Addis Ababa University
Addis Ababa Institute of Technology
School of Electrical and Computer Engineering

COST EFFECTIVE FREQUENCY CONTROL OF MICRO HYDRO-POWER PLANT

A thesis submitted to Addis Ababa Institute of Technology, School of Graduate Studies, Addis Ababa University

in partial fulfillment of the requirement for the Degree of Master of Science in Electrical Engineering (**Electrical Control Engineering).**

By

Hanna Berhanu Tafere

Advisor: Dr. Mengesha Mamo

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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.

Hanna Berhanu ______________
Name Signature

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Place Date of submission

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

Dr. Mengesha Mamo ______________
Advisor Name Signature

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List of Abbreviations

FLFC………………………Fuzzy logic frequency controller

ELC……………………………….Electronic load controller

FPGA………………………Field Programmable Gate Array

IG……………………………………Induction Generator

FL…………………………………………….Fuzzy Logic

MF…………..……………………….Membership Function

FIS……………………...……….Fuzzy Inference System

CLBs……………………………Configurable Logic blocks

ASICs……………...Application Specific Integrated Circuits

OTP………………….………….One-time Programmable

FLC…………………………..…….Fuzzy Logic Controller

A/D……………………………………….Analog to digital

D/A……………………………………….Digital to Analog

ROM……………………………………Read only Memory

GUI….…………………………….…Graphical user interface

VHDL……….…...…VHSIC Hardware Description Language

VHSIC……………….Very High Speed Integrated Circuits

EDA…………………………..Electronic design automation

IOB…………………………….………Input Output Block

SRAM………………………..Static random-access Memory

PLD…………………………….Programmable logic device

AGC…………………………Automatic generation control

NB……………………………………….....Negative Big

NM……………………….…………...Negative medium

NS……………………………..………Negative small

Z……………………………………………..…….Zero

PS……………………………………...…Positive small

PM………………………….…………Positive medium

PB…………………………………………..Positive big

AVC1……………….……Actuator valve normally closed 1

AVC2……………….……Actuator valve normally closed 2

AVC3…………………Actuator valve normally closed 3

AVC4…………………Actuator valve normally closed 4

AVO1………………..….Actuator valve normally open 1

AVO2…………………...Actuator valve normally open 2

AVO3……………..…….Actuator valve normally open 3

AVO4…………………...Actuator valve normally open 4

List of Notations/Symbols

P_{out}……………………………………………….output Power

T……………………………………………………...Torque

F……………………………………………………..Force

Pin…………………………………………….power input to turbine

H……………..…………………….total available head at turbine inlet

ρ…………………………………………………density of water

Q…………………..………………………volume flow rate of water

G…………………….……………gravitational acceleration

ω…………………………………………….rotational speed

η…………………………………….…………Efficiency

Q……………………………………………….....Flow rate

M…………………………………….………………Moment

G………………………………….………turbine gate position

N……………………………………turbine rotational speed

li…………………………………………………….……length

Ai……………………………..……………cross-section area

v…………………………………………………...water speed

Tw………………………………….………….water time constant

D………………………………..generator damping constant

V…………………………………………...electrical voltage

R……………………………..……………………resistance

I…………………………………………………………current

ABSTRACT

Micro Hydro-Power Plants (MHPPs) are a reliable solution for supplying small power consumers in areas located far from the distribution grid. However controlling frequency of the generated power is one of the main problems in micro hydro power plants. This thesis presents a control structure that ensures the frequency regulation of an induction generator (IG). Induction generator is chosen over synchronous generator because it has an advantage with price, robustness, simpler starting and controlling mechanism.

The main work of this thesis is to design a cost effective frequency controller for MHPP. For the control of the frequency, a fuzzy logic controller is used. The controller is modeled, designed and simulated to be simple, fast response fuzzy logic based frequency control system and lower cost. For lower cost, the fuzzy logic controller is realized using Field Programmable gate array rather than microcontrollers.

The frequency controller controls frequency of the micro hydro-power plant nearly constant. When the flow of water is minimum, the controller is designed to prevent component from damage by initiating a shutdown. It is observed from the simulation results that the overshoot of the fuzzy controller for 75% load change and 0.2 m^3/s flow rate is 2.74%, 3.04% and 3.46% and the settling times are 20.87, 27.65 and 39.82 seconds. Moreover, the comparison of fuzzy logic controller and PI controller is observed.

The fuzzy logic controller has been coded, compiled and simulated in VHDL using ModelSim-Altera. From simulation result, the system inferred maximum operating frequency is 5 MHz with a critical path of 199.3 ns.

Key words: Micro Hydro-power plant, Fuzzy Logic Controller, Induction Generator, VHDL

CHAPTER 1
INTRODUCTION

1.1 Background

Well-being of people living in urban and rural areas depends upon availability of energy. Energy is a very important factor for the developing of a country. This is because shortage of energy restricts people to use technologies. And if people have no access to technologies, there life would be hard to live. For the developing countries like Ethiopia energy is a main source for development. Especially for economic growth energy plays a big role, industries, hospitals, railways, universities, transportation and other organization use energy in daily works. So energy is an essential for countries all over the world.

The problem of increasing need for electricity is best addressed by encouraging energy conservation and the development of alternate energy sources. Other choices are building large scale hydroelectric, thermal and nuclear plants. All of this has major environmental, social and economic costs. The interest in distributed generation and renewable energy systems, such as mini-hydro, wind, solar, biomass and wave units have increased considerably for many reasons. Among them climate change, population growth, continuous need for energy and the harmful effect of the use of fossil fuels to the environment are reasons for renewable energy systems.

In Ethiopia hydro power plant is a main source of energy. But there are other renewable source of energy such as wind, solar, biomass and geothermal source of energy. But the desire for energy by the people is not fully satisfied. Especially those people living in rural areas of Ethiopia don’t have the access to electricity. This is because; the expansion of central electricity grid to areas that do not have electricity is either financially not possible or practical as these locations are geographically isolated and have a very low power demand and insufficient EEP’s power supply [1].

The water in small rivers can be used for electrical power generation using small hydro power plants. Small hydro generation plays an important role in electrification of rural and remote areas in developing countries. In rural areas of Ethiopia there are rivers which are used for only agricultural purpose but these rivers can be used for Small hydro generation. Small hydro generation can be Mini Hydro Power Plant, Micro Hydro Power Plant and Pico Hydro Power Plant. The generating capacity of Small hydro is up to 10 megawatts (MWs) [2]. The Mini Hydro is usually scaled less than 1000 kilowatts (KWs), and the Micro Hydro is less than 100 kilowatts (KWs) [2].

Micro Hydro Power Plant (MHPP) supplies electricity to small community in rural area (Dolf, 2012). Micro Hydro Power can be made on small streams, canals and river branch in the mountainous areas. Micro Hydro Power technology does not require the building of dam, reservoir or the storage of water. This makes Micro Hydro Power technology advantageous. The running water is only sidetracked from a river through a power channel towards a power house. The water that is used to run a turbine is taken from the same river with no loss. It requires no ignition of fuel of gas. Only water is used which is the natural source our country Ethiopia is rich of.

The impact of generating power from Micro Hydro Power Plant is to keep the parameters of power plants output power within their permissible limits. It is very important keeping the parameters of the output power for appropriate performance and effective use. In large hydropower system the mechanical governor is used to control the flow of water across the turbine to match the power produced to the demand from the grid. But mechanical control system is complicated to reduce and smaller account tends to be as expensive as the larger ones, this is because the cost per kW rises abruptly as the size is reduced. Mechanical control system is not a good choice for cost effective Micro Hydro Power Plant.

1.2 Problem Statement

In order to satisfy the people in rural area of Ethiopia with electrification MHPP is one choice. But people living in rural area and remote area of our country cannot afford the money for the implementation; they also cannot afford the money for the maintenance after it is implemented. Controlling the frequency of MHPP is one of the main problems. Frequency control is one of the most important topic in power system, since it is an indicator of energy balance and power quality in the system. The frequency control system is proposed to be low cost, easy to be understood and efficient so that the people in rural area can afford the maintenance cost.

There are different types of frequency controllers. The frequency can be controlled by governors. The electronic load controllers (ELC) govern the frequency by regulating the electrical load connected to the generator of the alternating current. Therefore, they maintain a constant electrical load on the generator in spite of changing users' load. The other governor which is the turbine governor, it governs by remain constant on the gate opening position to produce just the necessary power according to the connected load. This former governor takes a long time to stabilize the output and it becomes insufficient in case of large load variations where the stability of the system could be completely lost. So turbine governor has its own problem. Also The ELC waste useful energy that can be used gainfully. There are frequency controllers which are locally factory-made. But these are not wealthy and industrialized.

This thesis works on the low cost frequency control design. This frequency controller is cost effective, fast frequency control and fewer complexes. MHPP needs control to preserve an uninterrupted power at rated frequency. When there is modification on the grid load, variation are caused between turbine power output and the load [3].Also the water level affects the output frequency. When the users connect machines that need high levels of power, there will be large drop of frequency. The proposed fuzzy controller is designed to prevent all of these problems by keeping the frequency of the Micro Hydro Power Plant nearly constant. The fuzzy controller is an effective control in order to assure a good level of control. Furthermore the proposed controller is less expensive when compared with the frequency governors.

1.3. Objective of the thesis

1.3.1. General Objective

The general objective of this thesis is to design a low cost frequency controller for Micro Hydro Power Plant (MHPP).

1.3.2. Specific Objective

The specific objectives of the thesis are:

1. To study the Micro Hydro Power Plant model based on the mathematical equations.
2. To design a fuzzy controller using MATLAB (Fuzzy Inference System).
3. To code using the language VHDL.
4. To evaluate the performance of the controller using ModelSim-Altera.

1.4 Outline of the thesis

Chapter 1 which is the Introduction includes the background, problem description and the objective as well as the contribution of the thesis.

Chapter 2 the Literature review chapter begins with the introduction of MHPP and followed by the mathematical model of the MHPP and closed by the literature review.

The third is ***Chapter 3*** which is the Methodology; it starts with the introduction and followed by the description of fuzzy logic controller and FPGA.

The design of the controller takes place in ***Chapter 4,*** which is sub categorized by introduction, fuzzy logic controller design included fuzzifier design, rule and Defuzzification design.

Chapter 5 is dedicated to the evaluation of the performance of the fuzzy logic controller, the result obtained and a discussion is also held in this chapter.

The last is ***Chapter 6,*** in this chapter the conclusions, recommendations and suggestions for future work are all presented.

