

V' = volume flow in [m^3/s]

ρ = density [kg/m^3]

g = gravitational constant: 9.8 [m/s^2]

H_d = head in [m]

2.5 Control Systems of Micro Hydropower Plants

Like large hydropower plant, due to continuous variation in load demand and the presence of deferent types of loads with different characteristics, the voltage and frequency of micro hydropower systems may not be constant. Therefore, similar to that of large power plants, the voltages and frequency of micro hydropower plants should be kept at scheduled values. To keep these parameters at the scheduled values, the micro hydropower plants should be controlled. In a power system, usually, voltage and frequency are controlled separately. Voltage is maintained by control of reactive power of the synchronous generator with the voltage regulator built-in in most of these synchronous generators while frequency is maintained by balancing generation and demand, i.e. by balancing generation and demand of active power. The balance between generation and demand is achieved in two different ways [23].

3.5.1 Automatic Generation Control

Automatic generation control systems can be classified as mechanical-hydraulic governors, electro hydraulic governors and mechanical governors. Mechanical hydraulic governors are sophisticated devices which are generally used in large hydro power systems. They require heavy maintenance and are expensive to install, because of this using it for micro hydro power plants is uneconomical. Electro hydraulic governors are complex devices needing precision design and they are also expensive. 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. Hence conventional controllers are not ideally suited for controlling MHPP because of their cost and complexity [24].

3.5.2 Automatic Load Control

Generally, electrical loads change randomly as a result of which frequency of the system is changed randomly. It is possible to compensate the change in the electrical load, consequently the change in frequency using ballast loads [25].

2.6 Types of Controller

3.6.1 Proportional Controller

Proportional controller is mostly used in first order processes with single energy storage to stabilize the unstable process. The main usage of the P controller is to decrease the steady state error of the system. As the proportional gain factor K increases, the steady state error of the system decreases. However, despite the reduction, P control can never manage to eliminate the steady state error of the system. As we increase the proportional gain, it provides smaller amplitude and phase margin, faster dynamics satisfying wider frequency band and larger sensitivity to the noise. We can use this controller only when our system is tolerable to a constant steady state error. In addition, applying P controller decreases the rise time and after a certain value of reduction on the steady state error, increasing K only leads to overshoot of the system response. P control also causes oscillation if sufficiently aggressive in the presence of lags and/or dead time. The more lags (higher order), the more problem it leads. Plus, it directly amplifies process noise [26].

3.6.2 P-I Controller

P-I controller is mainly used to eliminate the steady state error resulting from P controller. However, in terms of the speed of the response and overall stability of the system, it has a negative impact. This controller is mostly used in areas where speed of the system is not an issue. Since P-I controller has no ability to predict the future errors of the system it cannot decrease the rise time and eliminate the oscillations. If applied, any amount of I guarantees set point overshoot [26].

3.6.3 P-D Controller

The aim of using P-D controller is to increase the stability of the system by improving control since it has an ability to predict the future error of the system response. In order to avoid effects of the sudden change in the value of the error signal, the derivative is taken from the output response of the system variable instead of the error signal. Therefore, D mode is designed to be proportional to the change of the output variable to prevent the sudden changes occurring in the control output resulting from sudden changes in the error signal. In addition, D directly amplifies process noise therefore D-only control is not used [26].

3.6.4 P-I-D Controller

P-I-D controller has the optimum control dynamics including zero steady state error, fast response (short rise time), no oscillations and higher stability. The necessity of using a derivative gain component in addition to the PI controller is to eliminate the overshoot and the oscillations occurring in the output response of the system. One of the main advantages of the P-I-D controller is that it can be used with higher order processes including more than single energy storage [26].

3.6.5 Fuzzy Logic Controller

Fuzzy logic idea is similar to the human being's feeling and inference process. Unlike classical control strategy, which is a point-to-point control, fuzzy logic control is a range-to-point or range-to-range control. To implement fuzzy logic technique to a real application requires the following three steps:

Fuzzification:

All machines can process crisp or classical data such as either '0' or '1'. In order to enable machines to handle vague language input such as such as 'HIGH', 'MEDIUM', 'LOW' and 'FAST', 'MEDIUM' or 'SLOW', the crisp input and output must be converted to linguistic variables with fuzzy components. Besides those conversions, both the input and the output must also be converted from crisp data to fuzzy data. All of these processes are called fuzzification. Generally, fuzzification involves two processes: derive the membership functions for input and output variables and represent them with linguistic variables. This process is equivalent to converting or mapping classical set to fuzzy set to varying degrees [27].

Fuzzy Inference Process:

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 process, and those rules are directly related to a human being’s intuition and feeling.

Defuzzification:

Calculate each associated output and put them into a table: 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. All of these processes are called defuzzification. Three defuzzification techniques are commonly used, which are: Mean of Maximum method, Center of Gravity method and the Height method. The Mean of Maximum (MOM) defuzzification method**:** computes the average of those fuzzy conclusions or outputs that have the highest degrees. For example, the fuzzy conclusion is: the change in frequency is large. By using the MOM method, this defuzzification can be expressed as [27],

$$\text{MOM (LARGE)} = \frac{\sum_{\dot{X} \in T} \dot{X}}{T} \tag{2.4}$$

$$T = \{x' \mid \mu_{LARGE}(x') = \text{Support } \mu_{LARGE}(x)\} \tag{2.5}$$

Where T is the set of output *x* that has the highest degrees in the set LARGE. A short coming of the MOM method is that it does not consider the entire shape of the output membership function, and it only takes care of the points that have the highest degrees in that function. For those membership functions that have different shapes but the same highest degrees, this method will produce the same result.

The Center of Gravity method (COG) is the most popular defuzzification technique and is widely utilized in actual applications. This method is similar to the formula for calculating the center of gravity in physics. The weighted average of the membership function or the center of the gravity of the area bounded by the membership function curve is computed to be the crispest value of the fuzzy quantity. For example, for the conclusion: change in frequency is large. The COG output can be represented as [27],

$$\text{COG (LARGE)} = \frac{\sum_X \mu\text{LARGE}\ (x) * \text{x}}{\sum_X \mu\text{LARGE}\ (x)} \tag{2.6}$$

If *x* is a continuous variable, this defuzzification result is

$$\text{COG (LARGE)} = \frac{\sum_X \mu\text{LARGE}\ (x)\text{x}dx}{\sum_X \mu\text{LARGE}\ (x)\text{dx}} \tag{2.7}$$

The Height Method (HM) defuzzification method is valid only for the case where the output membership function is an aggregated union result of symmetrical functions. This method can be divided into two steps. First, the consequent membership function Fi can be converted into a crisp consequent x = fi where fi is the center of gravity of Fi. Then the COG method is applied to the rules with crisp consequents, which can be expressed as [27],

$$\text{X} = \frac{\sum_{i=1}^{M} \text{wi fi}}{\sum_{i=1}^{M} \text{wi}} \tag{2.8}$$

Where wi is the degree to which the i^{th} rule matches the input data. The advantage of this method is its simplicity. Therefore many neuro-fuzzy models use this defuzzification method to reduce the complex of calculations.

Generally fuzzy logic controls is expressed using the architectures shown in Figure 2.5, which is a typical fuzzy closed-loop control system, the inputs are error and error rate, which are combined by block *M* to input to the fuzzy inference system. The lookup table is derived based on the membership function of inputs, the output and the fuzzy control rules. A control gain factor *G* is used to tune the output of the lookup table to obtain different output values. The interpolation block S is used to smooth the output element of the lookup table. A feedback signal is obtained from the output of the system [27].

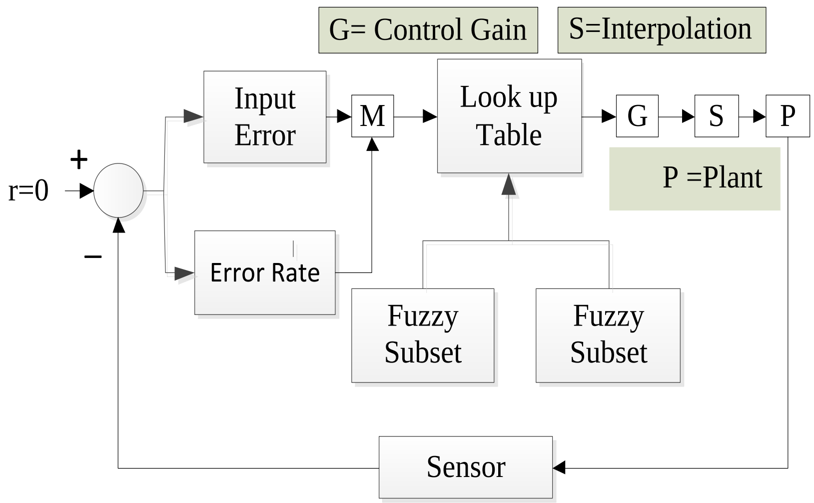


Figure 2.5: Block diagram of a fuzzy control system [27]

For a system that needs higher control accuracy, a multiple lookup table's fuzzy control system is needed. Two lookup tables are developed in this control system, a coarse and a fine table. During the application, the switch between the coarse and the fine table is under the control of the input error limit. This limit value can be defined by the user based on the real application. Two-set membership functions and control rules are utilized in this system to satisfy the requirement of higher control accuracy. When the system needs quick responses or quick actions, the coarse table is used. When the system needs high control accuracy or small control errors, the fine lookup table is selected. The sacrifice for this method is that more memory is needed to store both coarse and fine tables, and a little longer time is needed to make decision in selecting table in terms of the input error limit value [27].

2.7 Previous Works on Frequency Control of Micro Hydropower Plant

Several researches have been conducted on generation of power from MHPP and mechanism for controlling the frequency of MHPP. Different scholars used different technology and approaches to control the frequency of MHPP. From this some of the approaches [1] [2] [3] [4] [8] [9] [12] [19] are reviewed in the following paragraphs.

In [1,2, 3] Automatic generation control (AGC) have been purposed to control frequency of MHPP by using conventional governors such as mechanical-hydraulic governors, electro-hydraulic governors, purely mechanical and servo motor types. Mechanical hydraulic governors are sophisticated devices which are generally used in large hydro power plants. They require heavy maintenance and are expensive to install, making their usage in micro 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 types of conventional governing systems therefore, because of their cost and complexity, are not ideally suited for frequency control of standalone, micro hydro power systems where cost is a sensitive issue.

The papers [4, 12] proposed fuzzy controller to control the position of servo motors with spear valves to achieve automatic generation control. Proposed fuzzy controller will select the appropriate PI gain parameters throughout the operation of the plant. The input for this selection is the position of the gate opening. Based on the frequency and the demand power, the controller controls the servomotor in order to close or open the gate opening. This is usually applied in isolated, small hydro power systems. However, their complexity and cost is still higher for the application to standalone, micro hydro power systems.

A self-tuning fuzzy PI controller is proposed [8, 19], which is the combination of a conventional PI controller and a fuzzy controller. A load-frequency control based model using linear turbine assuming inelastic water column was proposed for isolated small hydropower plants [8, 19]. The controller is easy and effective to adjust the parameters of PI controller and could be applied to the system with various nonlinearities and wide range of parameter variations. Unfortunately, the cost of control system is still high for rural communities in developing countries such as Ethiopia.

In [9] Load control mode is developed for micro hydropower. 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 of 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 purpose.

In this thesis, fuzzy logic controller is proposed to control the frequency of micro hydro power plant by acting on electric valves. The input power is controlled by using simple electric valve. Because of their less cost and less complexity, they are ideally suited for frequency control of standalone, micro hydro power systems where cost is a sensitive issue.

2.8 Micro Hydro Power System Modelling

Mathematical modelling of any control system is the first and foremost task that a control engineer has to accomplish for design and analysis of any control engineering problem. It is nothing but the process or technique to express the system by a set of mathematical equations (algebraic or differential in nature). Differential equation model, state space model and transfer function model are commonly used mathematical models in designing a control system. All the systems considered in differential equation model and Transfer Function model are essentially Linear, Time Invariant system (commonly known as LTI). Whereas the state variable approach is applied to linear as well as non-linear systems only; If any practical system is to be modeled very accurately (taking into consideration all the practical aspects to perfectly represent the behavior of the system) the model would be Time varying and non-linear. But in most of the applications such complicated models can easily be reduced into simple time variant and linear, with negligible loss of accuracy and hence such approximations are very useful for mathematical analysis of the system. To find the transient or steady state response of SISO (Single Input Single Output) LTI (Linear Time Invariant) system transfer function model is useful. On the other hand for optimal control application state space model is useful. Handling and solving differential equations are quite cumbersome as compared to transfer function. In this thesis, the micro hydropower system is modeled in transfer function.

2.9 Turbine Modelling

Hydraulic turbine derives mechanical energy which in turn is converted into electrical energy from the force exerted by water as it falls from an upper to a lower reservoir. The hydraulic turbine dynamics models have a considerable influence on the dynamic stability of the power system [28.] There are two types of turbine models from these linear turbine model is used in this thesis which is expressed below. The linear model of the hydraulic turbines is modeled based on the following assumption [28].

I. The hydraulic turbine`s blade is considered as smooth i.e. its frictional resistance is neglected.
II. The fluid is considered as incompressible.
III. The velocity of water in penstock varies directly with gate opening and with the square root of the net head
IV. The developed output power of turbine is proportional to the product of head and velocity of flow.

The power developed by the turbine is a function of the water flow, 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 and runner blade angle. The effect of the runner blade movement is not considered in the modelling of turbines with fixed blades, such as Francis turbines. The flow in an impulse turbine depends upon the head and the nozzle opening only. The turbine dynamics is related to the generator dynamics through mechanical power P_m produced by the turbine. The relation between mechanical power P_m and mechanical torque M_m, expressed in per unit, is given by

$$P_m = \frac{n}{\omega_s} * M_m \qquad (2.9)$$

Normally, a simplifying assumption made is that $n = \omega_s$ at synchronous speed. 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 (2.9) yields [29, 30, 31].

$$P_m = M_m \qquad (2.10)$$

Since the water flow through the turbine Q and the mechanical power output p_m generated by the turbine describe the mass transfer and energy transfer in hydro turbine systems. They are considered in turbine modelling. Both variables are dependent on these parameters, the gate opening increment G_t, the rotating speed increment ω and the head increment H_d, expressed as non-linear functions of these parameter as follows.

$$Q = Q\ (H_d, \omega, G_t) \quad (2.11)$$

$$P_m = M\ (H_d, \omega,\ G_t) \quad (2.12)$$

Through linearization of the Equation (2.11) and Equation (2.12) around the steady state values, we obtain:

$$\Delta Q = \frac{\partial Q}{\partial H}\Delta H_d + \frac{\partial Q}{\partial G}\Delta G_t + \frac{\partial Q}{\partial \omega}\Delta\omega \quad (2.13)$$

$$\Delta P_m = \frac{\partial P_m}{\partial H}\Delta H_d + \frac{\partial P_m}{\partial G}\Delta G_t + \frac{\partial P_m}{\partial \omega}\Delta\omega \quad (2.14)$$

Normalizing Equation (2.13) and Equation (2.14) based on rated values; the following expressions that completely describe the turbine features are obtained:

$$\Delta\overline{Q} = a_{11}\ \Delta\overline{H}_d + a_{12}\Delta\overline{G_t} + a_{13}\ \Delta\overline{\omega}$$

$$\Delta\overline{P}_m = a_{21}\ \Delta\overline{H}_d + a_{22}\ \Delta\overline{G_t} + a_{23}\ \Delta\overline{\omega}$$

Where the following notations were used:

$\Delta\overline{Q} = \frac{\partial Q}{\partial Q_0}$, $\Delta\overline{P}_m = \frac{\partial P_m}{\partial P_{m0}}$, $\Delta\overline{H}_d = \frac{\partial H_d}{\partial H_{d0}}$, $\Delta\overline{G_t} = \frac{\partial G_t}{\partial G_{t0}}$, $\Delta\overline{\omega} = \frac{\partial \omega}{\partial \omega_0}$, $a_{11} = \frac{\partial Q}{\partial H_d}$, $a_{12} = \frac{\partial Q}{\partial G_t}$, $a_{13} = \frac{\partial Q}{\partial \omega}$, $a_{21} = \frac{\partial P_m}{\partial H_d}$, $a_{22} = \frac{\partial P_m}{\partial G_t}$, $a_{23} = \frac{\partial P_m}{\partial \omega}$