CHAPTER 2
Literature Review

2.1. Introduction

In today's life electricity plays an important role. In the wake of the issue of climate change, environmental degradation, population growth and non-stop need for electricity have made the renewable energy a top and important topic in the world. Micro Hydro Power Plant generation is one of the best finding of a renewable energy. Detail on MHPP and part of the components of MHPP are presented in this chapter. In addition, the mathematical model of the MHPP, different works on MHPP by different researches and unique aspects of the thesis are discussed in this chapter.

2.2. Micro Hydro Power Plant

Micro Hydro Power Plant is a type of hydroelectric power plant that typically produces from 5 KW to 100 KW of electricity using the natural flow of water. These power plants can provide power to an isolated home or small community, small factories and to supply an independent local mini-grid. They are also sometimes connected to electric power networks, particularly where net metering is offered. There are many of these installations around the world, predominantly in developing countries as they can provide an economical foundation of energy without the buying of fuel [4]. Micro Hydro Power Plant can be made on small streams, canals and river tributes in the hilly areas. This plant does not require the storage of water or building a reservoir or dam. It will produce power only by the flow of water or it might have small water storage ability. They are located in mountainous areas where hydropower resources are available. For villages far from the national grid, MHPPs are the best choice for electricity. MHPPs are not that much different from large hydro systems, except their power rating. The principles of operation, types of material units, the mathematical equations used and design of system components are essentially the same as large hydro power plants [5].

Micro Hydro Power Plant is the best option for providing a reliable and cheap energy to the rural communities of Ethiopia. In rural area of Ethiopia, the rivers are used for agricultural purpose, drinking for humans as well as animals and for washing clothes. But these rivers can be a source of energy. The geography of Ethiopia, with mountainous areas interconnected with rivers, streams and canals make MHPP implementation appropriate. Ethiopia has a population of 94 million, 85% of which living in the rural areas. The rate of electrification in the country is 10% and for rural Ethiopia it is almost zero (less than 1%) [6]. This 85% rural area people have very small chance to get electricity through the national grid. Also extending the national grid to rural area seems economically and mechanically not possible. Because of this, MHPPs could play a vital role to electrify off-grid rural areas of Ethiopia [1].

2.2.1. Components of Micro Hydro Power Plant

Micro Hydro systems have the following components: Electromechanical components

- A water turbine that converts the energy of flowing or failing water into mechanical energy that drives a generator, which generates electrical power-this is the heart of a micro hydropower system.
- A control mechanism to provide stable electrical power
- Electrical transmission lines to deliver the power to its destination

2.2.1.1 Civil work components

- An intake which includes trash racks, a gate and an entrance to a canal, penstock or directly to the depending on the type of development. The intake is generally built of reinforced concrete, the trash rack of steel, and the gate of wood or steel.

- A canal, tunnel and/or penstock, which carries the water to the powerhouse in developments where the powerhouse is located at a distance downstream from the intake. Canals are generally excavated and follow the controls of the existing terrain. Tunnels are underground and excavated by drilling and blasting or by using a tunnel-boring machine. Penstocks, which convey water under pressure, can be made of steel, iron, fiberglass, plastics, concrete or wood.
- A forebay tank and trash rack to filter debris and prevent it from being drawn into the turbine at the penstock pipe intake
- A penstock pipe to convey the water to the powerhouse

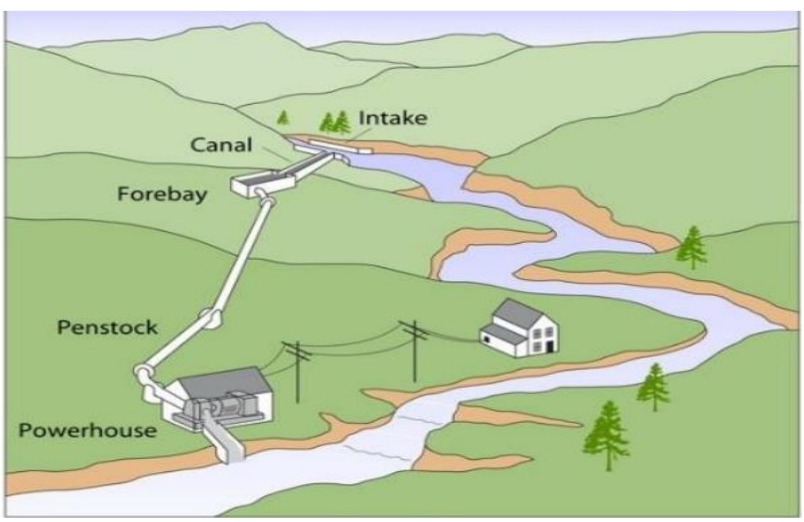

Figure 2.0.1: Micro hydro-power system [7]

Intake

The intake should be well located to prevent debris and high flows from being funneled into the intake. The intake may have a gate to allow the system to be dewatered for inspection and maintenance. Figure 2.2 shows an Example of an intake of a MHPP.

Figure 2.0.2: Example of an intake of a MHPP [8]

Canals

This is an excavated canals built of concrete, stone or would metal sheet. Most power conduits have enough slopes for water to flow. A pipe can also be used as a low pressure power conduit. It connects the intake and forebay.

Forebay

This is a basin located fast before the entrance to the penstock. It could be simple excavated area or pond or made of reinforced concrete. It maybe or may not exist and serves as a settling basin for sand and silt which damage turbine blades. It can also serve as storage.

Spillway

This is meant to get rid of excess water in the forebay. The spillway water must be safely directed to prevent excessive erosion of the forebay.

Penstock

This is pipe that conveys water under high pressure to the turbine wire mesh of reasonable strength should be put in front of the penstock to sieve unsettled sand. It can be installed above/ below the ground excessive template expansion of joints. Gates and valves can be incorporated at the end of the penstock.

Power house

This serves as an Engine room. It protects the turbine, generator and other electrical/machinery equipment. It could also have a workshop/office/sanitary and other facilitates.

Tail race

This is a short, open canal that leads water from power course back to the stream.

2.2.1.2 Electrical and Mechanical components of MHPP

Hydropower is based on the principle that flowing and falling water has a certain amount of kinetic energy potential associated with it. Hydropower comes from converting the energy in flowing water, by means of a water wheel or turbine, into useful mechanical energy. The energy can then be converted into electricity through means of an electric generator. Electrical and mechanical components of a micro hydro power plant are the turbine, generator, actuator and the driver.

Turbines

Hydropower is an environmentally friendly and efficient way to supply surrounding areas with power and electricity to live their daily lives. Engineers have the ability to produce mechanisms or create environments that cause water to produce energy naturally, which can be transferred into a generator to produce electricity. One way of producing this water energy is through use of a turbine. A turbine is a mechanism that accepts moving water, and contains a wheel or rotor that spins as the water impacts one of its blades. The faster the flow rates of water, the higher the frequency of the wheel or rotor. This rotation drives a shaft connected to the generator which ultimately produces power. There are guide vanes or wicker gates that can control the flow of water impacting the blades and therefore output power, which ultimately controls the efficiency of the turbine.

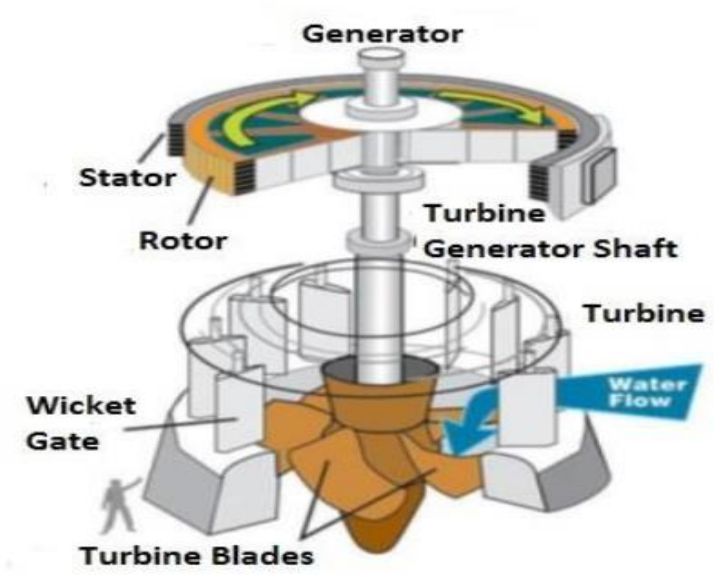

Figure 2.0.3: Kaplan turbine and electrical generator cut-away view [9]

All components of a hydropower system revolve around the turbine. The turbine converts hydraulic power from the water flowing from the reservoirs into mechanical shaft-power for the generator. There are different types of water turbines; they can be used in micro hydro installations. The turbine selection is contingent on the head of water, the volume of flow, and such factors [10].The hydraulic turbine classified according to the basis of energy intake as impulse turbine and reaction turbine. According to the direction of flow of water;axial flow turbines, radial flow turbines, tangential flow turbines and mixed flow turbines.According to the specific speed of the turbine, low specific speed turbine, medium specific speed turbine and high specific speed turbine. Also they are classified according to the water head and quality of water available as high head and small quantity of water flow, medium head and medium flow rate, low head and large flow rate.

Impulse turbine: the pressure of liquid does not change while flowing through the rotor of the machine. The total head of the entering fluid is changed into a great velocity head at the exit of the supply nozzle. One example of impulse turbine is Pelton wheel.

Reaction turbine: the pressure of liquid changes while it flows through the rotor of the machine. The change in fluid velocity and reduction in its pressure causes a reaction on the turbine blades; this is where the name reaction turbine may have been derived. Francis and Kaplan turbines can be an example of reaction turbine. In a reaction type turbine there are two types of energy conversions. First, the turbine is completely submerged in water, which creates a pressure drop between the inlet and outlet that is converted into axial power, also called the reactive part. Secondly, impulse forces are created because of changes in velocity vectors when the water flows between the turbine blades

The selection of turbine depends mainly on the plant's head and available flow.

Table 1 Types of Turbine

Kaplan	Used for low head, high flow plants
Pelton	Used for high head, low to medium flow plants
Francis	Used for medium to high head, medium flow plants

Spiral casing

Most of these machines have vertical shafts although some smaller machines of this type have horizontal shaft. The fluid enters from the penstock (pipeline leading to the turbine from the reservoir at high altitude) to a spiral casing which completely surrounds the runner. This casing is known as scroll casing or volute. The cross-sectional area of this casing decreases uniformly along the circumference to keep the fluid velocity constant in magnitude along its path towards the stay bane. This is so because the rate of flow along the fluid path in the volute decreases due to continuous entry or the fluid to the runner through the openings of the stay vanes. This is one of the main features that differentiate a Francis from other turbine types, only a part of the total specific energy at the inlet of the turbine is converted to kinetic energy before the runner is reached. The guide banes can also be used to regulate the flow rate.