The partial derivatives of flow and mechanical power with respect to head, rotational speed and gate position are called turbine coefficients. The turbine coefficients represent the nonlinear characteristics of a hydraulic turbine. The partial derivatives vary with the operating conditions of the turbine relative to gate opening position G_t and unit rotational speed ω. The influence of the turbine coefficients on the model accuracy is critical. These values have to be measured accurately on the field or taken from model tests. The partial derivative of mechanical power with respect to gate position $\frac{\partial P_m}{\partial G_t}$ is called turbine gain**.** Turbine Gain is a critical parameter for an accurate approximation of hydro power plants dynamics, and has to be measured precisely in the field. The partial derivative of flow with respect to rotational speed $\frac{\partial Q}{\partial \omega}$ is usually considered to be negligible. The deviation of mechanical power with rotational speed $\frac{\partial P_m}{\partial \omega}$ is known as turbine self-regulation. The value of the turbine self-regulation is negative with an absolute value usually near unity. In inter connected power system the hydraulic units are synchronized with the system as a result speed vibration $\Delta\omega$ is fairly small and usually neglected. Consequently, the above equation is simplified to the equation below [32, 33, 34].

$$\Delta\overline{Q} = a_{11}\Delta\overline{H}_d + a_{12}\Delta\overline{G}_t \quad (2.15)$$

$$\Delta\overline{P}_m = a_{21}\,\Delta\overline{H}_d + a_{22}\,\Delta\overline{G}_t \quad (2.16)$$

Let's consider m_1, m_2... m_n the water masses in the pipe zones having the lengths $l_1, l_2, ..., l_n$ and cross-sections A_1, A_2,..., A_n of the real feed system. The equivalent system will have the length $L = l_1 + l_2 + ... + l_n$ and cross-section A, conveniently chosen. In this case, the mass conservation law in both systems will lead to the equation:

$$A\sum_{i=1}^{n} l_i = \sum_{i=1}^{n} l_i\,A \quad (2.17)$$

Since the water can be considered incompressible, the flow Q_i through each pipe segment with cross-section Ai is identical and equal with the flow Q through the equivalent pipe

$$Q = V^*A = Q_i = v_i^*A_i \text{ for } i = 1, 2, \ldots, n \quad (2.18)$$

Where V is the water speed in the equivalent pipe and v_i is the speed in each segment of the real pipe. From the mass conservation law it results:

$$V = \frac{Q}{A} = \frac{Q_i \sum l_i}{\sum A_i * l_i} = \frac{\sum l_i}{\sum A_i * l_i} * Q \quad (2.19)$$

Through linearization of Equation (2.19) around operation point we obtain:

$$\Delta Q = \frac{\partial Q}{\partial V}\Delta V$$

$$\Delta Q = A\Delta V \quad (2.20)$$

Normalize the above equation by dividing both sides by $Q_0 = AV_0$ which yield

$$\frac{\Delta Q}{Q_0} = \frac{A\Delta V}{AV_0}$$

$$\Delta\overline{Q} = \Delta\overline{V} \quad (2.21)$$

The velocity of the water in the penstock is given by the formula [35],

$$V = K_u G\sqrt{H_d} \quad (2.22)$$

Where V = water velocity

G_t = gate position

H_d = Hydraulic head at gate

K_u = a constant of proportionality

Through linearization of the Equation (2.22) around the steady state values, we obtain:

$$\Delta V = \frac{\partial V}{\partial H}\Delta H_d + \frac{\partial V}{\partial G}\Delta G_t$$

$$\Delta V = 0.5\Delta H_d + \Delta G_t \tag{2.23}$$

Normalize the above equation by dividing both sides by $V_0 = K_u G_{t0}\sqrt{H_{d0}}$ which yield

$$\frac{\Delta V}{V_0} = \frac{\Delta H_d}{2H_{d0}} + \frac{\Delta G}{G_0}$$

$$\Delta\overline{V} = 0.5\Delta\overline{H}_d + \Delta\overline{G_t} \tag{2.24}$$

Where the subscript 0 denotes initial steady-state values, the prefix Δ denotes small deviations, and the super bar "-" indicates normalized values based on steady-state operating values.

By Substituting Equation 2.24 in Equation (2.21) we obtain:

$$\Delta\overline{Q} = 0.5\Delta\overline{H}_d + \Delta\overline{G_t} \tag{2.25}$$

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

$$\Delta H_d A\rho a_g = -\rho AL\frac{d\Delta V}{dt} \tag{2.26}$$

Where L = length of conduit

A = pipe area

ρ = mass density

a_g = acceleration

ρAL = mass of water in the conduit

$\Delta H_d \rho a_g$ = incremental change in pressure at turbine gate

t = time in seconds

Dividing both sides of Equation (2.26) by, $A\rho a_g H_{d0} V_0$ the acceleration equation in normalized form becomes

$$\frac{\Delta H}{H_{d0}} = -\frac{L}{a_g}\frac{\Delta V}{H_{d0}}\frac{d}{dt}\left(\frac{\Delta V}{V_0}\right)$$

$$\Delta\overline{H}_d = -\frac{L}{a_g}\frac{\Delta V}{H_{d0}}\frac{d}{dt}(\Delta\overline{V})$$

$$\Delta\overline{H}_d = -T_W\frac{d}{dt}(\Delta\overline{V}) \tag{2.27}$$

Where $T_W = \frac{L}{a_g}\frac{\Delta V}{H_{d0}}$

T_w is referred to as the water time constant. It represents the time required for a head H_{d0} to accelerate the water in the penstock from standstill to the velocity V_0. It should be noted that T_w varies with load. Typically, T_w at full load lies between 0.5 s and 4.0 s. For load controlled micro hydro power systems, the water time constant remains constant. From Equation 2.26 and Equation 2.27, the relationship between change in velocity and change in gate position can be expressed as [35],

$$T_W\frac{d}{dt}(\Delta\overline{V}) = 2(\Delta\overline{G}_t - \Delta\overline{V}) \tag{2.28}$$

After Laplace transforming and simplifying Equation 2.28 we obtain:

$$\Delta\overline{V} = \frac{\Delta\overline{G_t}}{1+0.5T_w}$$

Substituting this equation in Equation 2.21 we obtain:

$$\Delta\overline{Q} = \frac{\Delta\overline{G_t}}{1+0.5T_w} \tag{2.29}$$

For an ideal turbine, without losses, the coefficients aij resulted from the partial derivatives in Equation 2.15 and Equation 2.16 have the following values: a_{11}= 0.5; a_{12} = 1; a_{21}=1.5; a_{22} = 1. After substituting this value in Equation 2.15 and Equation 2.16 we obtain:

$$\Delta\overline{Q} = 0.5\,\Delta\overline{H}_d + \Delta\overline{G}_t$$

$$\Delta\overline{P}_m = 1.5\Delta\overline{H}_d + \Delta\overline{G}_t$$

$$\Delta\overline{P}_m = 1.5(2)\,(\Delta\overline{Q} - \Delta\overline{G}_t) + \Delta\overline{G}_t$$

$$\Delta\overline{P}_m = 3\Delta\overline{Q} - 2\Delta\overline{G}_t \tag{2.30}$$

After substituting Equation 2.29 in Equation 2.30 the transfer function of the turbine is determined as follows: [35]

$$\frac{\Delta\overline{P}_m}{\Delta\overline{G}_t} = \frac{1-T_w}{1+0.5\,T_w} \tag{2.31}$$

In block diagram form,

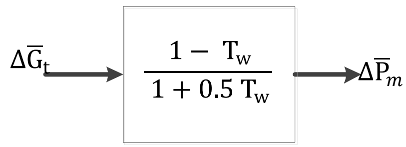


Figure 2.6: Linear turbine model

2.10 Synchronous Generator Modelling

The physical characteristics of the synchronous generators and their performance affect the system stability. The complete mathematical modeling of the synchronous machine is fairly complex system for stability analysis of power systems. The second-order synchronous generator model, referred to as the "classical" model, is widely used for simplified analysis of power system dynamics. The following assumptions are made in order to develop the mathematical model of a synchronous machine [36].

a) The three-phase stator winding is symmetrical distributed.

b) The capacitance of all the windings can be neglected.

c) Each of the distributed windings may be represented by a concentrated winding.

d) The change in the inductance of the stator windings due to rotor position is sinusoidal and does not contain higher harmonics.

e) Hysteresis loss is negligible but the influence of eddy currents can be included in the model of the damper windings.

f) In the transient and sub transient states the rotor speed is near synchronous speed.

g) The magnetic circuits are linear (not saturated) and the inductance values do not depend on the current.

The kinetic energy of the rotor at synchronous machine is [37],

$$KE = \frac{1}{2} J \omega^2_{sm} * 10^{-6} MJ \tag{2.32}$$

Where J = rotor moment of inertia in kg-m^2

$$\omega_r = \frac{P_0}{2}\,\omega_{sm} \tag{2.33}$$

Where ω_r = rotor speed in rad (elect)/s

P_0 = number of machine poles

Substituting Equation 2.32 in Equation 2.33 we obtain:

$$KE = \frac{1}{2}J(\frac{2}{P_0}\omega_r)^2 * 10^{-6} MJ$$

$$KE = \frac{1}{2}(J\omega_r(\frac{2}{P_0})^2 * 10^{-6} MJ)\ \omega_r$$

$$KE = \frac{1}{2}M\omega_r \quad (2.34)$$

Where $M = (J\omega_r(\frac{2}{P_0})^2 * 10^{-6} MJ)$ = moment of inertia in MJ-s/elect rad

The kinetic energy of the rotor at synchronous machine using inertia constant H is

$$KE = \frac{1}{2}M\omega_r\ MJ = GH \quad (2.35)$$

$$H = \frac{1}{2G}M\omega_r MJ$$

Where G = machine rating (base) in MVA (3-phase)

H = inertia constant in MJ/MVA or MW-s/MVA

It follows that,

$$M\ (pu) = \frac{2H}{\omega_{r0}} \quad (2.36)$$

The Swing Equation [32],

$$J\frac{d^2\theta_m}{dt^2} = T_m - T_e NM \quad (2.37)$$

Where θ_m = angle in rad (mech)

T_m = turbine torque in Nm; it acquires a negative value for a motoring machine

T_e = electromagnetic torque developed in Nm

Equation (2.37) can therefore be converted into its more convenient power form by assuming the rotor speed to remain constant at the synchronous speed (ω_{sm}). Multiplying both sides of Equation (2.37) by ω_{sm} we can write

$$\omega_{sm}J\frac{d^2\theta_m}{dt^2} * 10^{-6} = P_m - P_e MW$$

Where P_m = mechanical power input in MW

P_e = electrical power output in MW; stator copper loss is assumed negligible.

Rewriting this equation

$$\frac{1}{2}(J\omega_r(\frac{2}{P_0})^2 * 10^{-6}MJ)\ \frac{d^2\theta_e}{dt^2} = P_m - P_e MW$$

Where θe = angle in rad (elect), $\frac{Md^2\theta_e}{dt^2} = P_m - P_e$ (2.38)

It is more convenient to measure the angular position of the rotor with respect to a synchronously rotating frame of reference. Let $\delta = \theta e - \omega_s t$; rotor angular displacement from synchronously rotating reference frame

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

Hence Equation (2.38) can be written in terms of δ as

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

With M as defined in Equation (2.36), we can write

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

Dividing throughout by G, the MVA rating of the machine,

$$\frac{2H}{\omega_{r0}}\frac{d^2\delta}{dt^2} = \overline{P}_m - \overline{P}_e \text{ p.u} \quad (2.39)$$

Where M (p.u) = $\frac{2H}{\omega_{r0}}$

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 [37],

$$\overline{P}_m = \overline{P}_{m0} + \Delta\overline{P}_m$$

$$\overline{P}_e = \overline{P}_{e0} + \Delta\overline{P}_e$$

$$\delta = \Delta\delta + \delta_o$$

$$\frac{2H}{\omega_{r0}}\frac{d^2(\Delta\delta + \delta 0)}{dt^2} = \overline{P}_{m0} + \Delta\overline{P}_m - \overline{P}_{e0} - \Delta\overline{P}_e$$

Since the value of $\overline{P}_{m0} = \overline{P}_{e0}$ is one, the above equation can be simplified to:

$$\frac{2H}{\omega_{r0}}\ \frac{d^2\delta}{dt^2} = \Delta\overline{P}_m - \Delta\overline{P}_e \quad (2.40)$$

If δ the angular position of the rotor in electrical radians with respect to a synchronously rotating reference and δ_o is its value at t = 0,

$$\delta = \omega_r t - \omega_{r0} t + \delta_0$$

Taking the time derivative,

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

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

$$\omega_0 \frac{d\Delta\overline{\omega}_r}{dt} = \omega_0 \frac{d\Delta\overline{\omega}_r}{dt}$$

$$\frac{d\omega_r}{dt} = \frac{d\Delta\omega_r}{dt} = \frac{d\omega_m}{dt} \quad (2.41)$$

Substituting Equation (2.41) in Equation (2.40),

$$\frac{d\Delta\overline{\omega}_r}{dt} = (\Delta\overline{P}_m - \Delta\overline{P}_e)/2H$$

With the Laplace transformation,

$$\Delta\overline{\omega}_r\,(s) = \frac{\Delta\overline{P}_m(s) - \Delta\overline{P}_e(s)}{2Hs} \quad (2.42)$$

In block diagram form,

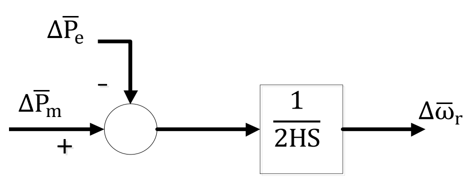


Figure 2.7:Block diagram of synchronous generator

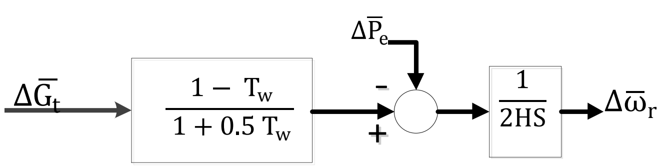


Figure 2.8: Generator model coupled with turbine

2.11 Load Modelling

Power system loads are all the pieces of electrical equipment people want to use in their homes and offices. For resistive loads, such as lighting and heating loads, the electrical power is independent of frequency. In the case of motor loads, such as fans and pumps, the electrical power changes with frequency due to changes in motor speed. The overall frequency-dependent characteristics of a composite load can be expressed as [37],

$$\Delta\overline{P}_e(s) = \Delta\overline{P}_D(s) = \Delta\overline{P}_{sl}(s) + D\Delta\overline{\omega}_r(s) \quad (2.43)$$

Where $\Delta\overline{P}_{sl}(s)$ = non-frequency sensitive consumer load change.
$D\Delta\overline{\omega}_r(s)$ = frequency sensitive load changes. D is expressed as percent change in load divided by percent change in frequency. Typical values of D are 1 to 2 percent.

Substituting Equation (2.43) in Equation (2.42),

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

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

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

$$\Delta\overline{\omega}_r(s) = \frac{\Delta\overline{P}_m(s) - \Delta\overline{P}_{sl}(s)}{(2Hs + D)} \quad (2.44)$$

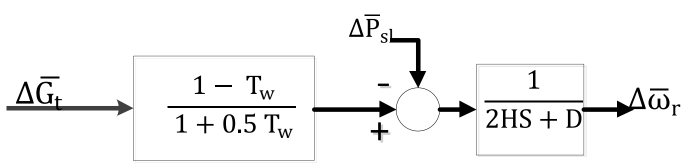


Figure 2.9: Turbine, load and generator block diagram

2.12 Electromagnetic Valve Modelling

Electromagnetic valve is the electromechanical actuator for linear (translational) motion. It is consisted of the magnetic circuit (magnetic subsystem), electrical inputs (electrical subsystem) and mechanical circuit (mechanical subsystem) [38].

Where dWe = electrical energy delivered from/to electrical subsystem.

dWm = mechanical energy delivered from/to mechanical subsystem.

dWf = magnetic energy stored in the coupling fields.

3.12.1 Electrical Subsystem Modelling

The electrical part can be modeled as an RL circuit including a resistance in series with an inductor. Because of the discontinuous power supply two cases are considered when the electrical model is derived; Case 1 when the power is on (energized) and Case 2 when the power is off (de-energized).