Stay Vanes and Wicket Gates

Water flow is directed toward the runner by the stay vanes as it moves along the spiral casing, and then it passed through the wicket gates. The basic purpose of the wicket gate is to convert a part of pressure energy of the fluid to the kinetic energy and then to direct the fluid on to the runner blades at the angle appropriate to the design. Moreover, they are pivoted and can be turned by a suitable governing mechanism to regulate the flow while the load changes. The wicket gates impart a tangential velocity and hence an angular momentum to the water before its entry to the runner.

Runner

It is the main part of the turbine that has blades on its periphery. During operation, runner rotates and produces power. For a mixed flow type Francis Turbine, the flow in the runner is not purely radial but a combination of radial and axial. The flow is inward, i.e. from the periphery towards the Centre. The main direction of flow changes as water passes through the runner and is finally turned into the axial direction while entering the draft tube.

Power and Efficiency Expressions

Considering runner generates torque of T with a rotational speed of N (rev/s), then power obtained from the runner can be expressed as:

$$P_{out} = T*\omega \qquad (2.2.1)$$

$$T = F*r \qquad (2.2.2)$$

$$\omega = 2\pi N \text{ [rad/s]} \qquad (2.2.3)$$

Where:

- *F* is the force in pounds or newton's.
- *r*is the radius or distance from the center to the edge in feet or meters.

The total head available at the nozzle is equal to gross head less losses in the pipeline leading to the nozzle (in the penstock) and denoted by *H*. Then available power input to the turbine becomes:

$$P_{in} = \rho gQH \qquad (2.2.4)$$

Where:

- P_{in} power input to turbine
- H total available head at turbine inlet [m]
- ρ density of water [kg/m^3]
- Q volume flow rate of water [m^3/s]
- G gravitational acceleration [m/s^2]

During conversion of energy (hydraulic energy to mechanical energy or vice versa) there occur some losses. They can be in many form and main causes of them are friction, separation and leakage [15.16].

For a turbine:

Fluid Input Power = Mechanical loss + Hydraulic losses + useful shaft power output

Where:

Hydraulic Losses = Impeller loss + Casing loss + Leakage loss

Considering all losses as one term:

$$P_{in} = P_{loss} + P_{out} \qquad (2.2.5)$$

Then, overall efficiency of turbine becomes:

$$\eta = \frac{\text{Pout}}{\text{Pin}} = \frac{\text{T}\omega}{\rho\text{gQH}} \qquad (2.2.6)$$

Generator

There are two types of generators used in hydroelectricity power generation. They are synchronous generators and induction generators. Induction machines are the most used electro-mechanical device. An induction generator is simple and rugged design, low-cost, low maintenance and direct connection to an Ac power sources. Synchronous generators are generators which are mostly used in large scale power generation. Synchronous 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. Whereas when the power output levels are generally low (less than 10 MW), induction generators are widely used. Both synchronous and induction generators have the ability to be used connected to the grid or standalone operation [17].

Actuator

An actuator is an element of a machine that is in charge for moving and controlling a mechanism or system. It requires a control signal and a source of energy to operate. The control signal might be electric voltage or current, air or human power. It is a mechanical device that takes energy and converts it into some kind of motion.

Drive Systems

The drive system couples the turbine to the generator. At one end, it allows the turbine to spin at the velocity that delivers the best efficiency. At the other end, it drives the generator at the velocity that produces correct voltage and frequency (frequency applies to alternating current systems only).The most efficient and reliable drive system is a direct, 1 to 1 coupling between the turbine and generator. This is possible for many sites, but not for all head and flow combinations. In many situations, especially with AC systems, it is necessary to adjust the transfer ration so that both turbine and generator run at their optimum (but different) speeds. These types of drive systems can use gears, chains, or belts, each of which introduces additional efficiency losses into the system. Belt systems tend to be more popular because of their lower cost [18].

2.3 PI Controller

A controller in the forward path, which changes the controller output corresponding to the proportional plus integral of the error signal is called PI controller. The PI controller increases the order of the system, increases the type of the system and reduces steady state error tremendously for same type of inputs.

2.4 Fuzzy Logic Controller

The concept of Fuzzy Logic (FL) was first introduced by Zadeh (1965) which is defined as the logic of human thinking. It deals with problems in engineering as a way of processing data which allows partial set membership rather than crisp set membership or non-membership by giving degrees of certainty to the answer of a logical question. In contrast to classical logic which is based on crisp sets of "true and false", fuzzy logic views problems as a degree of "truth", or "fuzzy sets of true and false. It provides a simple way to arrive at a definite conclusion and does not require precise, noise-free information and can be programmed safely. The output control of FL is a smooth control function a wide range of input data. [24-26].

Fuzzy controllers are used to control consumer products, such as washing machines, video cameras, and rice cookers, as well as industrial processes, such as cement kilns, underground trains, and robots. Fuzzy control is a control method based on fuzzy logic. Just as fuzzy logic can be described simply as "computing with words rather than numbers"; fuzzy control can be described simply as "control with sentences rather than equations". A fuzzy controller can include empirical rules, and that is especially useful in operator controlled plants.

Today control systems are usually described by mathematical models that follow the laws of physics, stochastic models or models which have emerged from mathematical logic. A general difficulty of such constructed model is how to move from a given problem to a proper mathematical model. Undoubtedly, today's advanced computer technology makes it possible; however managing such systems is still too complex. These complex systems can be simplified by employing a tolerance margin for a reasonable amount of imprecision, vagueness and uncertainty during the modeling phase. As an outcome, not completely perfect system comes to existence; nevertheless in most of the cases it is capable of solving the problem in appropriate way. Even missing input information has already tuned out to be satisfactory in knowledge-based systems.

Fuzzy logic allows to lower complexity by allowing the use of imperfect information in sensible way. It can be implemented in hardware, software or a combination of both. In other words, fuzzy logic approach to problems' control mimics how a person would make decisions, only much faster.

In control systems, the inputs to the systems are the error and the change in the error of the feedback loop, while the output is the control action. The general architecture of a fuzzy control is depicted in figure 2.4. To implement fuzzy logic technique to a real application requires the following three steps:

- **Fuzzification** – convert classical data or crisp data into fuzzy data or membership functions (MF).
- **Fuzzy Inference Process** – combine membership functions with the control rules to derive the fuzzy output.
- **Defuzzification** – use different methods to calculate each associated output and put them into a table: the lookup. Pick up the output from the look-up table based on the current input during an application.

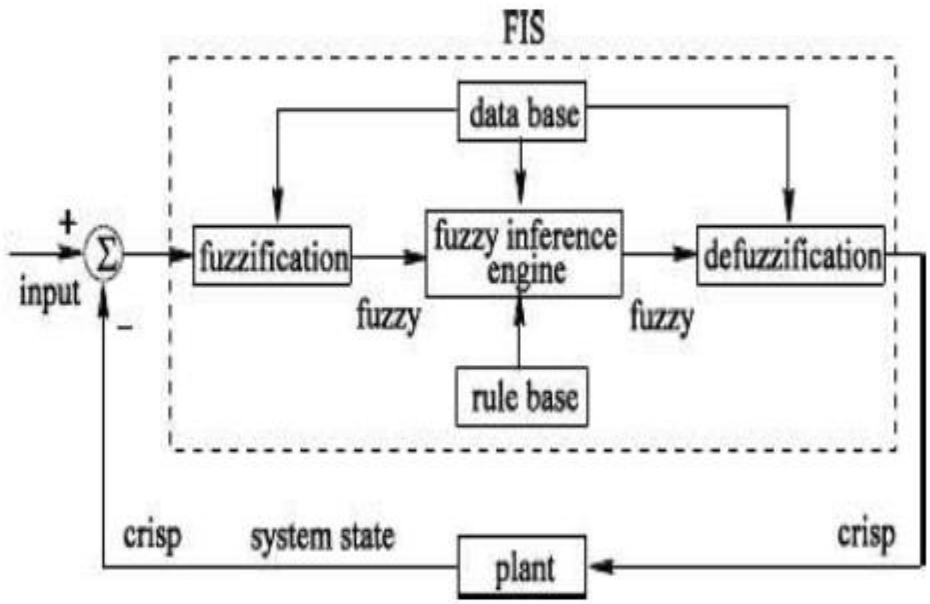

Figure 2.0.4 Fuzzy Logic Controller [25]

2.4.1 Fuzzification

Fuzzification is the process of making a crisp quantity _fuzzy‘. We do this by simply recognizing that many of the quantities that we consider to be crisp and deterministic are actually not deterministic at all: they carry considerable uncertainty. If the form of uncertainty happens to arise because of imprecision, ambiguity, or vagueness, then the variable is probably fuzzy and can be represented by a membership function.

In the real world, several devices such as a digital voltmeter generate crisp data, but these data are subject to experimental error. The information shown in Figure 2.5 shows one possible range of errors for a typical voltage reading and the associated membership function that might represent such imprecision.

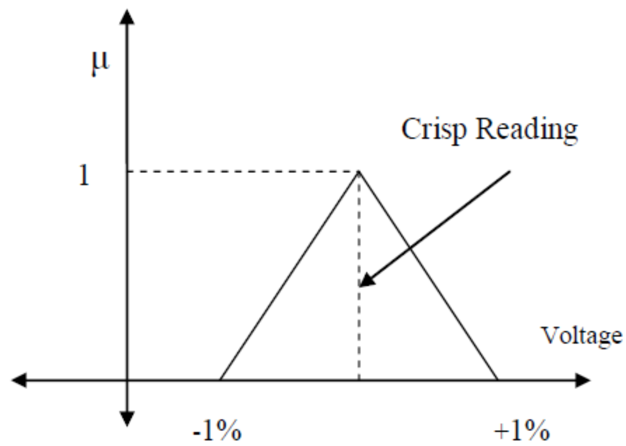

Figure 2.0.5 Membership functions showing imprecision in 'crisp voltage reading'

Since the membership function essentially embodies all fuzziness for a particular fuzzy set, its description is the essence of a fuzzy property or operation. Just as there are an infinite number of ways to characterize fuzziness, there are an infinite number of ways to graphically depict the membership functions that describe this fuzziness. The most common forms of membership functions are those that are normal, monotonic and symmetrical.

Because of the importance of the "shape" of the membership function, a great deal of attention has been focused on development of these functions. The membership functions associate a weighting factor with values of each input and the effective rules. These weighting factors determine the degree of influence or degree of membership (DOM) each active rule has. By computing the logical product of the membership weights for each active rule, a set of fuzzy output response magnitudes are produced. All that remains is to combine and defuzzify these output responses [27]

2.4.2 Rule Base

The rule base is used to describe fuzzy sets and fuzzy operators in form of conditional statements. A single fuzzy if-then rule can be as follows,

If x is A then y is Z,

Where A is a set of conditions that have to be satisfied and Z is a set of consequences that can be inferred. In rule with multiple parts, fuzzy operators are used to combine more than one input: AND = min, OR = max and NOT = additive complement. Geometrical demonstration of fuzzy operators is shown in figure 2.6

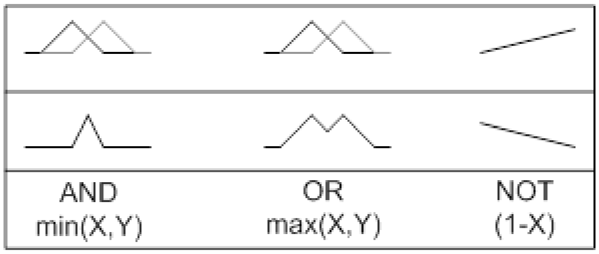

Figure 2.0.6 Graphical interpretations of fuzzy operators [27]

The rule base is a simple graphical tool for mapping the fuzzy logic control system rules. It accommodates two or more input variables and expresses their logical product (AND or OR) as one output response variable. The degree of membership for rule matrix output can take value of maximum, minimum of the degree of previous of the rule [28]. It is often probable, that after evaluation of all the rules applicable to the input, we get more than one value for the degree of membership. In this case, the simulation has to take into consideration, all three possibilities, the minimum, the maximum or an average of the membership-degrees.

2.4.3 Fuzzy Inference

Inference mechanism allows mapping given input to an output using fuzzy logic. It uses all pieces describes in previous sections: membership functions, logical operations and if-then rules. The most common types of inference systems are Mamdani and Sugeno. They vary in ways of determining outputs.

Mamdani method

Below examples ate based on two fuzzy control rules in the form of

R_1: if x is A_1 and y is B_1 then z is C_1

R_2: if x is A_2 and y is B_2 then z is C_2

Result: z is C_i where x equals x_o and y equals y_o.

The firing levels of the rules, denoted by α_i, i = 1, 2 are calculated by,

$$\alpha_1 = A_1(x_o) \wedge B_1(y_o) \qquad (2.4.1)$$

$$\alpha_2 = A_2(x_o) \wedge B_2(y_o) \qquad (2.4.2)$$

The individual rule outputs are derived by,

$$C_1'(\omega) = (\alpha_1 \wedge C_1(\omega)) \qquad (2.4.3)$$

$$C_2'(\omega) = (\alpha_2 \wedge C_2(\omega)) \qquad (2.4.4)$$

Then the overall system output is calculated by the individual rule outputs,

$$C(\omega) = C_1'(\omega) \vee C_2'(\omega) = (\alpha_1 \wedge C_1(\omega)) \vee (\alpha_2 \wedge C_2(\omega)) \qquad (2.4.5)$$

Finally, to obtain a deterministic control action, chosen Defuzzification mechanism must be implemented.

Sugeno method

Below examples are based on two fuzzy control rules in the form of

R_1: if x is A_1 and y is B_1 then z is $z_1 = a_1x_1 + b_1y_1$

R_2: if x is A_2 and y is B_2 then z is $z_2 = a_2x_2 + b_2y_2$

Result: z_o, where x equals x_o and y equals y_o.

The firing levels of the rule are calculated in the same way as in Mamdani method, based on (2.4.1) and (2.4.2) equations. The individual rule outputs are calculated from the below relationships,

$$z_1 = a_1x_0 + b_1y_0 \qquad (2.4.6)$$

$$z_2 = a_2x_0 + b_2y_0 \qquad (2.4.7)$$

If there are n rules in the rule matrix, the crisp control result derived from the following equations,

$$z_o = \frac{\sum_{i=1}^{n} \alpha i z i}{\sum_{i=1}^{n} \alpha i} \qquad (2.4.8)$$

Where α_i is a firing level of the i rule, and i = 1,…, n.

The Sugeno method works well with linear techniques, as it is computationally efficient. It is suitable to apply optimization and adaptive techniques. Furthermore, it guarantees continuity of the output surface and it is well suited to mathematical analysis. An advantage of the Mamdani method is that is it intuitive and has widespread of acceptance. It can be well suited to human input [27].

2.4.4 Defuzzification

Defuzzification task is to find one single crisp value that summarizes the fuzzy set. There are several mathematical techniques available: centroid, bisector, mean, maximum, maximum and weighted average. Figure 2.7 demonstrate illustration of how values for each method are chosen.

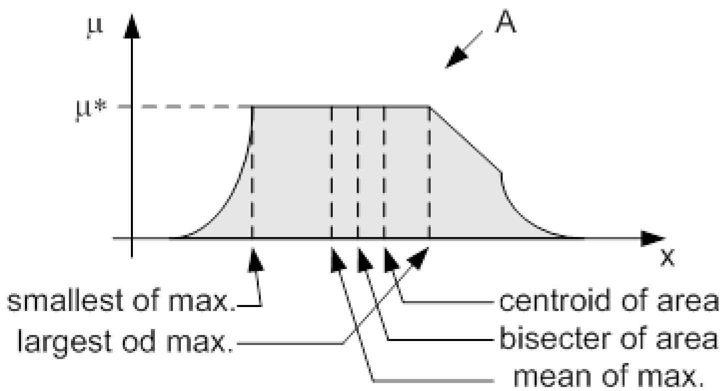

Figure 2.0.7 Graphical demonstrations of Defuzzification methods [27]

Centroid Defuzzification is the most commonly used method, as it is very accurate. It provides center of the area under the curve of membership function. For complex membership functions it puts high demands on computation. It can be expressed by the following formula,

$$z_o = \frac{\int \mu i(x)xdx}{\int \mu i(x)dx} \qquad (2.4.9)$$

Where $z_o$is defuzzified output, u_i is a membership function and x is output variable.

Bisector defuzzification uses vertical line that divides area under the curve into two equal areas.

$$\int_{\alpha}^{z} \mu A(x)dx = \int_{z}^{\beta} \mu A(x)dx \qquad (2.4.10)$$

Mean of maximum defuzzification method uses the average value of the aggregated membership function outputs.

$$z_o = \frac{\int_{x\prime} xdx}{\int_{x\prime} dx'} \qquad (2.4.11)$$

Where x' = {x; μ_A(x) = μ*}.

Smallest of maximum defuzzification method uses the minimum value of the aggregated membership function outputs.

$$z_o \in \{x|\mu(x) = \min(\omega)\, \mu(\omega)\} \qquad (2.4.12)$$

Largest of maximum defuzzification method uses the minimum value of the aggregated membership function outputs.

$$z_o \in \{x|\mu(x) = \min(\omega)\, \mu(\omega)\} \qquad (2.4.13)$$

Weighted average defuzzification method, based on peak value of each fuzzy sets, calculates weighted sum of these peak values [29]. According to these weight values and the degree of membership for fuzzy output, the crisp value of output is determined by the formula

$$z_o = \frac{\sum \mu(x) i * W i}{\sum \mu(x) i} \qquad (2.4.14)$$

Where μ_i is the degree of membership in output singleton i, W_i and is the fuzzy output weight value for the output singleton i. [27].

2.5 Field Programmable Gate Array (FPGA)

Field Programmable Gate Arrays (FPGAs) are semiconductor devices that are based around a matrix of configurable logic blocks (CLBs) connected via programmable interconnects. FPGAs can be reprogrammed to desired application or functionality requirements after manufacturing. This feature distinguishes FPGAs from Application Specific Integrated Circuits (ASICs), which are custom manufactured for specific design tasks. Although one-time programmable (OTP) FPGAs are available, the dominant types are SRAM based which can be reprogrammed as the design evolves.

A Field Programmable Gate Array is a digital integrated circuit that can be programmed to do any type of digital function. When the FPGA-based system is used for implementing the desired FLC, many possible designs can be tried due to the reusability of the FPGA. Often, a hardware implementation on the FPGA-based system is supported by many existing EDA tools for modeling, synthesis, verification, and implementation. The major advantage of using the EDA tools is that the same hardware description language code for modeling can be directly used for synthesis, verification, and implementation. Also, the general architecture of the FLC is invariant except for the change in the number of input and output variables, the number of fuzzy terms, the membership functions, the bit resolutions, and the control rule base according to the different applications. The FPGA consists of three major configurable elements:

1) Configurable Logic Blocks (CLBs) arranged in an array that provides the functional elements and implements most of the logic in an FPGA.

2) Input-output blocks (IOBs) that provide the interface between the package pins and internal signal lines.

3) Programmable interconnect resources that provide routing path to connect inputs and outputs of CLBs and IOBs onto the appropriate network.

2.5.1 VHDL (VHSIC Hardware Description Language)

VHDL is a programming language that describes a logic circuit by function, data flow behavior, and/or structure. This hardware description is used to configure a programmable logic device (PLD), such as a field programmable gate array (FPGA), with a custom logic design [32]. The general format of a VHDL program built around the concept of Blocks which are the basic building units of a VHDL design. Within these design blocks a logic circuit of function can be easily described.

A VHDL design begins with an Entity block that describes the interface for the design. The interface defines the input and output logic signals of the circuit being designed. The Architecture block describes the internal operation of the design. Within these blocks are numerous other functional blocks used to build the design elements of the logic circuit being created.

After the design is created, it can be simulated and synthesized to check its logical operation. Simulation is a bare bones type of test to see if the basic logic works according to design and concept. Synthesis allows timing factors and other influences of actual field programmable gate array (FPGA) devices to affect the simulation thereby doing a more thorough type of check before the design is committed to the FPGA or similar device.

2.5.2 ModelSim-Altera

ModelSim is a multi-language HDL simulation environment, for simulation of hardware description languages such as VHDL, Verilog and SystemC, and includes a built-in C debugger [33]. ModelSim can be used independently, or in conjunction with Intel Quartus Prime, Xilinx ISE or Xilinx Vivado [34]. In this thesis the ModelSim is in conjunction with Quartus II. Simulation is performed using the graphical user interface (GUI), or automatically using scripts.

2.6 Cost Analysis

Fuzzy Logic is an example for an alternative design methodology which can be applied in developing both linear and non-linear systems for embedded control. By using fuzzy logic, the development costs are reduced and there is better performance and quality in the end product. Also, the products can be brought to market faster and in a cost effective method.