Case 1 - Energizing:

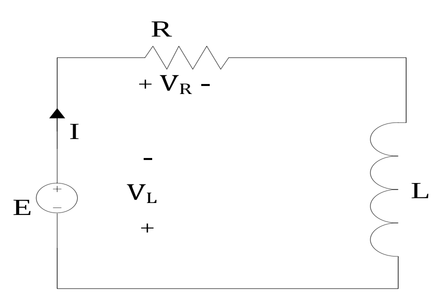


Figure 2.10: Electrical circuit when power is on [38]

As seen in Figure 2.11. According to Kirchhoff's Voltage Law, the sum of all voltage drops equals zero. Using KVL, the mathematical equation for the first case can be expressed as [38],

$$E - V_R - V_L = 0 \tag{2.45}$$

Where $V_R = RI$

$$V_L = \frac{d}{dt}(L(x_a)I) = L(x_a)\frac{dI}{dt} + I\frac{dL(x_a)}{dt}\frac{dx_a}{dt} \tag{2.46}$$

Total reluctance is the sum of reluctance due to the upper and lower gap. Inductance of coil varies due to variation in total reluctance which can be written as [38],

$$L(x_a) = \frac{N^2}{R'} = \frac{\mu_0 A_p N^2}{(l_g{,}off - x_a)^2} = L' \frac{x_a}{l_g{,}off - x_a}$$

Where μ_0 = the permeability in air
A_p = the cross sectional area of the armature.
N = number of turns in the coil
l_g = the air gap inside the valve
x_a = armature's position
L' = total reluctance

Inserting Equation (2.45) into Equation (2.46), the electrical circuit expression becomes

$$E - IR - L(x_a)\frac{dI}{dt} - I\frac{dL(x_a)}{dt} = 0$$

$$\frac{dI}{dt} = \frac{E - IR - I\frac{dx_a}{dt}\frac{dL(x_a)}{dt}}{L(x_a)} \tag{2.47}$$

Case 2 – de-energizing:

When the power is low, no power supply E is connected to the circuit. The inductor will operate as a source and current will flow through the loop until the energy has been absorbed in the circuit. Using Kirchhoff's Voltage Law, the mathematical expression can be derived:

$$-IR - L(x_a)\frac{dI}{dt} - I\frac{dL(x_a)}{dt}\frac{dx_a}{dt} = 0 \tag{2.48}$$

3.12.2 Magnetic Subsystem Modelling

Due to the current in the coil, a magnetic field will appear inside the valve and result in a magnetic force affecting the armature. The change in the magnetic force can be expressed as [39]

$$\frac{dF_M}{dt} = \frac{B^2 dA_p}{2\mu_0 dt} \tag{2.49}$$

Where B = the magnetic field

When the valve is assumed to be very long the magnetic field is given by

$$B = \mu_0 \frac{NI}{l_g}$$

As a function of the armature's position, the air gap is expressed as, [39]

$$l_g(xa) = l_g, off - x_a \tag{2.50}$$

Combining Equation (2.48), Equation (2.49), and Equation (2.50), the magnetic force can eventually be ex- pressed as

$$F_m = \frac{\mu_0 A_p N^2 I^2}{2(l_g, off - x_a)^2} \tag{2.51}$$

3.12.3 Mechanical Subsystem Modelling

Mechanical subsystem is defined by second Newton's law [40],

$$\sum F = Ma = M\frac{dv}{dt} = M\frac{d{x_a}^2}{dt^2}$$

$$F_M - k_s(x_a - x_{a0}) - b\left(\frac{dx_a}{dt}\right) - F_0 = M\frac{dv^2}{dt^2}$$

$$\frac{d{x_a}^2}{dt^2} = \frac{F_M - k_s(x_a - x_{a0}) - b\left(\frac{dx_a}{dt}\right) - F_0}{M} \tag{2.52}$$

Where F = net force

M = mass of the armature

a = the armature's acceleration

k_s = spring constant

b = the viscous friction coefficient

v = the armature's velocity

To obtain state-space model define, $x = x_1$ = Displacement of plunger, $\dot{x_1} = x_2$ =Velocity of plunger, $x_3 = i$ = Current flowing through solenoid coil.

$$\dot{x_1} = x_2$$

$$\dot{x_2} = \frac{1}{M}\left(\frac{\mu_0 A_p N^2 {x_3}^2}{2(a + x_1)^2} - k_s(x_1) - b(x_2) - F_0\right)$$

$$\dot{x_3} = \frac{a + x_1}{x_1 L'}\left(E - x_3 R - x_3 x_2 \frac{x_1 L'}{(a + x_1)^2}\right) \tag{2.53}$$

In block diagram form,

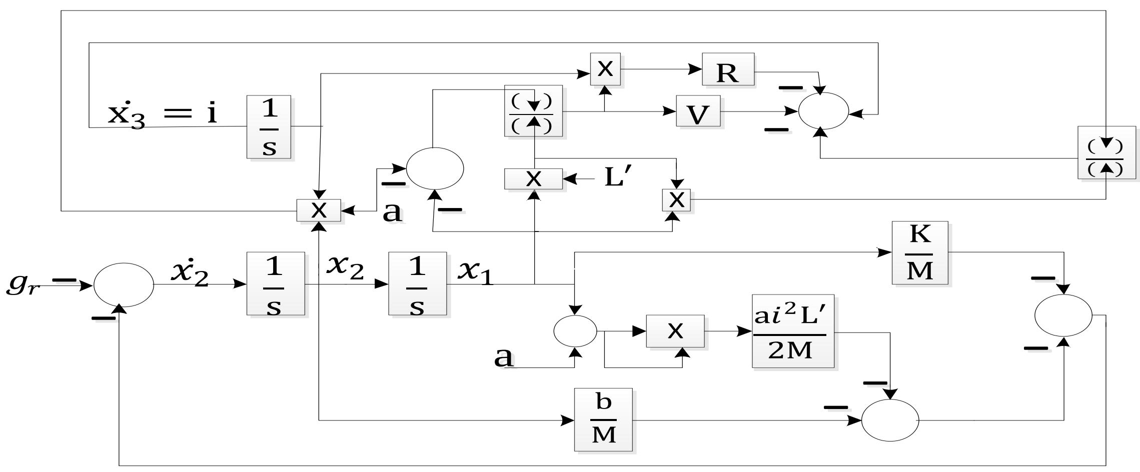


Figure 2.11: Electromagnetic valve model

2.13 Fuzzy Logic Controller Modelling

The principal work of a control is to balance a generator load towards 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 frequency of output power. Fuzzy logic controller is proposed in this thesis. The input to the fuzzy controller is the flow rate of the water, frequency error and change in frequency error. The output of the controller is the change in output power produced and change in input load.

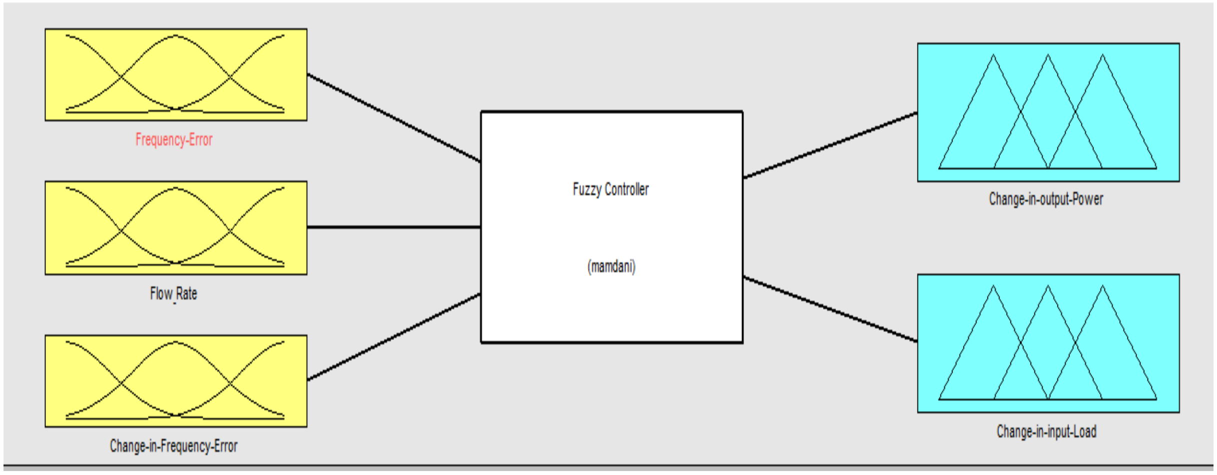


Figure 2.12: Fuzzy logic controller

2.14 Overall Model of the System

All the different components of a micro hydropower plant have been modeled in the previous sections. Putting together all the transfer functions obtained results in the block diagram shown in below.

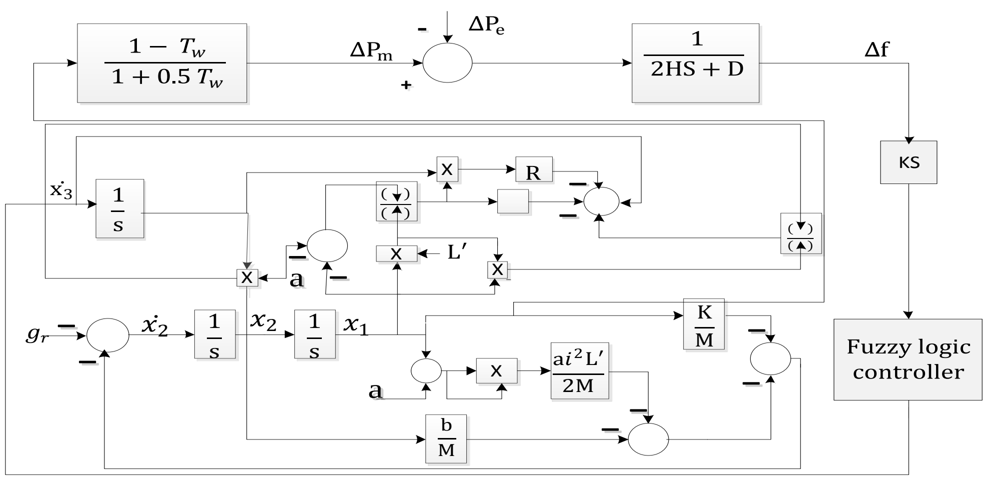


Figure 2.13: The over all model of the proposed frequency control system

CHAPTER 3

DESIGN OF THE CONTROL SYSTEM OF MHPP

3.1 Introduction

The proposed fuzzy logic controller changes the states of each electromagnetic valve to control the frequency of micro hydropower plant and the energy dissipated on electromagnetic valve. This chapter presents the design and analysis of the proposed control system for micro hydropower plant.

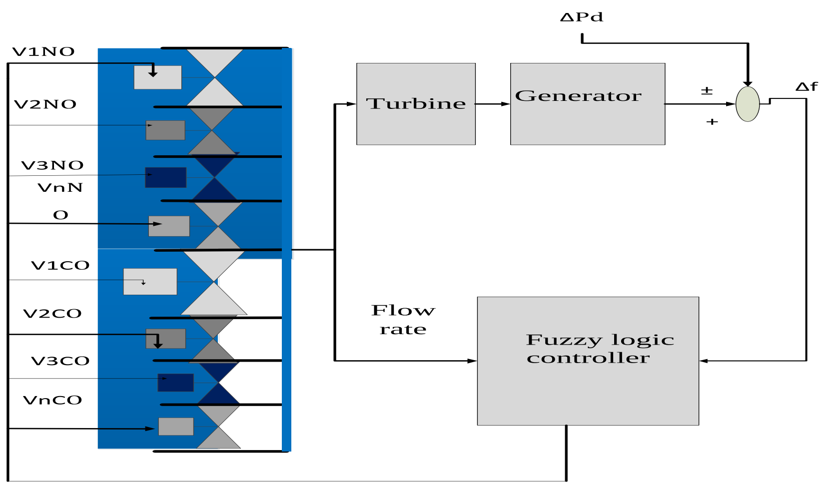
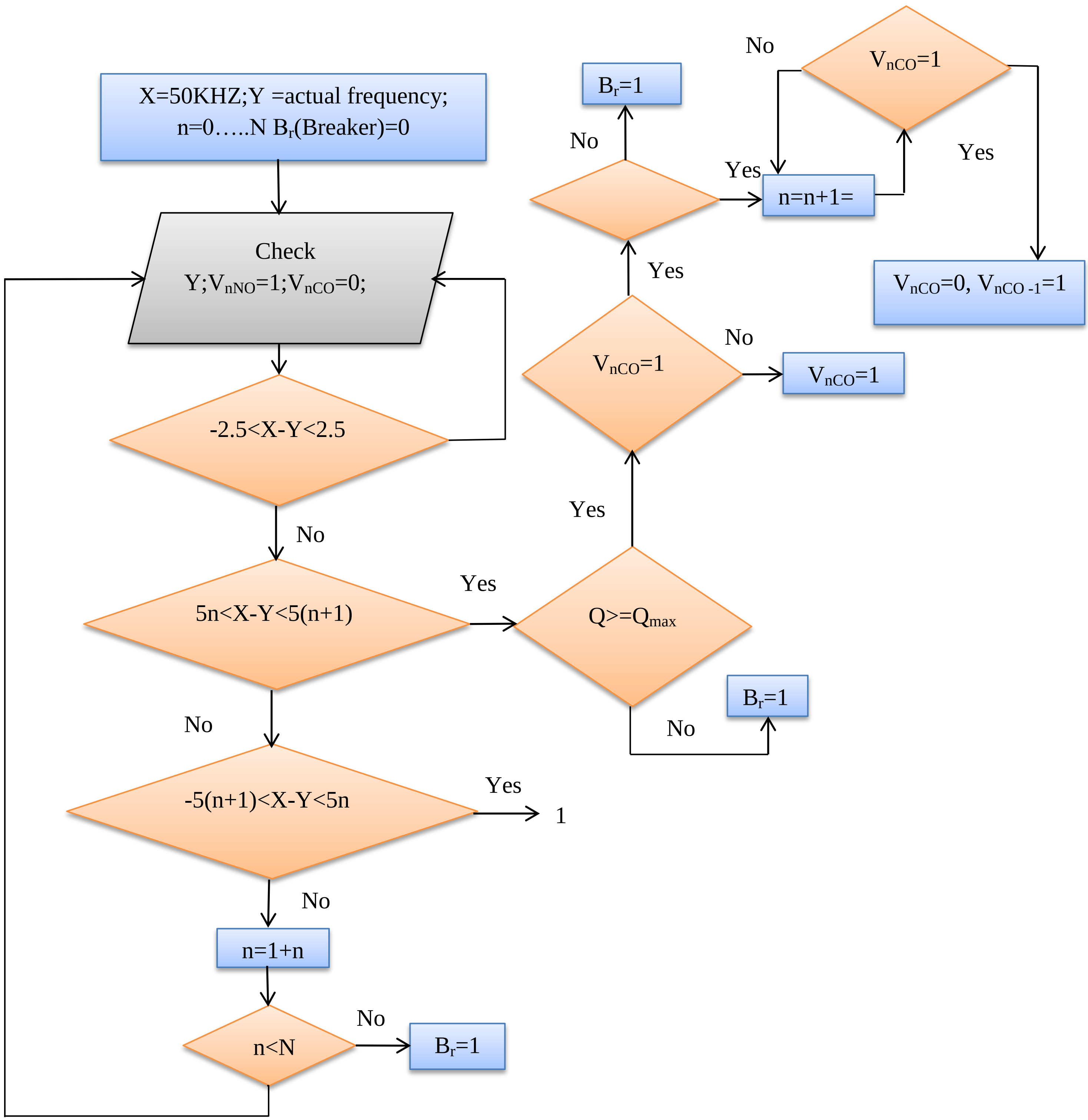
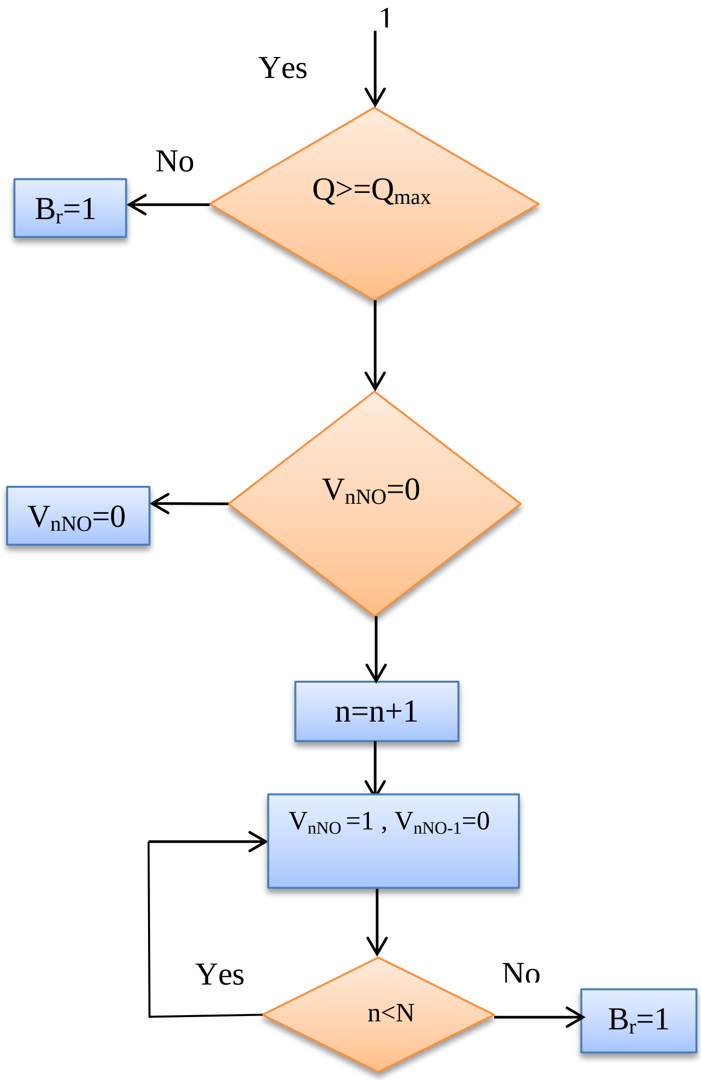