The paper by H. Ferdinando entitled by “The implementation of low cost Fuzzy Logic Controller for PLC TSX 37-21”, this paper proposed the implementation of fuzzy logic controller for PLC TSX 37-21 and the idea was implemented to control the speed of DC motor. FLC is designed with 2 inputs and 1 output (5 labels for each input/output). For this the PLC is programmed with several methods. This product is priced by 59 US Dollar on RF Ideas [35].

Electronic Load Controller is used to stabilize the generator output (frequency and voltage) due to the load change in consumer by diverting the excess power to the dummy load (ballast). This controller is out for sale by 70-120 US Dollar [36].

A paper by Salman Mohagheghi, Ganesh K. Venayagamoorthy, Satish Rajagopalan,and Ronald G. Harley, entitled by “Hardware Implementation of a Mamdani Fuzzy Logic Controller for a Static Compensator in a Multimachine Power System”, compares the price of FLC with conventional controllers. In this paper results showed that the PI controller injects a considerably larger amount of reactive power into the power system, which, in turn, means higher currents through the inverter switches. Therefore, in the case of the conventional controller, switches with higher current ratings are required. Simulation results indicate that the

STATCOM controlled by the fuzzy controller reduces the peak reactive power injection by almost 60 Mvar. Based on a typical conservative price of 50 $/kvar, this reduction results in approximate savings of $4000 [37].

Water worth principle

Many of us around the world take water for granted. Why shouldn't we, when water is all around? It comes out of our faucets and collects in puddles on the sidewalk when it rains. Lakes and rivers brim with water. Water is fast becoming more precious than gold or oil.

The need to supply a growing population with sufficient fresh water in the context of increasing water scarcity and declining water quality has brought sustainable water resources management to the forefront of the global development agenda. For centuries, dams have played a key role in human development, bringing about significant social and economic improvements. About 30-40% of irrigated land worldwide relies on water stored behind dams (World Commission on Dams, 2000) and hydropower accounted for 16% of world electricity in 2008 (IEA, 2010).

Moreover, water is not equally distributed around the world. Some countries have more water than others, but most have enough water to meet people's needs. What they don't always have is the means to make that water available to people. Rich, developed countries can tap into hard-to-reach sources of water much more easily than poor, less-developed countries, where people often don't have enough money to dig wells or build dams to create reservoirs.

The fuzzy controller is used first to regulate the frequency output of the plant in spite of changing user loads. Second, it limits the waste of the available water. Whereas the ballast loads are usually resistive electrical loads used to heat water which make the water evaporate. The fuzzy controller is design in chapter four of this thesis. It is able to maintain MHPP frequency in spite of the load variations. In addition, it minimizes the waste of water by limiting the dissipated power on the ballast load. The fuzzy supervisor manages to use the available water based on consumer demand.

2.7 Previous works

The scientific community is widely interested in modeling and control of renewable energy plants, specifically on hydro and micro-hydro power plant. Different researches have been worked on the controlling mechanism of controlling the frequency on micro hydro power plant. Different researcher used different approaches to control the frequency of MHPP. From this some of the approaches are reviewed in the following paragraphs.

1. **Alex Jose and Dr. Jayaprakash,** discussed Depletion of fossil fuels, pollution due to fossil fuels, and awareness about non-conventional source, and abundance of water sources in hilly areas changed the attention to renewable source of energy. Hydroelectricity is the term referring to electricity generated by hydro power; the

production of electrical power through the use of the gravitational force of falling or flowing water. It is the most widely used form of renewable energy, accounting for 16 percent of global electricity generation 3,427 terawatt-hours of electricity production in 2012. Small hydro is the development of hydroelectric power on a scale serving a small community or industrial plant. The definition of a small hydro project varies but a generating capacity of up to 10 megawatts (MW) is generally accepted as the upper limit of what can be termed small hydro. According to present survey, nearly two billion people in the world have no access to electrical energy. The great majority of these live in isolated rural areas in developing countries, where conventional grid-extension electricity supply is not economically viable, and small diesel sets may be inappropriate due to fuel costs, absence of reliable supplies, and a general lack of technical support. An important characteristic of rural energy demand is its low density: particularly in remote districts, provision must be made for a large number of users with low levels of demand, leading to the need for a wide range of scheme sizes for small power generation for differing household densities.

2. **I. Salhi, S. Doubabi**, proposed Automatic generation control (AGC) 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.
3. **Shrikant S. Katre and Dr. V.N. Bapat,** reviews the operation of Induction generators in grid connected and self-excitation mode is well known. In many countries induction generators are used for electrical power generation by wind energy. Low cost, robustness and ease of maintenance are attractive features of induction generators. Even though these generators are used at some places for micro hydro power generation, very small scale generation known as Pico hydro generation offers excellent opportunity for them. Slip ring induction motors are used for micro power generation and squirrel cage induction motors are used for Pico power generation. These generators have an inherent problem of terminal voltage variation with increase in load.
4. **S. Mbabazi and j. Leary,** proposed a self-tuning fuzzy PI controller, 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. 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.

5. **V. Pandey**, developed load control mode for MHPP. 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.
6. **G.M. Masters** presented a paper that 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.
7. **Ayele Nigussie** presented load control mode for MHPP. In load control mode, a ballast load is controlled so that the total load connected to the synchronous generator is kept constant. The controller is simulated using MATLAB and implemented using microchip PIC16F877A. however using ballast load has its own effect which is, 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.
8. **Jemal Hayato** presented a paper that proposed fuzzy logic controller to tune the parameters of PI controller for frequency control of a micro hydropower plant and to supervise the energy dissipated on the ballast load. however using ballast load has its own effect which is, 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.
9. **Yalemzerfe Getnet** presented a paper on the designing and simulation of fuzzy logic based frequency controller for standalone micro hydro power plant. A 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. But implementation was not done in this paper.

In this thesis, fuzzy logic controller is proposed to control the frequency of micro hydro power plant. 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.

CHAPTER 3
Mathematical Model of the MHPP

For the design and analysis of a control system, the first step that has to be done is the mathematical modeling. It is a method of simulating real-life situations with mathematical equations to forecast their future behavior. It uses mathematical equations such as state space, differential equation and transfer function. In this thesis accurate mathematical representation of power system components is significant for dynamic and transient stability studies. State space modeling is applied for both linear and non-linear systems. Solving differential equations are complicated and bulky, but the transfer function modeling is quite easy when compared to differential equation modeling.

The MHPP is a non-linear system; it is also a non-stationary system that has a defining feature which varies to a large extent with the unpredictable load on it and this make it hard to design an efficient and accurate controller [3]. In this thesis, the linearity of the majority of the proposed hydro power model is considered. The linear model representation of the components of the micro hydropower system is presented. This model is based on the mathematical equations that contain the whole operation of MHPP.

The measurement of Head (H) and Flow (Q) is important for the modeling of the system. An essential requirement for MHPP generation is a continuous water supply from a stream with a combination of adequate Head (H) over a reasonable stretch of the stream and adequate flow (Q) to meet expected power demand.

Measuring Head (H):- Head is the vertical distance that waterfalls the forebay or intake the turbine. It is measured in meters. The gross Head (H) is the maximum available vertical fall in the water, from the upstream level to the downstream level. The actual head seen by a turbine will be slightly less than the gross head due to losses incurred when transferring the water into and away from the machine. Trigonometric method and Carpenter’s level are methods for measuring Head (H).

Measuring Flow (Q):- Flow rate is the quantity of water available in a stream or river and may vary widely over the course of a day, week, month and year. In order to adequately assess the minimum continuous power output to be expected from the micro-hydropower system, the minimum quantity of water available must be determined. The purpose of a hydrology study is to predict the variation in the flow during the year. It is important to know the mean stream flow and the extreme high- and l0w-flow rates.

Environmental and climatic factors and human activities in the watershed determine the amount and characteristics of stream flow on a day-to-day and seasonal basis. Generally, unless considering a storage reservoir, it should be used the lowest mean annual flow as the basis for the system design. There are a variety of techniques for measuring stream flow rate; the most commonly used include the Bucket or container method; the Velocity-Area float method; the Weir method and the Current meter method.

3.1 Turbine modeling

When water flows from high elevation to the hydro turbine, gravitational potential energy is converted into kinetic energy. Then, the turbine shaft obtaining mechanical energy from the conversion drives the machine to generate electricity. The time constants of the turbine are less smaller than the time constants of the reservoir and penstock which are series connected to elements in the system. The linear model of hydraulic turbine is modeled by taking different assumption: the penstock is modeled by assuming that the flow is incompressible when the rate of change of flow in the penstock is obtained by equating the rate of change of momentum of the water in the penstock to the net force. For a stationary, lossless and friction free flow which is the hydraulic turbine's blade is considered as smooth. Also the developed output power of turbine is proportional to the product of head and velocity of flow.

As parameters describing the mass transfer and energy transfer in the turbine we will consider the water flow through the turbine Q and the moment M generated by the turbine and that is transmitted to the electrical generator. The moment developed by the turbine is a function of the water flow, the runner blade angle and the net head. These variables can expressed as non-linear functions of the turbine rotational speed N, the turbine gate position G and the net head H of the hydro system.

$$Q = Q(H, N, G) \qquad (3.1)$$

$$M = M(H, N, G) \qquad (3.2)$$

Through linearization of the equation (3.1) and (3.2) around the steady state values, we obtain:

$$\Delta Q = \frac{\partial Q}{\partial H}\Delta H + \frac{\partial Q}{\partial N}\Delta N + \frac{\partial Q}{\partial G}\Delta G \qquad (3.3\ a)$$

$$q = a_{11}h + a_{12}n + a_{13}g \qquad (3.3\ b)$$

$$\Delta M = \frac{\partial M}{\partial H}\Delta H + \frac{\partial M}{\partial N}\Delta N + \frac{\partial M}{\partial G}\Delta G \qquad (3.4\ a)$$

$$m = a_{21}h + a_{22}n + a_{23}g \qquad (3.4\ b)$$

Where the following notations were used:

$q = \frac{\Delta Q}{Qo}$, $n = \frac{\Delta N}{No}$, $m = \frac{\Delta M}{Mo}$, $h = \frac{\Delta H}{Ho}$, $g = \frac{\Delta G}{Go}$, Which represent the non-dimensional variations of the parameters around the steady state variables.