Figure 3.1: Components of a micro hydropower plant

Flow chart of the system





3.2 Electro Magnetic Valve Design

Assuming a step consumer load change, the change in electrical power in s-domain is given by [37]

$$\Delta\overline{P}_e(s) = \Delta\overline{P}_D(s) = \Delta\overline{P}_{sl}(s) + D\Delta\overline{\omega}_r(s) \quad (3.1)$$

$$\Delta\overline{\omega}_r(s) = \frac{\Delta\overline{P}_m(s) - \Delta\overline{P}_{sl}(s)}{(2Hs + D)} \quad (3.2)$$

The final value theorem is applied to find the steady state power error

$$\Delta\overline{\omega}_r(s) = \lim s \to 0 \frac{\Delta\overline{P}_m(s) - \Delta\overline{P}_{sl}(s)}{(2Hs + D)} \quad (3.3)$$

Simplifying Equation (3.3) an equation that relates steady-state frequency error and change in non-frequency sensitive load becomes $\Delta PD = -D\Delta f$. In per-unit, angular frequency and frequency are equal. Therefore, at steady-state, the relationship between change in load and change in frequency is a linear one. Practically, the steady-state frequency error cannot be zero. The standard frequency deviation in any electric power system should not be greater than 1% of the nominal frequency. However, in standalone, micro hydro power systems frequency control is not as rigorous as that of large scale power systems. A frequency deviation up to 2.5 HZ (0.05P.U) can be tolerated. Thus, the allowable maximum steady-state power error is 0.072 per unit.

To meet steady-state performance in this system, the output power of each valve is determined. The valve with minimum power output is already found to be 0.076 per unit. Then, the i^{th} valve output is determined by trial and error. Assuming there are eight electromagnetic valves, four are normally open and the remaining four are normally closed. Normally open valve and normally closed valve with the same i^{th} value have the same power output.

Table 3.1: Power output capacity of each valve.

Valve No.	Per unit Power output capacity
1	0.076
2	0.096
3	0.135
4	0.192

According to the design, the total power output of all valves is 52kw. Each valve was designed based on their needed capacity to limit steady state error as specified. The flow rate of water and the diameter of each pipe are determined by using the following equations:

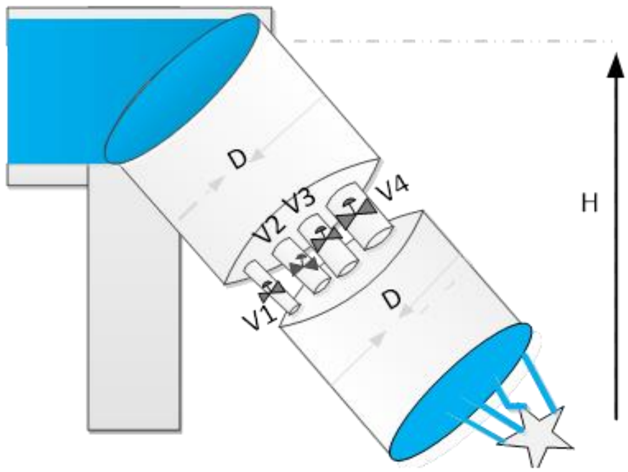


Figure 3.2: Valve and pipe of a proposed micro-hydropower system

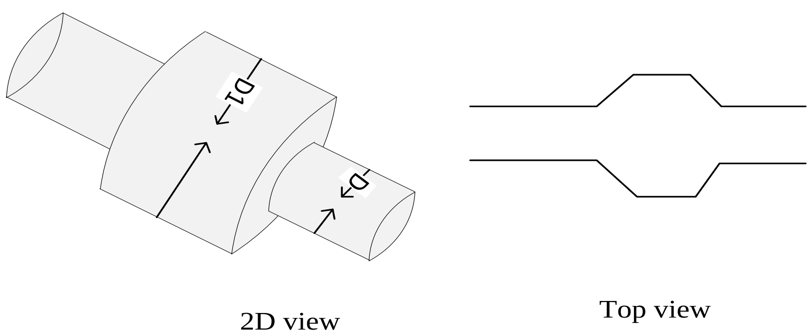


Figure 3.3: The shape of the proposed pipe

$$P_{th} = QgH_d \tag{3.4}$$

Where P = theoretical power output (KW)

Q = flow rate (m^3/s)

H_d = net head (m)

g = gravititional constant

Since the total power output and net head is known which is 52kw and 17m respectively, we can determine the total flow rate of the water.

$$Q = 52kw/(9.81*17) = 0.33m^3/s$$

To determine the diameter of the main pipe D, the following formula is used.

$$D = 0.52(P)^{0.43}/(H_d)^{0.6} = 0.52m. \quad (3.5)$$

Similar calculation is done to determine D1, which is sum of the diameter of each pipe and summarized in the table below.

Table 3.2: Diameter of each pipe and flow rate of water in each pipe

Valve No.	Per unit Power output capacity	Flow rate (Q)	Diameter(D)
1	0.076	0.024	0.17
2	0.096	0.03	0.19
3	0.135	0.042	0.22
4	0.192	0.06	0.25

Pressure on each pipe is given as,

$$P_{th} = pQ \quad (3.6)$$

Where p is pressure, therefore by using power and flow rate above the pressure of the water on the main pipe can be determined.

$$p = P_{th}/Q = 52kw/0.33m^3/s = 157.58*10^3 \text{ Pa}$$

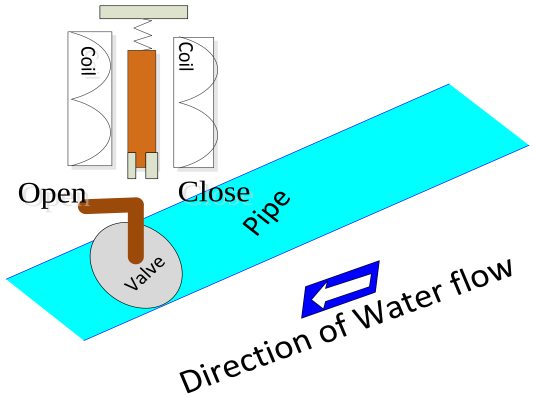


Figure 3.4: Basic component of the valve

To open the valve electromagnetic force push the plunger to the right directly and push the main valve clockwise indirectly, to close the valve electromagnetic force push the plunger to the left directly and push the main valve anticlockwise indirectly. The total torque needed to close the valve Tct, and the total torque to open the valve Tot are expressed mathematically in Equation 3.7 and in Equation 3.8 respectively.

$$T_{ct} = T_h + T_{bf} + T_{ss} + T_{su} \quad (3.7)$$

Where T_{su} = Seating and Unseating Torque

T_{bf} =Bearing Friction Torque

T_{ss} = Stem Seal Friction Torque

T_h = Hydrostatic Torque

$$T_{ot} = T_{bf} + T_{ss} + T_d \quad (3.8)$$

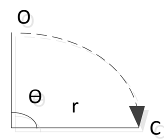
Where T_d is Dynamic Torque

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.

$$F_{ct} = T_{ct} / d$$

$$F_{ot} = T_{ot} / d \quad (3.9)$$

Where d is distance moved by plunger



d = r*sinθ

The valve move 90^0 when it changes from closed to open state, and therefor $\theta=90^0$. By using the torque taken from the manual and the radius of the valve r from Table 3.2 the electromagnetic force is determined for each valve and summarized in Table 3.3 below.

Table 3.3: Force and torque to close and to open the valve

Valve No.	Electromagnetic force to close the valve (N)	Torque to close the valve(N. m)	Electromagnetic force to open the valve (N)	Torque to open the valve (N. m)
1	647.1	55	175.65	14.76
2	800.2	76	237.47	22.37
3	1027.3	113	299.27	32.7
4	1224	153	415.52	51.69

The electromagnetic force for normally open and normally closed valve with the same i^{th} value is equal. For example, F_m for normally open V_1 and normally closed V_1 is equal. The other parameters of the valve are determined by using Equation 2.50, and summarized in Table 3.4

Table 3.4: Parameters of the valve

Valve No.	No of turns(N)	Current(I) in Amp	Mass of plunger(kg)	Total reluctance(L')in H
1	598	1.73	3.05	38.32
2	546	1.94	3.37	42.6
3	450	2.49	3.73	36.4
4	415	2.82	3.92	39.25

3.3 Fuzzy Logic Controller Design

Fuzzy logic controller based on Mamdani's fuzzy inference method is used to control the system, and in order to design this fuzzy controller which can control the system effectively each step of the controller fuzzification, rule base, inference engine and defuzzification was designed appropriately.

4.3.1 Fuzzifier Design

The first step in fuzzification is determine inputs and outputs which, it has three input frequency e(t), change in frequency error Δe(t) and flow rate Q(t), and two output change in output power ΔP(t) and change in input load ΔL(t). The first input to the fuzzy logic controller is change in frequency. This input, when compared to the rated frequency of the generator, will tell the controller if each valve needs to be on/off or if it is operating at its initial condition. The second input to the controller is flow rate of water. This input describes how fast the water flow and when it is compared to the rated flow rate of the water, will tell the controller if each valve needs to be on/off or if it is operating at its initial condition. It used to save energy used by the valve simultaneously to save the valve itself and other component by giving signal for controller to close the valve when there is low amount of water. The third input to the controller is the rate of change of frequency. This input describes how fast the frequency is changing. The outputs of the controller are change in output power and change in input load. The controller control the output power by controlling the valve based on those three input signal. It also control the second output, change in input load based on the amount of water available.

The second step is chose an appropriate membership function for inputs and outputs which, for simplicity in implementation and also to have an acceptable performance. As shown from Figure 3.5 to Figure 3.8 triangular and trapezoidal shapes have been adopted for the membership functions for all inputs and outputs variables. The shape of the membership function and the universe of discourse for each function is found by trial and error after many simulations were done.

The third step is chose the correct labels for each fuzzy set which, in this thesis namely as linguistic variable. Because the actual frequency can be higher than the desired one as well as lower, the error can be negative as well as positive. Values of error (e) with a Negative sign mean that the current output frequency f(t) has a value above the set-point f_{sp} since $e(t) = f_{sp} - f(t) > 0$. A positive value describes the magnitude of the difference $f_{sp} - f(t)$. On the other hand, linguistic values of e(t) with a positive sign mean that the current value of f is below the set-point value. The change-of-error (Δe) with a negative sign means that the current output frequency f (t) has increased when compared with its previous value f(t-1), since Δe(t) = e(t) - e(t - 1) = -f(t) + f(t -1) < 0. Linguistic values of Δe(t) with a positive sign mean that f(t) has decreased its value when compared to f(t -1). For flow rate of water since amount of water is variable in different season the flow rate of water can be higher than the desired one as well as lower, but it is always greater than zero. The output variable, change in power generated can be positive or negative like the input variables, the frequency error and change in frequency error since the load on the system are not constant but the second out pout variable input load is always positive.

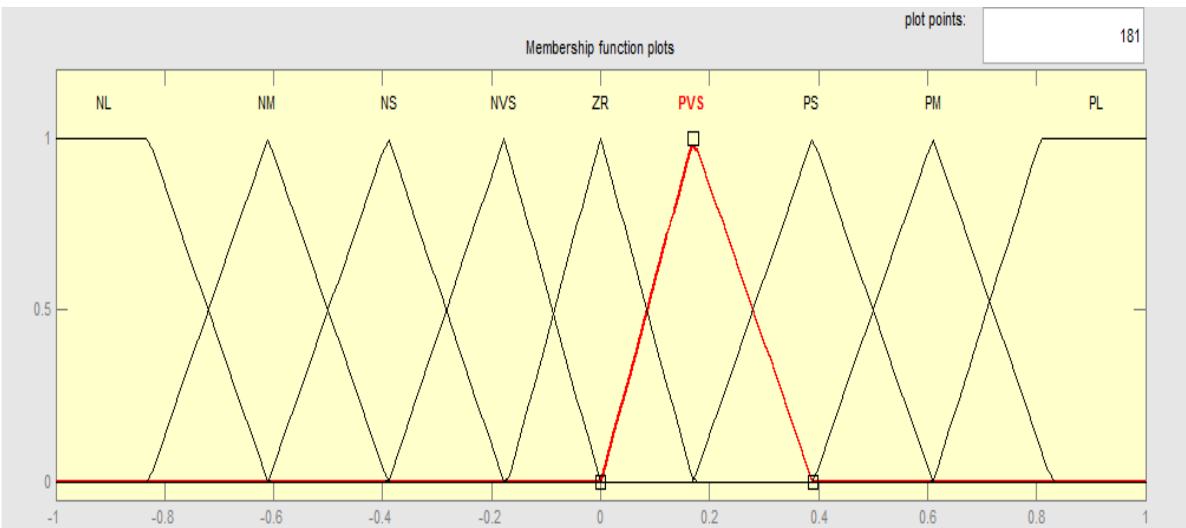


Figure 3.5: Input member ship function for error in frequency and change in error frequency

Nine fuzzy subsets Negative Very Small (NVS), Negative Small (NS), Negative Medium (NM), Negative Large (NL), Zero (ZE), Positive Very Small (PVS), Positive Small (PS), Positive Medium (PM) and Positive Large (PL) are chosen for the input variable frequency error and change in frequency error. From these NL and PL are trapezoidal type and the all the remaining membership functions are triangular type. The universe of discourse of each membership function is shown in Table 3.5 with degree of membership.

The frequency error and change in frequency error are normalized to [-1, 1] and the input scaling factor for error and change in error are found by trial and error to make the range of frequency error and change in frequency error normalized and found to be 36.5 and 50, respectively. The membership functions for frequency error and change in frequency error are made more in number in order to activate only the required valve and to minimize error.

Table 3.5: Membership function universe of discourse of error and change of error in frequency

e /Δe	Degree of membership								
	NL	NM	NS	NVS	ZR	PVS	PS	PM	PL
-1 to -0.83	1	0	0	0	0	0	0	0	0
-0.83 to -0.72	0.5 to 1	0.5 to 0	0	0	0	0	0	0	0
-0.72 to -0.61	0 to 0.5	1 to 0.5	0	0	0	0	0	0	0
-0.61 to -0.5	0	0.5 to 1	0 to 0.5	0	0	0	0	0	0
-0.5 to -0.39	0	0 to 0.5	0.5 to 1	0	0	0	0	0	0
-0.39 to -0.28	0	0	1 to 0.5	0 to 0.5	0	0	0	0	0
-0..28 to -0.17	0	0	0.5 to 0	0.5 to 1	0	0	0	0	0
-0.17 to -0.085	0	0	0	1 to 0.5	0 to 0.5	0	0	0	0
-0.085 to 0	0	0	0	0.5 to 0	0.5 to 1	0	0	0	0
0 to 0.085	0	0	0	0	1 to 0.5	0 to 0.5	0	0	0
0.085 to .17	0	0	0	0	0.5 to 0	0.5 to 1	0	0	0
0.17 to 0.28	0	0	0	0	0	1to 0.5	0 to 0.5	0	0
0.28 to 0.39	0	0	0	0	0	0.5 to 0	0.5 to 1	0	0
0.39 to 0.5	0	0	0	0	0	0	1 to 0.5	0 to 0.5	0
0.5 to 0.61	0	0	0	0	0	0	0.5 to 0	0.5 to 1	0
0.61 to 0.72	0	0	0	0	0	0	0	1 to 0.5	0 to 0.5
0.72 to 0.83	0	0	0	0	0	0	0	0.5 to 0	0.5 to 1
0.83 to 1	0	0	0	0	0	0	0	0	1

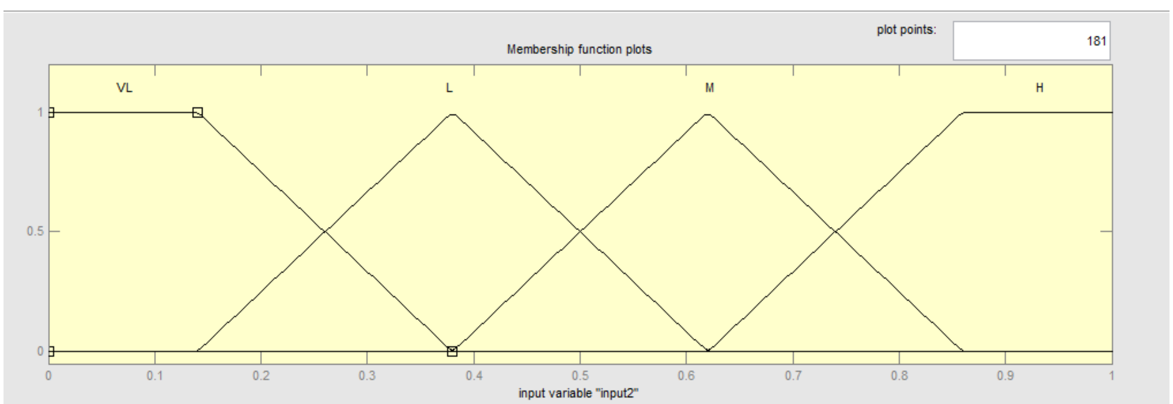


Figure 3.6: Input member ship function for flow rate

Four subsets, Very low (VL), Low (L), Zero (ZE), Medium (M), and High (H) are used for the input variable flow rate. The membership functions Very Low (VL) and High (H) are trapezoidal types. The membership functions Low (L), Zero (ZE), and Medium (M) are triangular types. The universe of discourse of each membership function is shown in Table 3.6 with degree of membership. The flow rate of water is normalized to [0, 1] and the input scaling factor for flow rate of water are also found by trial and error to make the range of flow rate of water found to be $0.3m^3/s$.

Table 3.6: Membership function universe of discourse of change in flow rate

Q	Degree of membership			
	VL	L	M	H
0 to 0.14	1	0	0	0
0.14 to 0.26	1 to 0.5	0 to 0.5	0	0
0.26 to 0.38	0.5 to 0	0.5 to 1	0 to 0.5	0
0.38 to 0.5	0	1 to 0.5	0.5 to 1	0
0.5 to 0.62	0	0.5 to 0	1 to 0.5	0
0.62 to 0.86	0	0	0.5 to 0	0 to 0.5
0.86 to 1	0	0	0	0.5 to 1

4.3.2 Rule Base Construction and Rule Evaluation:

Once the membership is found for each of the linguistic labels, an intelligent decision can be made onto what the output should be. Basically a linguistic controller contains rules in the if-then format, but they can be presented in different formats.

In the case of the fuzzy logic frequency controller, the desired effect is to keep the output frequency of the generator at its rated value under varying loads and varying flow rate of water. From this desired goal, rules are made for every combination of frequency error, change in frequency error and flow rate of water on what the output power should be in order 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 3.7 to Table 3.10. After rule base construction rule evaluation which focuses on operation in the antecedent of the fuzzy rules is done. AND/OR fuzzy operation are used in antecedent part which AND operation is used in this design.

Table 3.7: Rule table for ΔP when Q is high and medium (Q=H and Q=M)

Error (e)	Error Derivative (Δe)								
	NL	NM	NS	NVS	ZR	PVS	PS	PM	PL
NL	ZR	PVS	PS	PM	PL	PL	PL	PL	PL
NM	NVS	ZR	PVS	PS	PM	PL	PL	PL	PL
NS	NS	NVS	ZR	PVS	PS	PM	PL	PL	PL
NVS	NM	NS	NVS	ZR	PVS	PS	PM	PL	PL
ZR	ZR	ZR	ZR	ZR	ZR	ZR	ZR	ZR	ZR
PVS	NL	NL	NM	NS	NVS	ZR	PVS	PS	PM
PS	NL	NL	NL	NM	NS	NVS	ZR	PVS	PS
PM	NL	NL	NL	NL	NM	NS	NVS	ZR	PVS
PL	NL	NL	NL	NL	NL	NM	NS	NVS	ZR

Table 3.8: Rule table for ΔP when Q is low (Q=L)

Error (e)	Error Derivative (Δe)								
	NL	NM	NS	NVS	ZR	PVS	PS	PM	PL
NL	ZR	PVS	PS	PM	PL	PL	PL	PL	PL
NM	NVS	ZR	PVS	PS	PM	PL	PL	PL	PL
NS	NS	NVS	ZR	PVS	PS	PM	PL	PL	PL
NVS	NM	NS	NVS	ZR	PVS	PS	PM	PL	PL
ZR	ZR	ZR	ZR	ZR	ZR	ZR	ZR	ZR	ZR
PVS	NM	NM	NM	NS	NVS	ZR	PVS	PS	PM
PS	NM	NM	NM	NM	NS	NVS	ZR	PVS	PS
PM	NM	NM	NM	NM	NM	NS	NVS	ZR	PVS
PL	NM	NM	NM	NM	NM	NM	NS	NVS	ZR

Table 3.9: Rule table for ΔP when Q is very low (Q=VL)

Error (e)	Error Derivative (Δe)								
	NL	NM	NS	NVS	ZR	PVS	PS	PM	PL
NL	ZR	PVS	PS	PM	PL	PL	PL	PL	PL
NM	NVS	ZR	PVS	PS	PM	PL	PL	PL	PL
NS	NS	NVS	ZR	PVS	PS	PM	PL	PL	PL
NVS	NM	NS	NVS	ZR	PVS	PS	PM	PL	PL
ZR	ZR	ZR	ZR	ZR	ZR	ZR	ZR	ZR	ZR
PVS	NS	NS	NS	NS	NVS	ZR	PVS	PS	PM
PS	NS	NS	NS	NS	NS	NVS	ZR	PVS	PS
PM	NS	NS	NS	NS	NS	NS	NVS	ZR	PVS
PL	NS	NS	NS	NS	NS	NS	NS	NVS	ZR

Table 3.10: Rule table for ΔL

Q	ΔL
VL	L
L	M
M	H
H	VH

4.3.3 Aggregation of the Rule Output (Fuzzy Inference)

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. For the linguistic rule stated earlier, the output, change in output power P, would receive a membership that was equal to the minimum of the three inputs, flow rate of water, frequency error and change in frequency error.

4.3.4 Defuzzification Design

After the rules are evaluated, each output membership function will contain a corresponding membership. From these memberships, a numerical (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. Naturally there are trade-offs to each method. The method that was chosen for this thesis was the Centroid method. The output defuzzification membership functions for ΔP and ΔL are shown in Figure 3.7 and Figure 3.8 respectively.

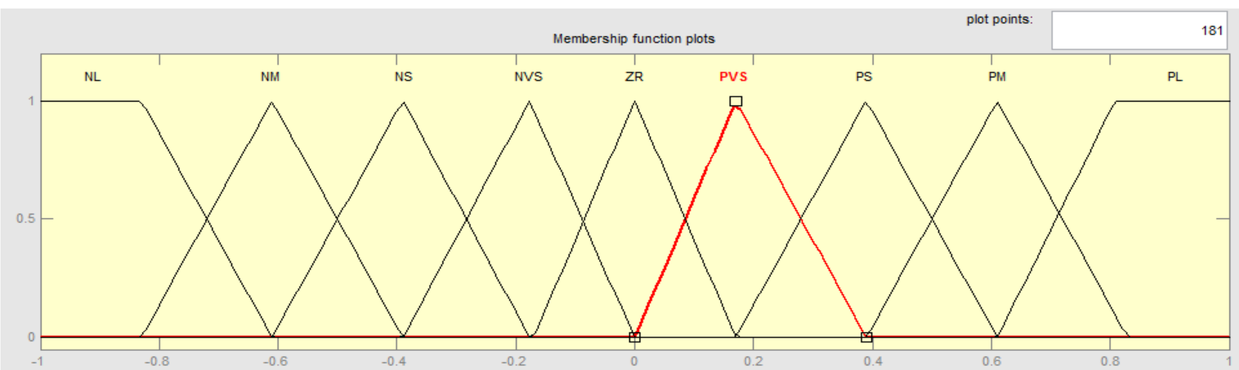


Figure 3.7: Output member ship function for ΔP

Nine fuzzy subsets Negative Very Small (NVS), Negative Small (NS), Negative Medium (NM), Negative Large (NL), Zero (ZE), Positive Very Small (PVS), Positive Small (PS), Positive

Medium (PM) and Positive Large (PL) are chosen for the output variable change in output power ΔL. The universe of discourse of each membership function is shown in Table 3.11 with degree of membership.

Table 3.11: Membership function universe of discourse of change in output power

ΔP	Degree of membership								
	NL	NM	NS	NVS	ZR	PVS	PS	PM	PL
-1 to -0.9	1	0	0	0	0	0	0	0	0
-0.9 to -0.765	0.5 to 1	0.5 to 0	0	0	0	0	0	0	0
-0.765 to -0.67	0 to 0.5	1 to 0.5	0	0	0	0	0	0	0
-0.67 to -0.525	0	0.5 to 1	0 to 0.5	0	0	0	0	0	0
-0.525 to -0.43	0	0 to 0.5	0.5 to 1	0	0	0	0	0	0
-0.43 to -0.285	0	0	1 to 0.5	0 to 0.5	0	0	0	0	0
-0.285 to -0.17	0	0	0.5 to 0	0.5 to 1	0	0	0	0	0
-0.19 to -0.095	0	0	0	1 to 0.5	0 to 0.5	0	0	0	0
-0.095 to 0	0	0	0	0.5 to 0	0.5 to 1	0	0	0	0
0 to 0.095	0	0	0	0	1 to 0.5	0 to 0.5	0	0	0
0.095 to .19	0	0	0	0	0.5 to 0	0.5 to 1	0	0	0
0.19 to 0.285	0	0	0	0	0	1to 0.5	0 to 0.5	0	0
0.285 to 0.43	0	0	0	0	0	0.5 to 0	0.5 to 1	0	0
0.43 to 0.525	0	0	0	0	0	0	1 to 0.5	0 to 0.5	0
0.525 to 0.67	0	0	0	0	0	0	0.5 to 0	0.5 to 1	0
0.67 to 0.765	0	0	0	0	0	0	0	1 to 0.5	0 to 0.5
0.765 to 0.9	0	0	0	0	0	0	0	0.5 to 0	0.5 to 1
0.9 to 1	0	0	0	0	0	0	0	0	1

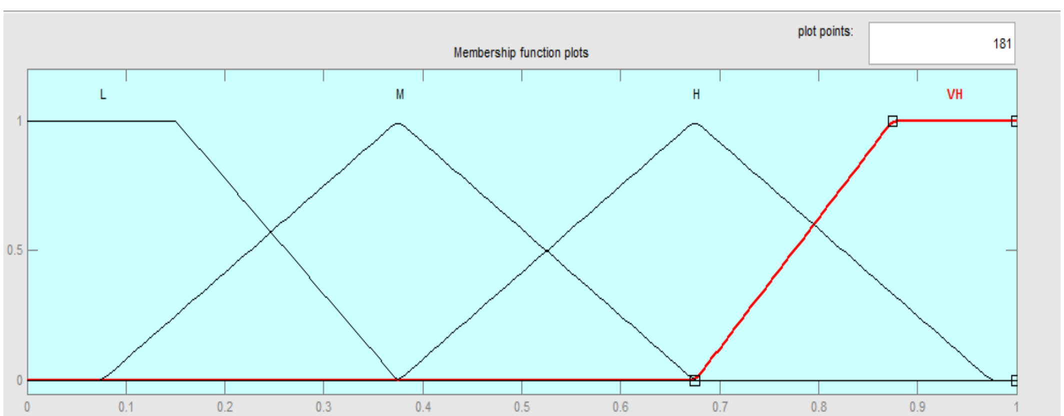


Figure 3.8: Output member ship function for ΔL

Four subsets, Low (L), Medium (M), High (H) and Very high (VH) are used for the output variable input load (ΔL).

Table 3.12: Membership function universe of discourse of change in input load.

ΔL	Degree of membership			
	L	M	H	VH
0 to 0.075	1	0	0	0
0.075 to 0.225	1 to 0.5	0 to 0.5	0	0
0.225 to 0.375	0.5 to 0	0.5 to 1	0 to 0.5	0
0.375 to 0.525	0	1 to 0.5	0.5 to 1	0
0.525 to 0.675	0	0.5 to 0	1 to 0.5	0
0.675 to 0.825	0	0	0.5 to 0	0 to 0.5
0.825 to 0.975	0	0	0	0.5 to 1
0.975 to 1	0	0	0	1

4.3.5 Simulink Model of MHPP for Frequency Controller

All the components of MHPP are modelled to design the controller and to analyse the simulation results. The Simulink model of electromagnetic valve and the overall Simulink model of the MHPP control system are shown in Figure 3.9 and in Figure 3.10 respectively.