$a_{11} = \frac{\partial Q}{\partial H}, a_{12} = \frac{\partial Q}{\partial N}, a_{13} = \frac{\partial Q}{\partial G}, a_{21} = \frac{\partial M}{\partial H}, a_{22} = \frac{\partial M}{\partial N}, a_{23} = \frac{\partial M}{\partial G}$

The partial derivatives of flow and moment with respect to net head, turbine gate position and rotational speed are called turbine coefficients which are a_{21}, a_{22}, and a_{23}. This coefficients stand for the nonlinear characteristics of a hydraulic turbine. Based on the operating conditions of the turbine comparative to gate opening position and rotational speed the partial derivatives vary. The partial derivative of the moment M with respect to the gate position G is called turbine gain. The turbine gain is significant parameter for an accurate approximation of hydro power plants dynamics. It has to be measured carefully. The turbine coefficients have an influence on the model accuracy. The value of the turbine coefficients have to be measured precisely on the field or taken from model tests. The effect of the partial derivative of the water flow through the turbine with respect to rotational speed $\frac{\partial Q}{\partial N}$ is usually considered to be negligible. The partial derivative of moment with respect to rotational speed is known as turbine self-regulation. In inter connected power system the hydraulic units are matched with the system as a result the rotational speed is nearly one and usually neglected. So that the above equations (3.3 b) and (3.4 b) is simplified to the below equations [11, 12],

$$q = a_{11}h + a_{13}g \qquad (3.5)$$

$$m = a_{21}h + a_{23}g \qquad (3.6)$$

The hydraulic feed system of the turbine has a complex geometrical configuration, consisting of pipes or canals with different shapes and cross-sections. Therefore, the feed system will be considered as a pipe with a constant cross-section and the length equal with real length of the studied system. In order to consider this, it is necessary that the real system and the equivalent system to contain the same water mass. Let consider $m_1, m_2, \ldots, m_n$ the water masses in the pipe zones having the lengths $l_1, l_2, \ldots, l_n$ and cross-sections $A_1, A_2, \ldots, A_n$ of the real feed system. The equivalent system will have the length $L = l_1 + l_2 + \ldots + l_n$ and cross-section A, conveniently chosen.

In this case, the mass conservation law in both systems will lead to the equation:

$$A \sum_{i=1}^{n} li = \sum_{i}^{n} li.Ai \qquad (3.7)$$

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

$$Q = v.A = Qi = vi.Ai, \text{ for } i=1,2,\ldots,n \qquad (3.8)$$

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:

$$v = \frac{Q}{A} = \frac{Qi \sum li}{\sum li.Ai} = \frac{\sum li}{\sum li.Ai}.Q \qquad (3.9)$$

The dynamic pressure loss can be computed considering the inertia force of the water exerted on the cross-section of the pipe:

$$F_i = -m*a = -L*A*\rho*a = -A\frac{L*\gamma}{g}\frac{dv}{dt} \qquad (3.10)$$

Where L is the length of the penstock or the feed canal, A is the cross-section of the penstock, γ is the specific gravity of water (1000 Kgf/m^3), a is the water acceleration in the equivalent pipe, and g=9.81 m/$s^2$is the gravitational acceleration. The dynamic pressure loss can be expresses as:

$$H_d = \frac{Fi}{A} = -\frac{\gamma*L}{g}.\frac{dv}{dt} = -\frac{\gamma*L}{g}\frac{\sum li}{\sum li*Ai}\frac{dQ}{dt} \qquad (3.11)$$

Using non-dimensional variations, from (3.11) it results:

$$\frac{\Delta Hd}{Hdo} = \frac{Qo}{Hd} * \frac{\rho L*\sum li}{\sum li*Ai} * \frac{d(\frac{\Delta Q}{Qo})}{dt} \qquad (3.12)$$

Or in non-dimensional form:

$$h_d = -T_w\frac{dq}{dt} \qquad (3.13)$$

Where T_w is the water time constant of the hydropower system. It represents the time required for a head to accelerate the water in the penstock from standstill to the velocity. Tw varies with load. Usually Tw at full load lies between 0.5 s and 4 s. For load controlled micro hydro power systems, the water time remains constant. And the variables have the following meaning:

$$h_d = \frac{\Delta Hd}{Hdo},\ q = \frac{\Delta Q}{Qo},\ T_w = \frac{Qo}{Hdo}\frac{\rho L \sum li}{\sum liAi}\ [s] \qquad (3.14)$$

It must be noted that this is a simplified method to compute the hydraulic pressure loss, which can be used for run-of-the river hydropower plants, with small water head [13].

Using the Laplace transform in relation (3.13), it results

$$h_d(s) = -sT_w + q(s), \text{ and } q(s) = -\frac{1}{sTw}h_d(s) \qquad (3.15)$$

Replacing (3.15) in (3.3 a) and (3.4 a) and doing some simple calculations, we obtain:

$$q(s) = \frac{a_{12}}{1+a_{11}Tws}n(s) + \frac{a_{13}}{1+a_{11}Tws}g(s) \qquad (3.16)$$

$$h_d(s) = -\frac{a_{12}Tws}{1+a_{11}Tws}n(s) - \frac{a_{13}Tws}{1+a_{11}Tws}g(s) \qquad (3.17)$$

$$m(s) = \left(a_{21} - \frac{a_{12}Tws}{1+a_{11}Tws}\right)n(s) + \left(a_{23} - \frac{a_{13}Tws}{1+a_{11}Tws}\right)g(s) \qquad (3.18)$$

The mechanical power generated by the turbine can be calculated with the relation

$$P = \eta * \gamma * Q * H,$$

This can be used to obtain the linearized relations for variations of these values around the steady state values:

$$p = \eta * g * Q_o * h + \eta * g * H_o * q \qquad (3.19)$$

Where η is the turbine efficiency, andγ, Q, and H were defined previously.

On the other hand, the mechanical power can be determined using the relation P = Mω=2πM*N, which can be used to obtain the linearized relations for variations of these values around the steady state values:

$$n = \frac{2\pi No}{P}p - \frac{(2\pi No)^2}{Po}m \qquad (3.20)$$

Where P_o=M_o.$w_o$is the steady state power generated by the turbine for a given steady state flow Qo and a steady state head Ho, and No is the steady state rotational speed. The transfer functions T for different modules are given by the following relation:

$$Tqn(s) = \frac{a_{12}}{1+a_{11}Tws}, Tqg(s) = \frac{a_{13}}{1+a_{11}Tws}, Thn(s) = -\frac{a_{12}Tws}{1+a_{11}Tws},$$

$$Tmn(s) = a_{21} - \frac{a_{12}Tws}{1+a_{11}Tws}, Tmg(s) = a_{23} - \frac{a_{13}Tws}{1+a_{11}Tws} \qquad (3.21)$$

For an ideal turbine, without losses, the coefficients a_{ij} resulted from the partial derivatives in equation (3.14-3.18) have the following values: a_{11}=0.5; a_{12}=a_{13}=1; a_{21}=1.5; a_{23}=1. In this case the transfer functions are given by the following relation:

$$Tqn(s) = \frac{1}{1+0.5Tws}, Tqg(s) = \frac{1}{1+0.5Tws}, Thn(s) = -\frac{Tws}{1+0.5Tws} \qquad (3.22)$$

$$Tmn(s) = 1.5 - \frac{Tws}{1+0.5Tws} \qquad (3.23)$$

Using these relations, the block diagram of the hydraulic turbine, for small variation operation around the steady state point, where the transfer functions for different is as follows: [13]

$$Tmg(s) = \frac{1-Tws}{1+0.5Tws} \qquad (3.24)$$

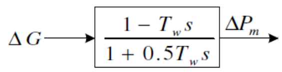

Figure 3.0.1 Turbine model

3.2 Induction Generator Modeling

The modeling of the squirrel cage induction generator modeling is resulting from an induction machine and reactive load generations undertaken by excitation capacitor. For variable speed generation, the choice of an induction generator is considered attractive due to its flexible rotor speed characteristic in contrast to the constant speed characteristic in contrast to the constant speed characteristic of a synchronous generator. I have selected a 4-pole, 3.2 kW squirrel cage induction generator, directly coupled to the turbine. The main characteristics of the selected generator are given in the table below:

Table 2 Induction generator characteristics [18]

Type	Induction Generator
Output power	3.2 kW
Efficiency	0.9
Frequency	50 Hz
Power factor	0.8
Synchronous speed	1500 rpm
Rotor speed	1560 rpm
Rotor inertia	0.02

3.2.1 Electrical System

We will assume that the squirrel cage induction generator is modeled using Park method in a reference frame linked to its stator, given as the following equations [14],

$$V_{ds} = R_s I_s + \frac{d\varphi ds}{dt} \qquad (3.25a)$$

$$V_{qs} = R_s I_{qs} + \frac{d\varphi qs}{dt} \qquad (3.25b)$$

$$0 = R_r I_{dr} - \omega r \boldsymbol{\varphi}_{qr} + \frac{d\varphi dr}{dt} \qquad (3.26)$$

$$0 = R_r I_{qr} - \omega r \boldsymbol{\varphi}_{qr} + \frac{d\varphi qr}{dt} \quad (3.27)$$

$$\boldsymbol{\varphi}_{ds} = L_s I_{ds} + M I_{dr} \quad (3.28a)$$

$$\boldsymbol{\varphi}_{qs} = L_s I_{qs} + M I_{qr} \quad (3.28b)$$

$$\boldsymbol{\varphi}_{dr} = L_r I_{dr} + M I_{ds} \quad (3.28c)$$

$$\boldsymbol{\varphi}_{dr} = L_r I_{ds} + M I_{qs} \quad (3.28d)$$

In this equations subscript "s" refers to the stator and "r" the rotor.

- R_s and R_r ate the single phase winding resistance;
- V_{ds}, V_{qs} stator voltages (there is no rotor voltage components because the rotor is short-circuited);
- I_{ds}, I_{qs}, I_{dr} and I_{qr} are current ones;
- $\boldsymbol{\varphi}_{ds}$, $\boldsymbol{\varphi}_{qs}$, $\boldsymbol{\varphi}_{dr}$ and $\boldsymbol{\varphi}_{qr}$ refer to magnetic flux;
- L_s and L_r are total stator and rotor inductances and M is the magnetized inductance.

3.2.2 Electromagnetic Torque

The electromagnetic torque T_e is expressed as follows:

$$T_e = 1.5p(\boldsymbol{\varphi}_{ds} i_{qs} - \boldsymbol{\varphi}_{qs} i_{ds}) \quad (3.29)$$

Where p is the number of pole pairs.

3.2.3 Excitation System

The capacitor supplying the reactive power necessary for the motor to work in self-excited mode is modeled using the equation below,

$$i_{qs} = i_{ql} + \frac{dCVqs}{dt} \quad (3.30)$$

$$i_{ds} = i_{dl} + \frac{dCVds}{dt} \quad (3.31)$$

Where:

- i_{dql} are the d line currents in the d-q frame reference frame,
- qi_{dqc} are the electric charge in the d-q frame reference frame,
- C is the capacitance of capacitor excitation.