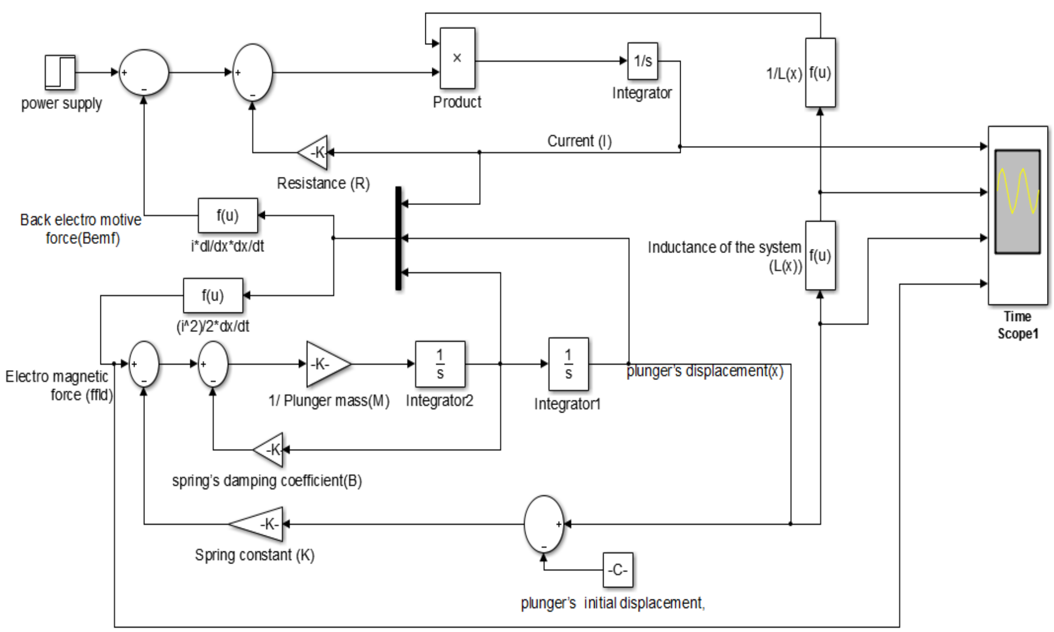


Figure 3.9: Simulink model of electromagnetiv valve

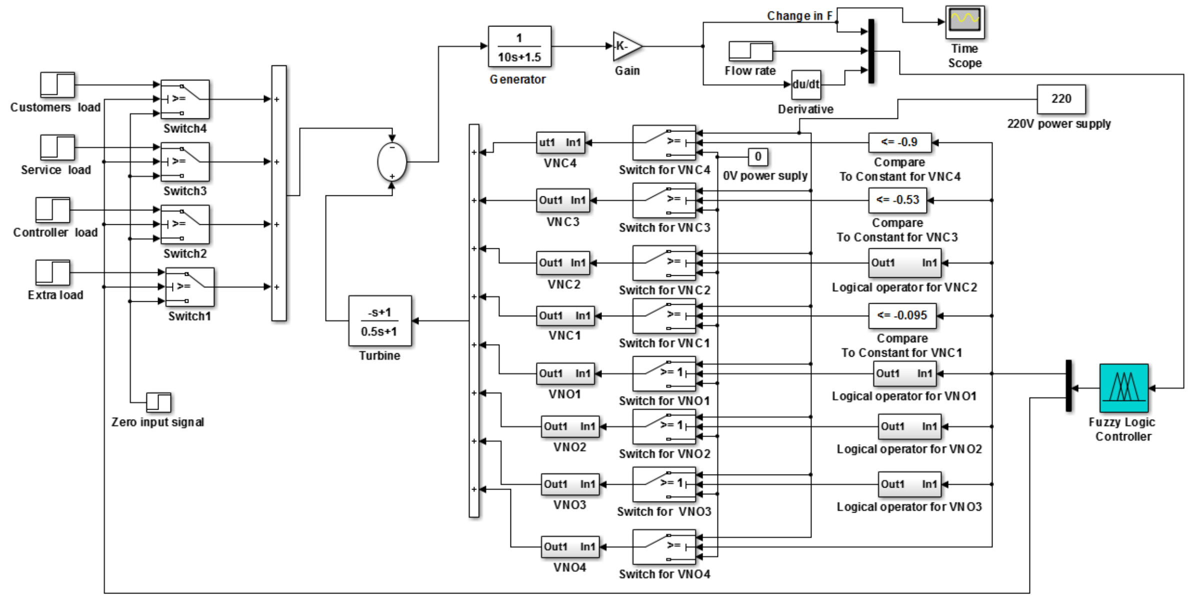


Figure 3.10: The overall Simulink Simulation model

CHAPTER 4

SIMULATION RESULTS AND DISCUSSIONS

4.1 Introduction

Once the Micro hydro Power Plant model is established, it is simulated and studied with and without fuzzy controller in the software Mat lab Simulink. The Simulink model shown in Figure 3.9 is used to carry out simulation studies and analyse the performance of fuzzy controller under different operating condition

4.2 Simulation Results

The response of the system is tested for different damping constant of the generator, under varying load and flow rate of water. The scope shows the P.U value of frequency deviation and change in demand load. The damping constants of the generators for micro hydropower plant may vary from 1 to 2 depending on the load and internal damping constant of the generator [24]. Thus, to see the effect of variation of damping constant of the generator on the system the response of the system is tested for damping constant of 1, 1.5 and 2.

The maximum power output produced is assumed to be 52kw from this 10kw is assumed to be used by constant load, load which are always running and the remaining 42kw is assumed to be used by variable load, load which are not always running. This means the output power which supplies the variable demand power can vary from 0-42kw according to power needed by customer. Thus, to see the effect of load variation on the system the response of the system is tested for load acceptance 15%, 35%, 55% and 75% as well as 15%, 35%, 55% and 75% load rejections.

The frequency deviation of the micro hydropower system without controller and with fuzzy controller for a 75% load rejection and 75% load addition is shown in Figure 4.1 and Figure 4.2 respectively. The results are obtained assuming the damping constant of the generator equal to 1, 1.5, 2 and flow rate of water 0.25 m^3/s. From the simulation result, the P.U value of change in demand power is 0.74 P.U, a frequency deviation without controller is 0.731, 0.437 and 0.316 P.U and the overshoot is 13.15%, 8.7% and 6.28% for damping constant of the generator equal to 1, 1.5, 2 respectively whereas with fuzzy controller frequency error is eliminated and there is an overshoot of 2.74%, 3.04% and 3.46% and the settling time is 27.65, 20.87 and 39.82sec for damping constant of the generator equal to 2, 1.5, 1 respectively.

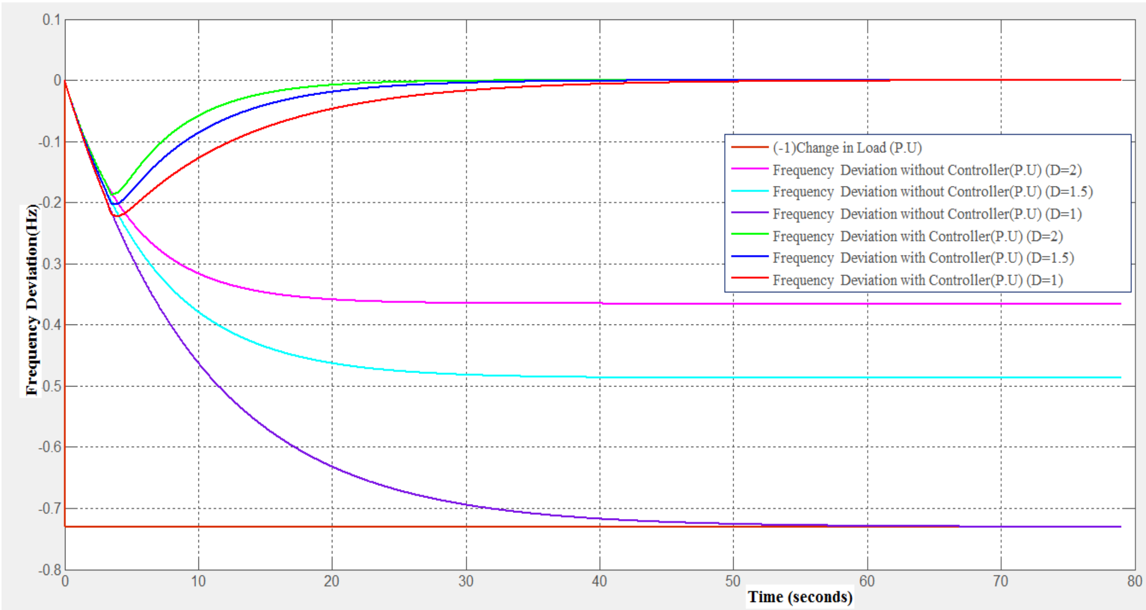


Figure 4.1: Frequency response for 0.75 P.U load rejection (D=1.5, 1 and 2) and (Q=0.25)

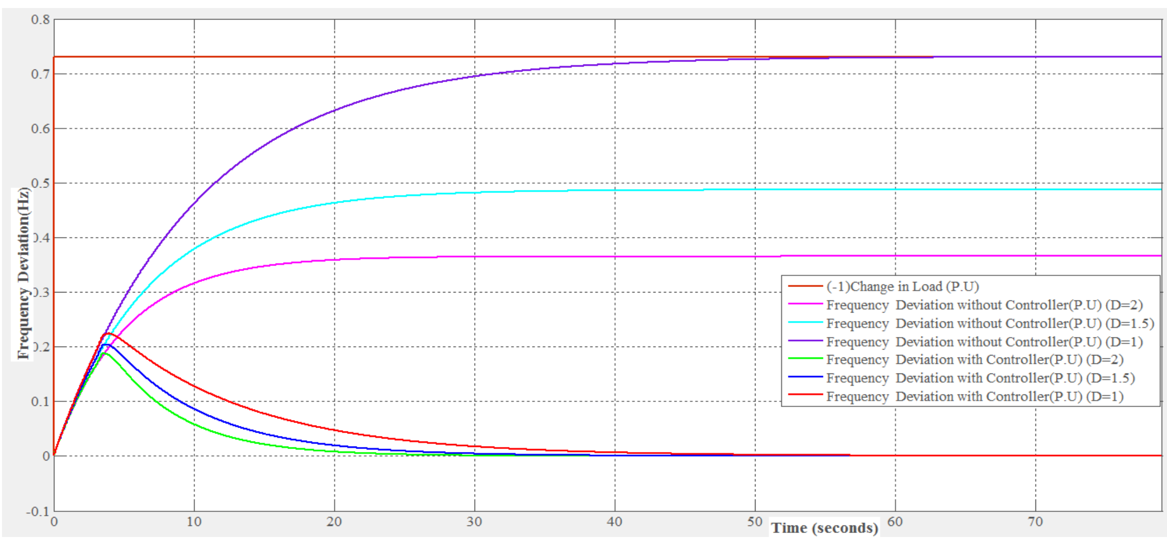


Figure 4.2: Frequency response for 0.75 P.U load addition (D=1.5, 1 and 2) and (Q=0.25)

Similar tests were done for 15%, 35% and 55% load change as shown in the following figures and summarized in Table 4.1 to Table 4.3.

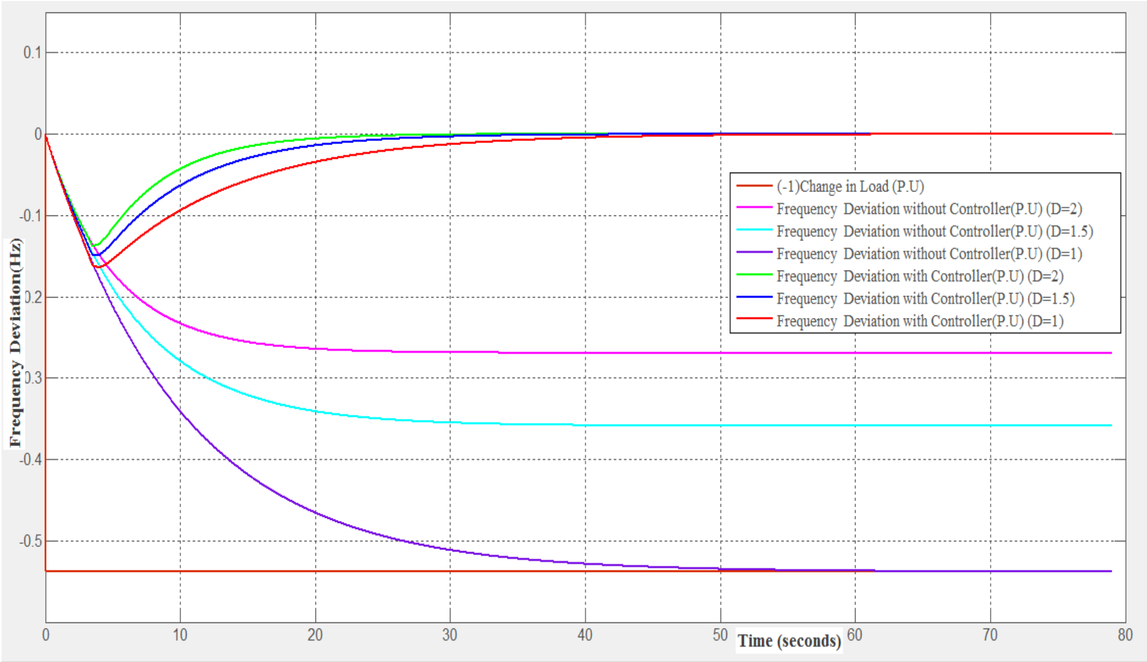


Figure 4.3: Frequency response for 0.55 P.U load rejection (D=1.5, 1 and 2) and (Q=0.25)

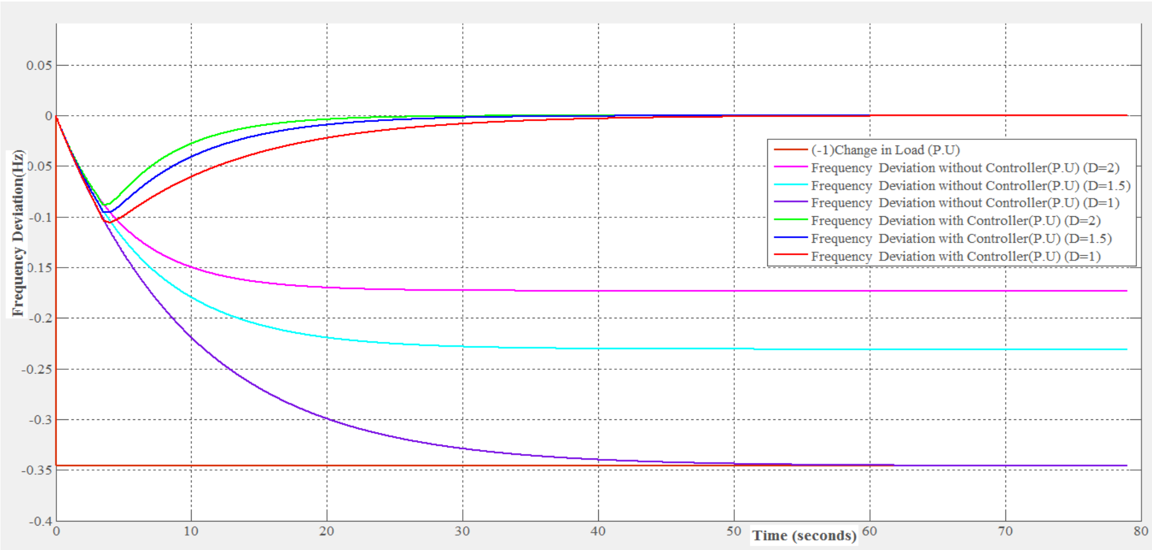


Figure 4.4: Frequency response for 0.35 P.U load rejection (D=1.5, 1 and 2) and (Q=0.25)

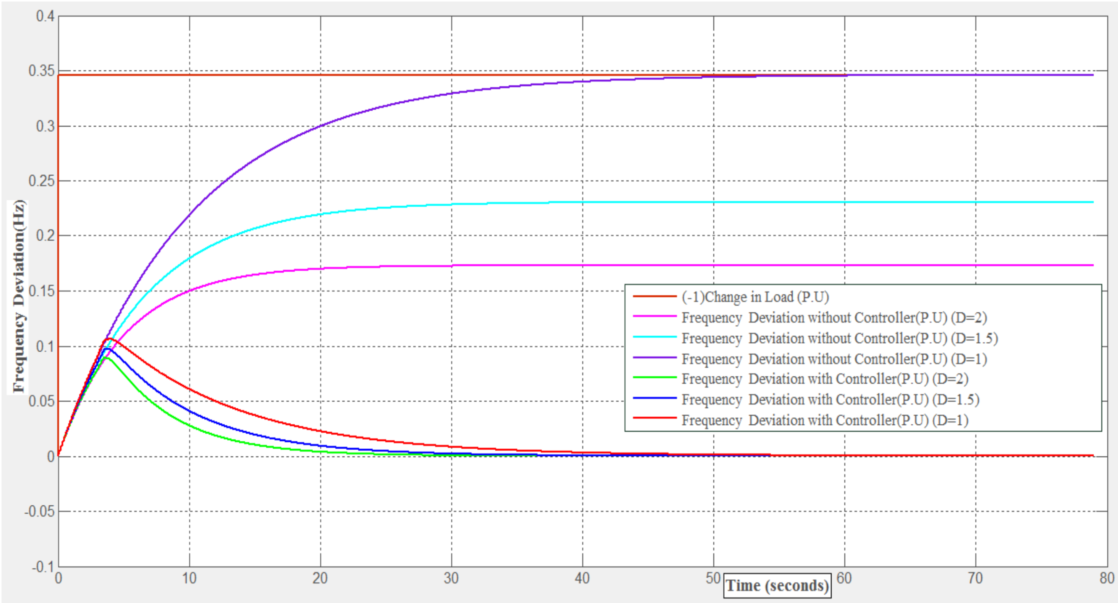


Figure 4.5: Frequency response for 0.35 P.U load addition (D=1.5, 1 and 2) and (Q=0.25)

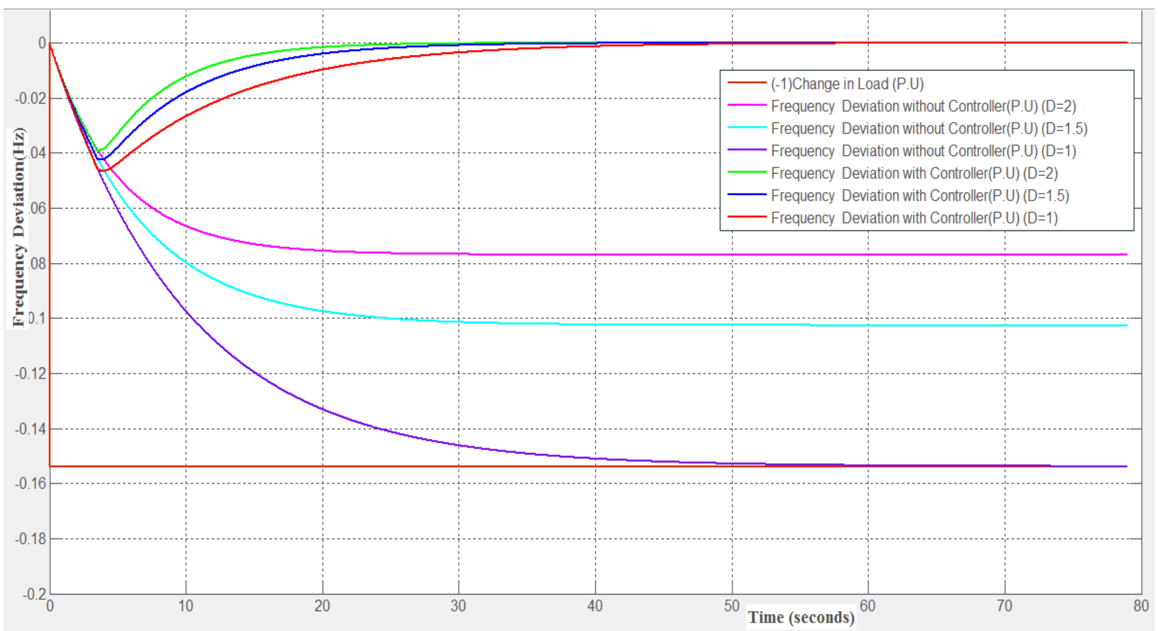


Figure 4.6: Frequency response for 0.15 P.U load rejection (D=1.5, 1 and 2) and (Q=0.25)

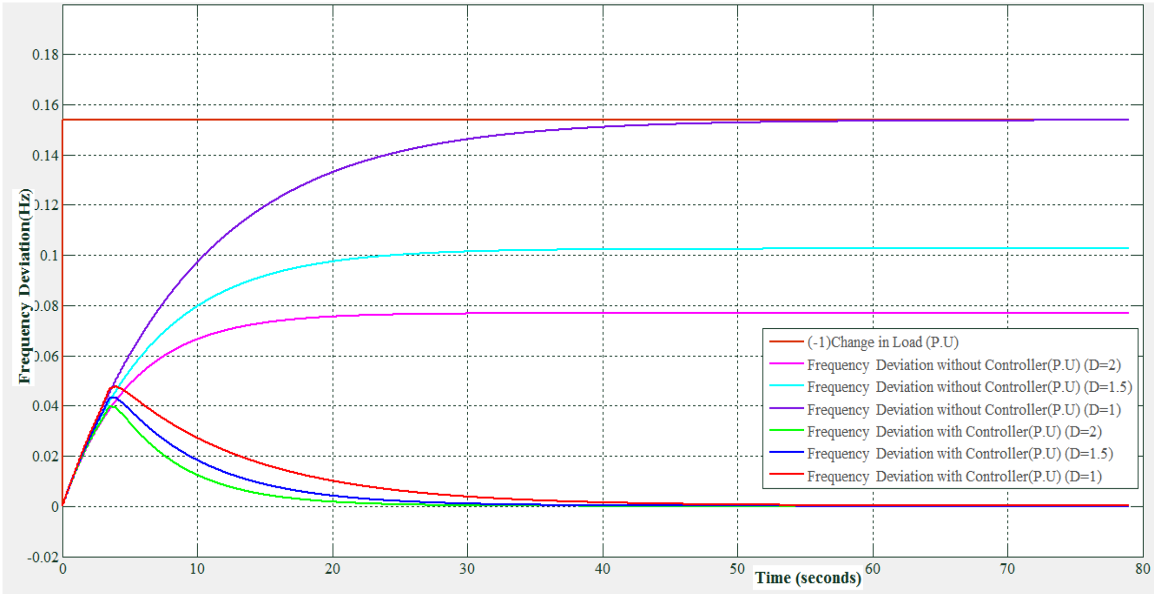


Figure 4.7: Frequency response for 0.15 p.u load addition (D=1.5, 1 and 2) and (Q=0.25)

Table 4.1: Transient and steady state performance of the proposed micro hydro frequency controller for damping constant 1, flow rate of 0.25 and sudden 15%, 35%, 55% and 75% load changes.

ΔP_D = 0.15, 0.35, 0.55 and .75		**Settling time(s)**	**Overshoot (undershoot)**	**Steady state frequency error(P.U)**
		D =1,Q = 0.25		
$\Delta P_D = 0.15$	Without controller	Not settled	2.825%	0.114
	With controller	38.12	0.175%	0
$\Delta P_D = 0.35$	Without controller	Not settled	5.88%	0.296
	With controller	38.68	1.1%	0
$\Delta P_D = 0.55$	Without controller	Not settled	9.72%	0.538
	With controller	39.23	2.28%	0
$\Delta P_D = 0.75$	Without controller	Not settled	13.54%	0.731
	With controller	39.82	3.46%	0

Table 4.2: Transient and steady state performance of the proposed micro hydro frequency controller for damping constants 1.5, flow rate of 0.25 and sudden 15%, 35%, 55% and 75% load changes.

ΔP_D = 0.15, 0.35, 0.55 and 0.75		**Settling time(s)**	**Overshoot (undershoot)**	**Steady state frequency error(P.U)**
		D=1.5,Q=0.25		
ΔP_D = 0.15	Without controller	Not settled	1.55%	0.063
	With controller	26.08	0.05%	0
ΔP_D = 0.35	Without controller	Not settled	3.6%	0.181
	With controller	26.85	0.9%	0
ΔP_D = 0.55	Without controller	Not settled	6.14%	0.309
	With controller	27.17	1.98%	0
ΔP_D = 0.75	Without controller	Not settled	8.7%	0.437
	With controller	27.65	3.04%	0

Table 4.3: Transient and steady state performance of the proposed micro hydro frequency controller for damping constants 2, flow rate of 0.25 and sudden 15%, 35%, 55% and 75% load changes.

ΔP_D =0.15,0.35,0.55 and .75		**Settling time(s)**	**Overshoot (undershoot)**	**Steady state frequency error(P.U)**
		D = 2,Q = 0.25		
ΔP_D =0.15	Without controller	Not settled	0.925%	0.037
	With controller	19.25	0.025%	0
ΔP_D = 0.35	Without controller	Not settled	2.44%	0.123
	With controller	19.76	0.76%	0
ΔP_D = 0.55	Without controller	Not settled	4.36%	0.219
	With controller	20.15	1.76%	0
ΔP_D = 0.75	Without controller	Not settled	6.28%	0.316
	With controller	20.87	2.74%	0

The frequency deviation of the micro hydropower system with PI controller and with fuzzy controller for a 75% load rejection is shown in Figure 4.8. The results are obtained assuming the damping constant of the generator equal to 1, 1.5, 2 and flow rate of water 0.25 m^3/s. From the simulation result, the P.U value of change in demand power is 0.74 P.U, a frequency deviation with PI controller is 0.731, 0.437 and 0.316 P.U and the overshoot is 13.15%, 8.7% and 6.28% for damping constant of the generator equal to 1, 1.5, 2 respectively whereas with fuzzy controller frequency error is eliminated and there is an overshoot of 2.74%, 3.04% and 3.46% and the settling time is 27.65, 20.87 and 39.82sec for damping constant of the generator equal to 2, 1.5, 1 respectively.

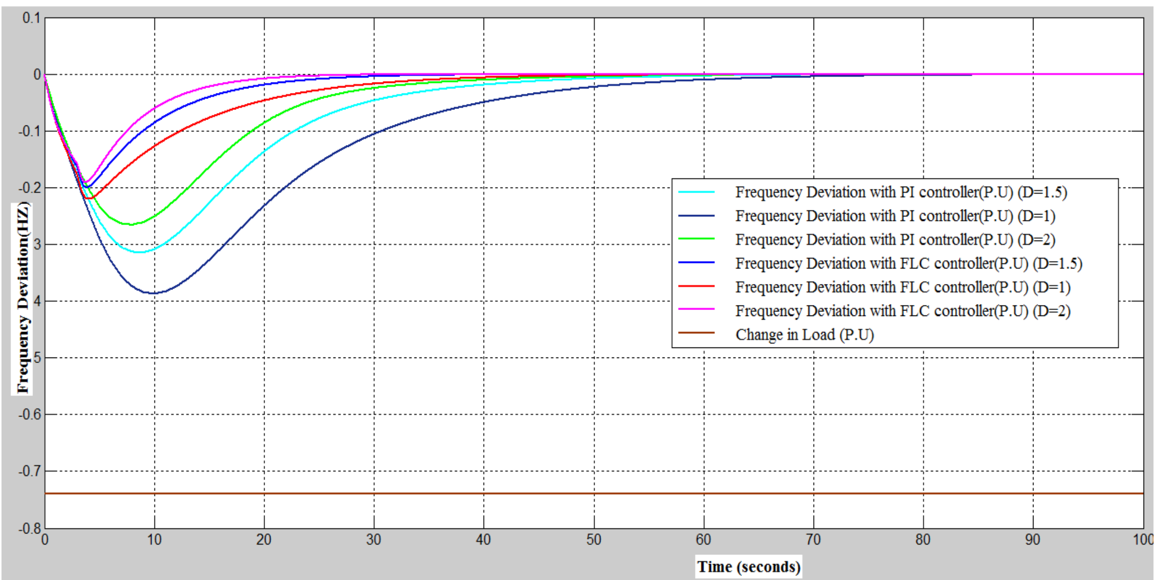


Figure 4.8: Frequency response for 0.75 P.U load rejection (D=1.5, 1 and 2)

Similar tests were done for 15% load change as shown in Figure 4.9 and summarized in Table 4.4 to Table 4.5.

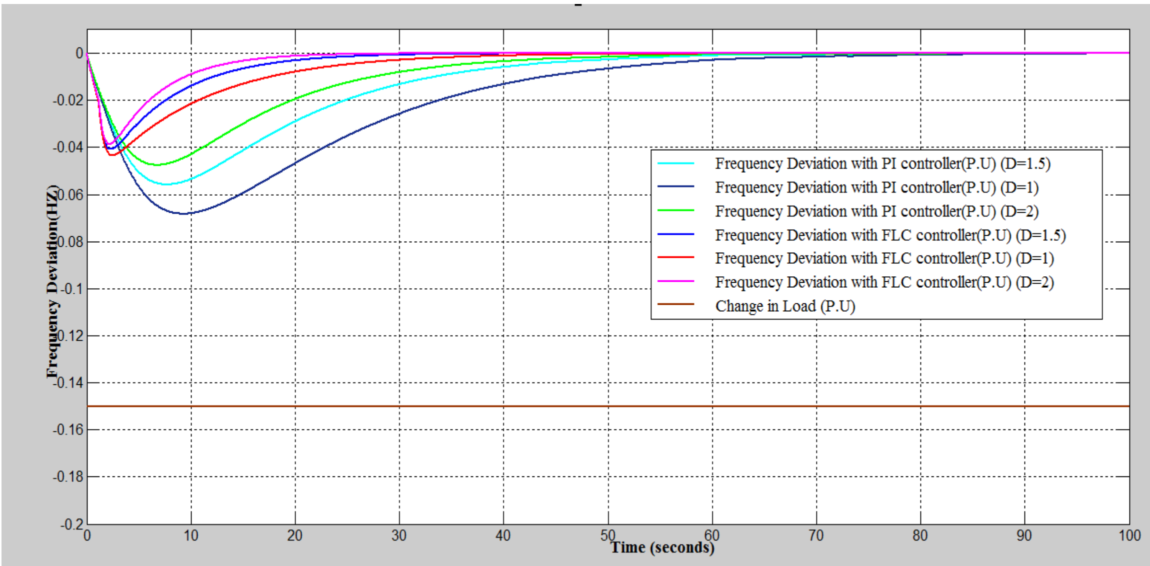


Figure 4.9: Frequency response for 0.15 P.U load rejection (D=1.5, 1 and 2)

Table 4.4: Transient and steady state performance of PI and FLC controller for damping constants 1.5, 1 and 2, flow rate of 0.25 and sudden 75%, load changes.

Controller		Settling time(s)	Overshoot (undershoot)	Steady state frequency error(P.U)
		$\Delta P_D = 0.73, Q = 0.25$		
D =2	With PI controller	69.8	4.42%	0
	With FLC controller	20.87	2.74%	0
D = 1.5	With PI controller	58.7	5.43%	0
	With FLC controller	27.65	3.04%	0
D = 1	With PI controller	47.6	6.82%	0
	With FLC controller	39.82	3.46%	0

Table 4.5: Transient and steady state performance of PI and FLC controller for damping constants 1.5 ,1, and 2, flow rate of 0.25 and sudden 15% load changes.

Controller type		Settling time(s)	Overshoot (undershoot)	Steady state frequency error(P.U)
		ΔP_D = 0.15,Q = 0.25		
D =2	With PI controller	67.2	0.23%	0
	With FLC controller	19.25	0.025%	0
D = 1.5	With PI controller	56.3	0.45%	0
	With FLC controller	26.08	0.05%	0
D = 1	With PI controller	45.7	0.72%	0
	With FLC controller	38.12	0.175%	0

The flow rate of water for micro hydropower plant varies depending on the season and other factor. Thus, to see the effect of variable flow rate on the system the response of the system is tested for flow rate of 0.07, 0.25 and 0.3 m^3/s.

When the flow rate is changed from 0.07m^3/s to 0.3m^3/s all load will be on since the system can produce power that can cover all loads. The frequency deviation of the micro hydropower system without controller and with fuzzy controller for 79% load change and for Q= 0.3m^3/s is shown in Figure 4.10.

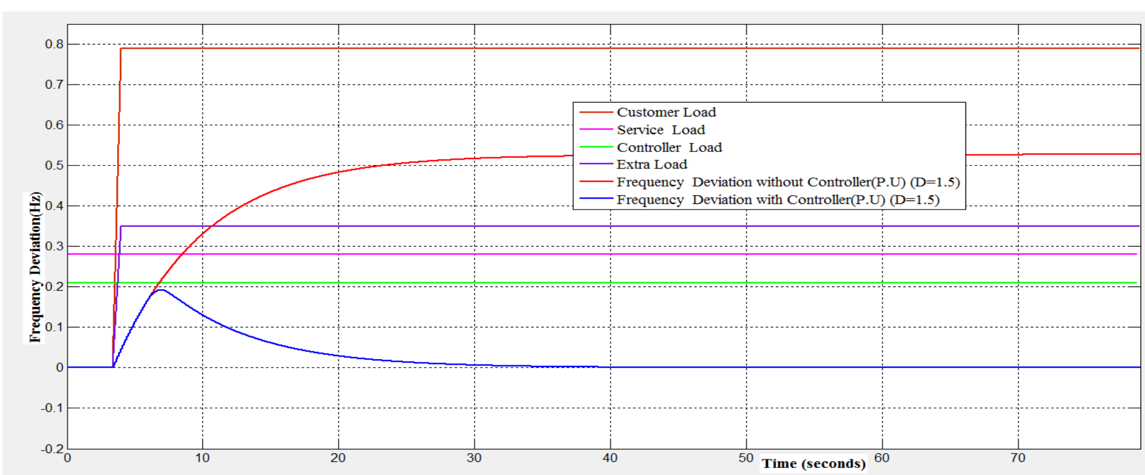


Figure 4.10: Frequency response for 0.79 P.U load addition (D =1.5, Q =0.3)

Similar tests were done for Q = 0.25m3/s, Q = 0.07m3/s.