3.2.4 Mechanical System

As the machine acts as a generator, the shaft mechanical torque is negative and can be modeled using the equation below,

$$J\frac{d^2\theta m}{dt} = T_{em} - B\omega_m - T_m \qquad (3.32)$$

With: $\frac{d\theta m}{dt} = \omega_m$

Where:

- $\omega_m$is the angular velocity of the rotor
- $\theta_m$is rotor angular position
- T_{em} electromagnetic torque
- T_m is net mechanical torque (from the turbine)
- J is combined rotor and load inertia coefficient
- B is combined rotor and load viscous friction coefficient

In equation (3.7), the machine acts as a generator if $T_m$is negative.

❖ At steady state, ω_m=ω_{sm},and

$$T_t = T_{em} + B\,\omega_{sm} \text{ or } T_m = T_t - B\,\omega_{sm} = T_e \qquad (3.33)$$

T_t is the torque produced by the turbine (Nm), from equation (3.33) the turbine torque less the rotational losses at ω_m= ω_{sm}. It is this torque T_m that is converted into electromagnetic torque. If, due to some disturbance, T_m>T_e then the rotor accelerates: if T_m<T_e then it decelerates.

❖ Rotor speed

$$\omega_m = \omega_{sm} + \Delta\,\omega_m = \omega_{sm} + \frac{d\delta m}{dt} \qquad (3.34)$$

Where $\delta_m$is the rotor angle expressed in mechanical radians and $\Delta\,\omega_m = \frac{d\delta m}{dt}$is the speed deviation in mechanical radians per second.

After substitution,

$$J\,\omega_{sm}\frac{d^2\delta m}{dt^2} + \omega_{sm}B\frac{d\delta m}{dt} = \frac{\omega sm}{\omega m}P_m - \frac{\omega sm}{\omega m}P_e \qquad (3.35)$$

Where:

❖ P_m is the net shaft power input to the generator
❖ P_e is the electrical air-gap power, both expressed in watts.

During a disturbance the speed of the machine is normally quite close to synchronous speed so that $\omega_m \approx \omega_{sm}$and also the combined rotor and load viscous friction coefficient is almost zero equation (3.35) becomes,

$$J\,\omega_{sm}\frac{d^2\delta m}{dt^2} = P_m - P_e \quad (3.36)$$

The coefficient J $\omega_{sm}$is the angular momentum of the rotor at synchronous speed and, when given the symbol M, allows equation (3.36) to be written as

$$M\frac{d^2\delta m}{dt^2} = P_m - P_e \quad (3.37)$$

The inertia constant is given the symbol H defined as the stored kinetic energy in mega joules (MJ) at synchronous speed divided by the machine rating S in megavolt-ampere (MVA) so that

$$H = \frac{0.5J\omega sm^2}{S} \text{ and } M = \frac{2HS}{\omega sm} \quad (3.38)$$

The power angle and angular speed can be expressed in electrical radians and electrical radians per second respectively, rather than their mechanical equivalent, by substituting

$$\delta = \frac{\delta m}{p/2} \text{ And } \omega_s = \frac{\omega sm}{p/2} \quad (3.39)$$

Where, p is the number of poles. Introducing the inertia constant and substituting equations (3.39) into equation (3.37), we will obtain:

$$\frac{2HS}{\omega r}\frac{d^2\delta}{dt^2} = P_m - P_e \quad (3.40)$$

The equations in (3.40) can be rationalized by defining an inertia coefficient M and damping power P_d such that,

$$M = \frac{2HS}{\omega r},\ P_d = D\frac{d\delta}{dt} \quad (3.41)$$

Then the equation (3.39) takes the common form,

$$M\frac{d^2\delta}{dt^2} = P_m - P_e - P_d \quad (3.42)$$

Often it is more convenient to replace the second-order differential equation (3.42) by two first-order equations:

$$M\frac{d\Delta\omega}{dt} = P_m - P_e - P_d \quad (3.43)$$

$$\frac{d\delta}{dt} = \Delta\omega$$

When inserting $M = \frac{2HS}{\omega sm}$ into equation (3.43),

$$\frac{2HS}{\omega sm}\frac{d\Delta\omega}{dt} = P_m - P_e - P_d \qquad (3.44)$$

Dividing throughout by S, the MVA rating of the machine or equation (3.44) becomes,

$$\frac{2H}{\omega sm}\frac{d\Delta\omega}{dt} = P_m - P_e - P_d \qquad (3.45)$$

$$\omega_{sm}\frac{d\Delta\omega}{dt} = \frac{d\omega r}{dt} = \frac{d\Delta\omega}{dt} \qquad (3.46)$$

Substituting equation (3.46) in equation (3.45),

$$\frac{d\Delta\omega r}{dt} = \frac{Pm - Pe - Pd}{2H}$$

With the Laplace transformation, the generator model will become [19],

$$\Delta\omega_r = \frac{Pm(s) - Pe(s)}{2Hs} \qquad (3.47)$$

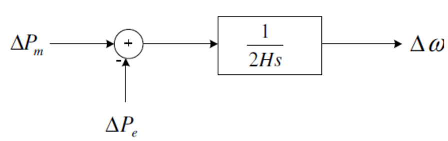

Figure 3.0.2 Generator model

The figure below represents the generator model coupled with the turbine,

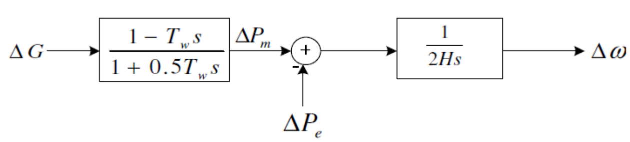

Figure 3.0.3 Generator model coupled with turbine

3.3 Load Modeling

If an electric circuit has an output port, a pair of terminals that produces an electrical signal, the circuit connected to this terminal (or its input impedance) is the load. Load affects the performance of circuits with respect to output voltage or currents, such as in sensors, voltage sources and amplifiers. An example of loads can be appliances and lights. There are two basic approaches to the determination of system-load characteristics: which are Measurement-based approach and component-based approach. The overall frequency-dependent characteristics of a composite load can be expressed as [19],

$$\Delta P_e(s) = \Delta P_d(s) = \Delta P_n(s) + D\Delta\omega_r(s) \qquad (3.48)$$

Recalling that, $P_d = D\frac{d\delta}{dt}$, and $\frac{d\delta}{dt} = \Delta\omega$

Where:

- $\Delta P_n(s)$ is non-frequency sensitive consumer load change.
- $D\Delta\omega_r(s)$ is frequency sensitive load changes
- D is expressed as percent change in load divided by percent change in frequency

By substituting equation (3.47) into equation (3.48), we will obtain

$$\Delta\omega_r(s) = \frac{\Delta Pm(s) - \Delta Pn(s) - D\Delta\omega r(s)}{2Hs}$$

$$\Delta\omega_r(s)\, 2Hs = \Delta Pm(s) - \Delta Pn(s) - D\Delta\omega_r(s)$$

$$\Delta\omega_r(s)(2Hs + D) = \Delta Pm(s) - \Delta Pn(s)$$

$$\Delta\omega_r(s) = \frac{\Delta Pm(s) - \Delta PL(s) - PBL(s)}{2Hs + D} \qquad (3.49)$$

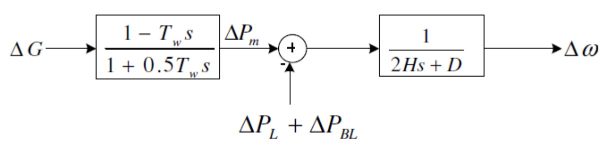

Figure 3.0.4 Generator, Load and turbine block diagram

3.4 Actuator Modeling

An actuator is s mechanism for turning energy into motion. Actuators can be categorized by the energy source they require to generate motion. To develop a robust control strategy, one must first develop a physical model of the actuator and then design a viable control scheme. The actuator modeling is consisted of the electrical subsystem, magnetic subsystem and mechanical subsystem. The figure below shows the interaction of subsystems,

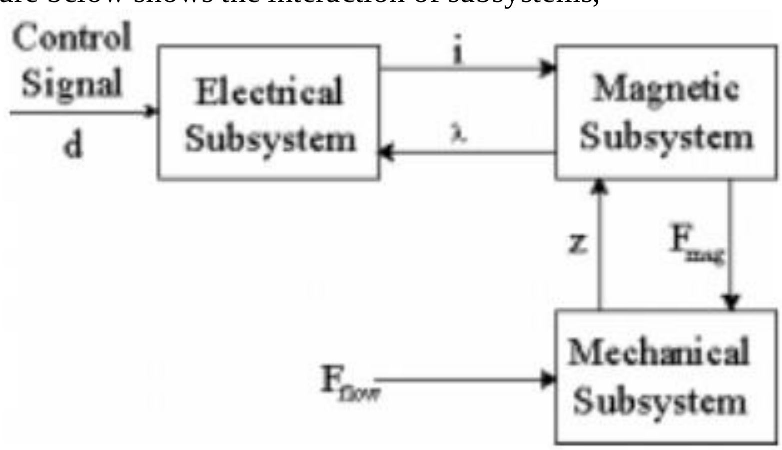

Figure 3.0.5 the interaction of subsystems of an EMV actuator [20]

3.4.1 Electrical Subsystem Modeling

The electrical subsystem can be modeled using the RL circuit. Due to the discontinuous power supply, there are two cases to be considered: the first case is when the power is on and the other case is when the power is off. Let's consider the figure below for case one:

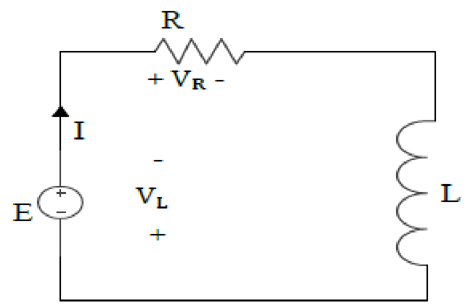

Figure 3.0.6 Electrical circuit when power is on [21]

According to Kirchhoff's Voltage Law, the sum of all drops equals zero. Using KVL, the mathematical equation can be given as [21],

$$E - V_R - V_L = 0 \qquad (3.4.1)$$

Where $V_R = RI$

The total reluctance can be calculated as,

$$L(X_a) = \frac{N^2}{R'} = L' \frac{Xa}{lg,off - Xa} \qquad (3.4.2)$$

Where,

- N is number of turns in the coil
- Lg the air gap inside the valve
- X_a armature's position
- L' total reluctance

By substituting equation (3.4.1) into equation (3.4.2), the electrical circuit expression becomes