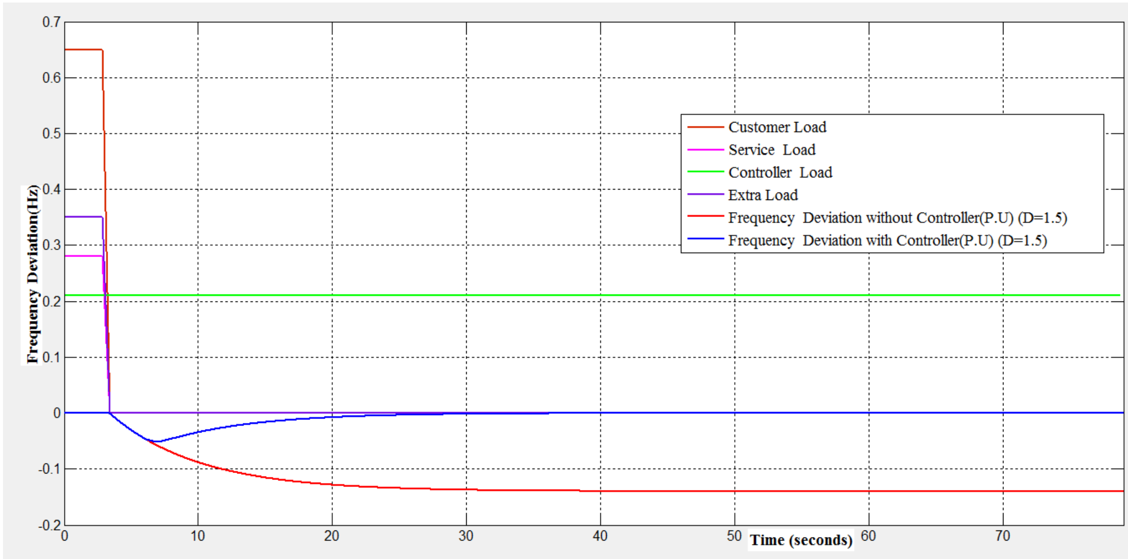


Figure 4.11: Frequency response for 0.65 P.U load rejection (D=1.5, Q=0.07)

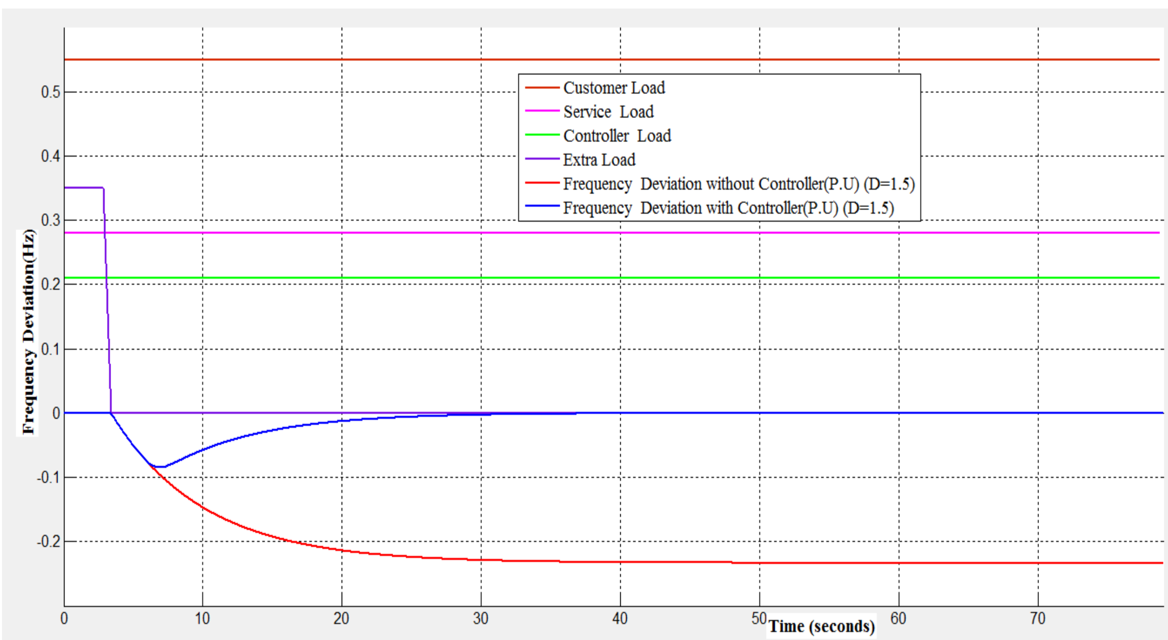


Figure 4.12: Frequency response for 0.35 P.U load rejection (D =1.5, Q = 0.25)

The proposed frequency controller saves energy dissipate compared with electronic load controller (ELC). Figure 4.13, Figure 4.14 and 4.15 shows the capability of fuzzy logic controller to save energy for 75%, 55% and 35% sudden load rejection, respectively. It is observed that when we use Electronic load controller for 35%, 55% and 75% sudden load rejection, the power on the ballast load is increased by 35%, 55% and 75% respectively. However, when fuzzy logic controller is used, the power dissipated on the valve increases initially by 18%, 21% and 24% respectively but it drops to zero after 0.25 seconds. This is achieved as a result of fuzzy logic controller acting on the valves with 35%, 55% and 75% output capacity for the corresponding load rejection.

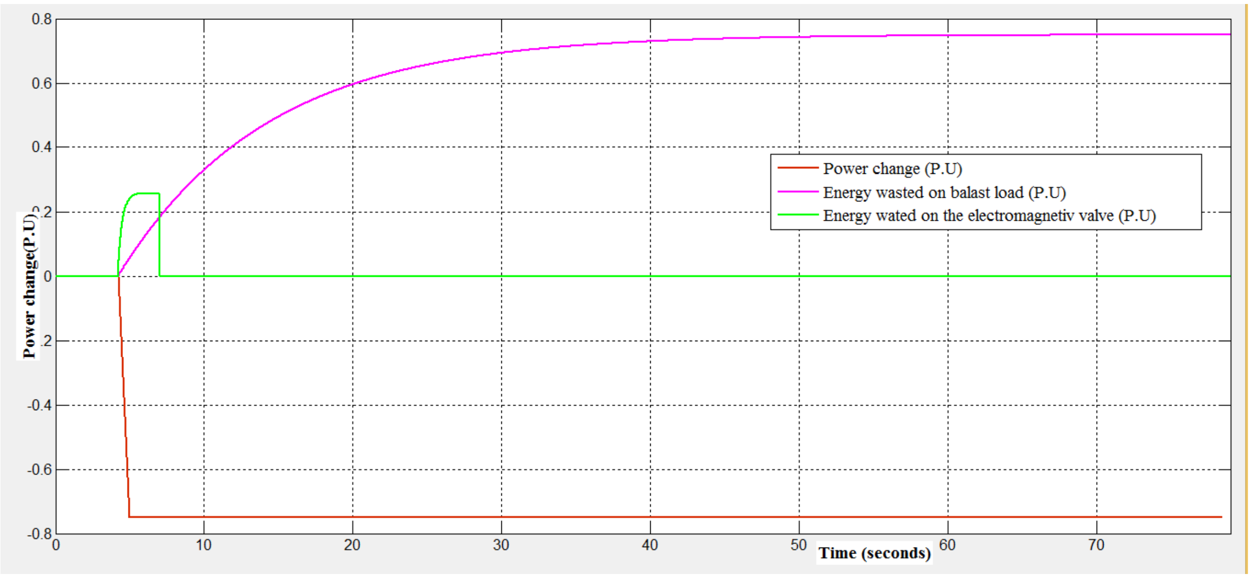


Figure 4.13: Energy dissipate on the valve and on the ballast load for 0.75 P.U load rejection

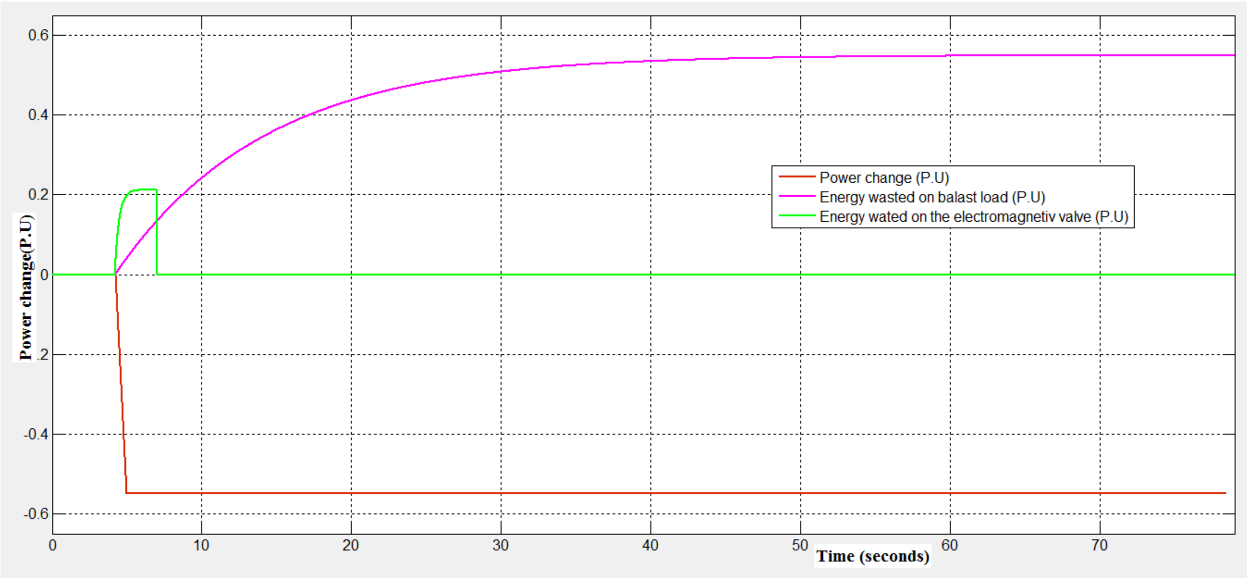


Figure 4.14: Energy dissipate on the valve and on the ballast load for 0.55 P.U load rejection

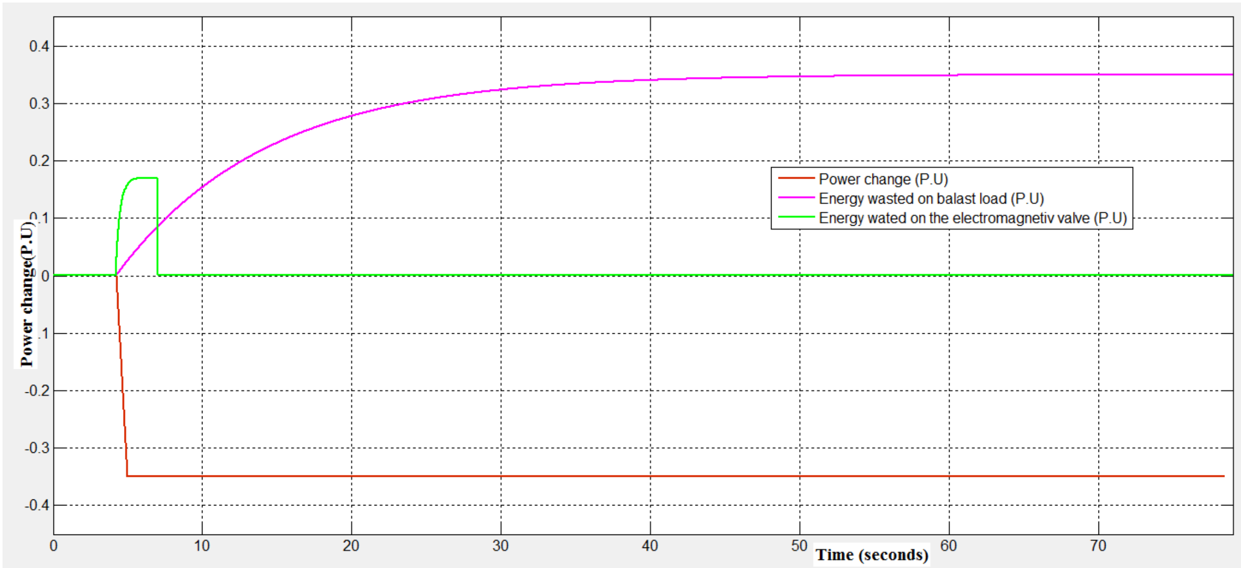


Figure 4.15: Energy dissipate on the valve and on the ballast load for 0.35 P.U load rejection

Table 4.6: Energy dissipate on the valve and on the ballast load for sudden 35%, 55% and 75% load rejection.

PD = 0.35, 0.55 and .75	Energy wasted on the valve (P.U)	Energy wasted on ballast load (P.U)
Pd = 0.35	0.18	0.35
Pd = 0.55	0.21	0.55
Pd = 0.75	0.24	0.75

It is concluded from Figure 4.1 to Figure 4.15 and from Table 4.1 to Table 4.6, that both the transient and steady state performances are improved with fuzzy controller. In addition to this energy dissipate is very small compared with electric load controller, and the controller works efficiently under all operating conditions.

4.3 Discussions

As it was mentioned in the previous section the first objective of the tests performed on the MHPP was to analyze its performance for large load change as well as for small load change.

As it can be seen from Figure 4.1 to Figure 4.10 and from Table 4.1 to Table 4.5, for any change in demand power and varying damping constant, the frequency return to its steady state in a very short time. This illustrates the capability and effectiveness of the proposed fuzzy controller for frequency control of micro hydropower plants.

The second objective of the tests performed on the MHPP was to see how the fuzzy logic controller performs to minimize the effect of frequency deviation on controlling device and other component, which are sensitive for frequency deviation. When water flow rate is high the system can produce more power and can supply power for all loads. However, when the flow rate is low and large amount of customer load are added to the system, the frequency deviation will be high and damage the controlling device and other component, in order to save this devices which are highly affected by frequency deviation, the controller isolate all loads except controller load from the system. Therefore, the controller saves the component by isolating all loads or some of the loads based on the flow rate of water, the proposed fuzzy controller, presented in figure 4.10 to figure 4.12 show different loads which are isolated or added to the system based on flow rate of water.

The third objective of the tests performed on the MHPP was to see how the fuzzy logic controller performs to minimize energy dissipated on the valve while keeping the frequency within the acceptable range for different values of load rejection. It is seen from Figure 4.1 to Figure 4.15 that for any change in demand power, the fuzzy logic controller guaranties the stability of the plant by returning frequency to its steady state in a very short time. Moreover, while controlling the frequency, when loads are rejected the fuzzy controller commands the valve to produce less energy and decreases the dissipated power on the valve. Thus, it also saves water and life time of each component. Figure 4.13, Figure 4.14 and 4.15 shows the capability of fuzzy logic controller to save energy for 75%, 55% and 35% sudden load rejection, respectively.

CHAPTER 5

CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

5.1 Conclusions

Considering the situation in our country where many villages still live without electricity especially those in the rural area, this thesis was aimed to develop a simple and cost effective solution to bring basic energy services to rural areas by using available hydropower resources. Fuzzy controller was proposed to improve MHPP. It can maintain MHPP frequency in spite of load variation, and it can manage the available water depending on flow rate of water by using the available water for only the more preferred load. The proposed controller can be used for micro hydro power plant with different power output and head by varying number and size of valve. Moreover, good transient and steady state responses for different operating points of the processes can be achieved by increasing the number of membership functions.

A mathematical model of micro hydropower plant was developed and tested through simulation using Matlab/Simulink. It is observed from the simulation results that the average overshoot for 75% load change and $0.25m^3/s$ flow rate is 3.04% and the settling time is 27.65 seconds. Moreover, for $0.07m^3/s$ (very low flow rate) and 75% load addition the controller isolate load from the system and save component which can be affected by frequency deviation. In addition to this since there is no power supplied to the valve when average customer load is on, energy wasted on valve is always around zero under steady state condition. It is further observed that energy is not wasted on valve when flow rate is low.

In conclusion, because of all the reasons mentioned above, the proposed fuzzy controller can be recommended as a promising alternative controller to control micro-hydro power plants in regions where no grid will be installed in the future.

5.2 Recommendations

In this thesis, MHPP frequency control system is modeled by assuming linear turbine model however, the performance of the plant can be investigated with a nonlinear turbine model.

The controller can be modified to engage genetic algorithm for further improvements in the performance of the micro hydropower plants. Furthermore, MHPP can be made more accurate and attractive by introducing voltage controller.

5.3 Future work

Of the renewable energies which may be relevant for rural electrification, only MHPP is considered in this thesis. However, there are other renewable energy resource such as solar and wind. Therefore, as a future work, the performances of the proposed controller can be investigated for hybrid system. Moreover, the performances of the frequency controller can be investigated for mini hydro power plant. In addition, the cost benefit of micro hydropower plants with the proposed controller can be analyzed in detail for a certain river that used for rural electrification in Ethiopia, and the hardware of fuzzy logic controller can be developed for micro hydropower plants on this river.

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