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

$$\frac{dI}{dt} = \frac{E - IR - I\frac{dXa}{dt}\frac{dL(Xa)}{dt}}{L(Xa)} \qquad (3.4.3)$$

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:

$$-IR - L(X_a)\frac{dI}{dt} - I\frac{dL(Xa)}{dt} = 0 \qquad (3.4.4)$$

3.4.2 Mechanical Subsystem Modeling

Using second Newton's Law [22],

$$F = Ma \qquad (3.4.5)$$

$$a = \frac{dv}{dt} = \frac{dSa^2}{dt^2} \qquad (3.4.6)$$

By inserting equation (3.4.6) into equation (3.4.5),

$$F = M\frac{dv}{dt} = M\frac{dSa^2}{dt^2} \qquad (3.4.7)$$

$$F_M - k_s(x_a - x_{a0}) - b(\frac{dSa}{dt}) - F_o = M\frac{dv^2}{dt^2} \qquad (3.4.8)$$

$$\frac{dSa^2}{dt^2} = \frac{FM - ks(Sa - Sao) - b\left(\frac{dSa}{dt}\right) - Fo}{M} \qquad (3.4.9)$$

Where:

- F is net Force
- M is mass of the armature
- A is the armature's acceleration
- Ks is spring constant
- b is the viscous friction coefficient
- v is the armature's velocity

From state space representation, let $x=x_1$, $\dot{x}_1 = x_2$, $x_3=I$, where the presentation are displacement, velocity and current flowing through solenoid coil respectively.

$$\dot{x}_1 = x_2 \qquad (3.4.10)$$

$$\dot{x}_2 = \frac{F}{m} - \frac{b}{m}x_2 = u - \frac{b}{m}x \qquad (3.4.11)$$

$$\dot{x}_3 = \frac{a+x1}{x1L'}(E - x_3R - x_3x_2\frac{x1L'}{(a+x1)^2}) \qquad (3.4.12)$$

3.4.3 Magnetic Subsystem Modeling

The change in the magnetic force can be expressed as [23],

$$\frac{dFm}{dt} = \frac{B^2dAp}{2\mu o dt} \qquad (3.4.13)$$

Where B is the magnetic field

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

$$B = \mu o \frac{NI}{lg} \qquad (3.4.14)$$

As a function of the armature's position, the air gap is expressed, [23]

$$l_g(Xa) = l_g\text{, off-}Xa \qquad (3.4.15)$$

Combining equation (3.4.4), equation (3.4.13) and equation (3.4.15), the magnetic force can eventually expressed as,

$$Fm = \frac{\mu o A p N^2 I^2}{2(lg,off-Xa)^2} \qquad (3.4.16)$$

CHAPTER 4
DESIGN OF THE CONTROLLER

4.1 Introduction

This chapter represents the design of the proposed controller for micro hydro-power plant. In order to overcome the drawbacks, the proposed fuzzy logic controller is presented to quench the deviations in the frequency due to different load disturbances.

While it is relatively easy to design a PI controller, the inclusion of fuzzy rules creates many extra design problems, and although many introductory textbooks explain fuzzy control, there are few general guidelines for setting the parameters of a simple fuzzy controller. The approach here is based on three step design procedure that builds on PI control:

1. Start with a PI controller
2. Insert an equivalent, linear fuzzy controller
3. Make it gradually nonlinear

To take into account the nonlinear behavior of MHPP towards the load variations, PI controller's parameters should vary with the load variation and hence the resultant power supply would have the potential to be of higher quality. Fuzzy logic controller is a cost effective, human thinking and an intelligent nonlinear control. There are different types of fuzzy logic controls such as self-tuning and self-organizing controllers. In this thesis the self-tuning controller is used. The self-tuning controller readjusts the PI gains in real-time to improve the process output response, during the system operation. The self-tuning controller is used because the PI control has nonlinear characteristics and intellectual faculties, and simultaneously endows fuzzy control with an established PI-control configuration.

4.2 Fuzzy Logic Controller Design

Fuzzy logic controller can be design based on Mamdani's fuzzy inference method or Sugeno's fuzzy inference method. But in this thesis the Mamdani's fuzzy inference method is used to control the frequency of the micro hydro-power plant and with the intention of design this fuzzy controller each step of the controller Fuzzification, rule, fuzzy inference and defuzzification was designed.

To design a fuzzy controller reliable and smart enough, the design has to rely not only on an accurate MHPP modeling, but also on:

- Expert experience and control engineering knowledge.
- Based on the operator's control actions. Fuzzy if-then rules can be deduced from observations of an operator's control actions or a log book. The rules express input-output relationships.
- Based on a fuzzy model of process. A linguistic rule base may be viewed as an inverse model of the controlled process. Thus the fuzzy control rules might be obtained by

inverting a fuzzy model of the process. This method is restricted to relatively low order systems, but it provides an explicit solution assuming that fuzzy models of the open and closed loop systems are available. Another approach is fuzzy identification or fuzzy model-based control.

- Based on learning. The self-organizing controller is an example of a controller that finds the rules itself. Neural networks are another possibility.

There is no design procedure in fuzzy control such as root-locus design, frequency response design, pole placement design, or stability margins, because the rules are often non-linear. Therefore we will settle for describing the basic components and functions of fuzzy controllers, in order to recognize and understand the various options in commercial software packages for fuzzy controller design.

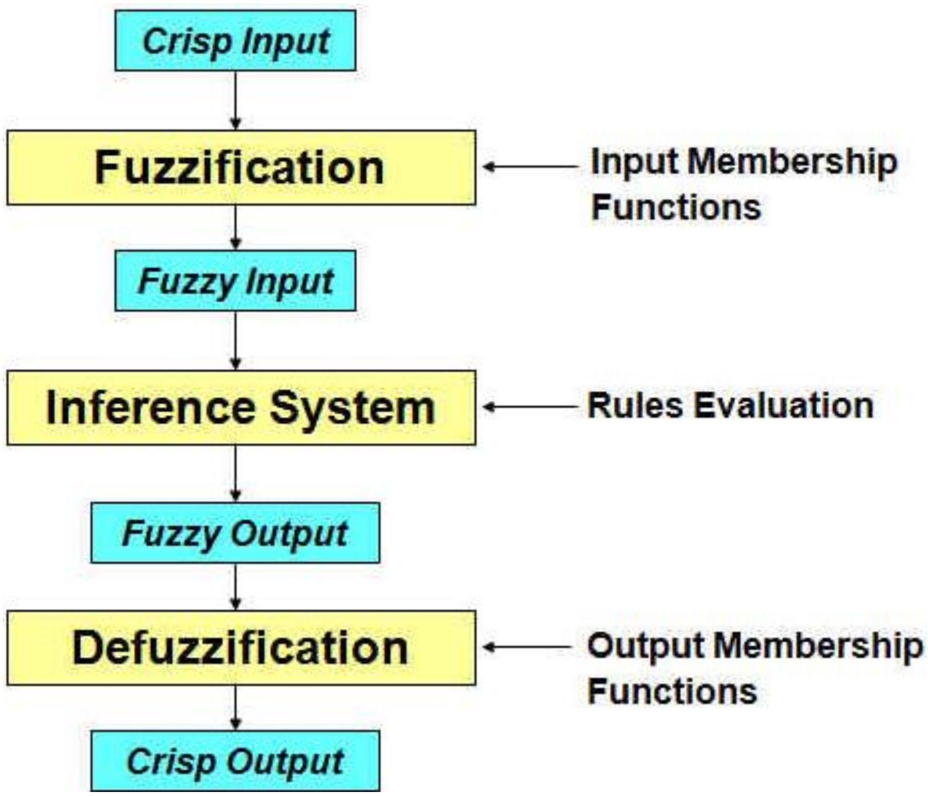

Figure 4.0.1 Flow chart of Fuzzy logic

4.2.1 Fuzzifier Design

The first step found in the design of fuzzy logic controller is Fuzzification. The first move in Fuzzification is to determine the inputs and outputs of the controller. The inputs are frequency error e, change in frequency error Δe and the disturbance Pd. The outputs of the fuzzy controller are ΔKp and ΔKi and Xs. The output Xs acts on a servo motor that varies the water flow Q when the disturbance exceeds a certain limit value compared to the nominal turbine power and it acts on when the frequency of the generator goes away from its nominal value. The input to the fuzzy logic controller which is the frequency error, when this input is compared to the rated frequency of the generator will inform the controller if the actuator valve needs to be on/off or if it is operating at its initial condition. The other input to the controller is the change of the frequency error. This input to the controller describes how fast the frequency is changed. And the other input of the controller which is the disturbance describes the order to open the gate opening based on how fast the water flow and when it is compared to the rated flow rate of the water, will inform the controller if the actuator needs to be on/off or if it is operating at its initial condition. The proposed fuzzy controller has been design to adjust on-line the parameters of proportional gain Kp and integral gain Ki of a PI controller based on the frequency error e and the change in frequency Δe. Kp is the sum of the reference value Kp* and ΔKp. Ki is the sum of the reference value Ki* and ΔKi. Kp* and Ki* are the reference values of the controller.

The other step in Fuzzification is chosen an appropriate membership function for inputs and outputs. Every element in the universe of discourse is a member of a fuzzy set to some grade, maybe even zero. The grade of membership for all its members describes a fuzzy set, such as Negative (N). In fuzzy sets elements are assigned a grade of membership, such that the transition from membership to non-membership is gradual rather than abrupt. The set of elements that have a non-zero membership is called the support of the fuzzy set. The function that ties a number to each element of the universe is called the membership function. According to fuzzy set theory the choice of the shape and width is subjective, but a few rules of thumb apply. As shown from the below figures 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 inputs frequency error e and the change in frequency error Δe are used as numerical variables from the real system. The inputs are most often hard or crisp measurements from some measuring equipment, rather than linguistic. To convert numerical values of the inputs to linguistic variables several fuzzy sets are presented. 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 $F_r(t)$ has a value above the reference-point F_{ref} since $e = F_{ref} - F_r(t) > 0$. Positive value describes the magnitude of the difference e. Then again, the values of error e with a positive sign mean that the current value of F_r is below the reference-point value. The change of frequency error Δe with a negative sign means that the current output frequency $F_r(t)$ has increased when compared with its previous value $F_r(t-1)$, since $e = -F_r(t) + F_r(t-1) < 0$. Values of Δe with a positive sign mean that $F_r(t)$ has decreased its value when compared to $F_r(t-1)$. For input e seven fuzzy sets are chosen: negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM), and positive big (PB); and three fuzzy sets are chosen for Δe: negative (N), zero (Z), positive (P).

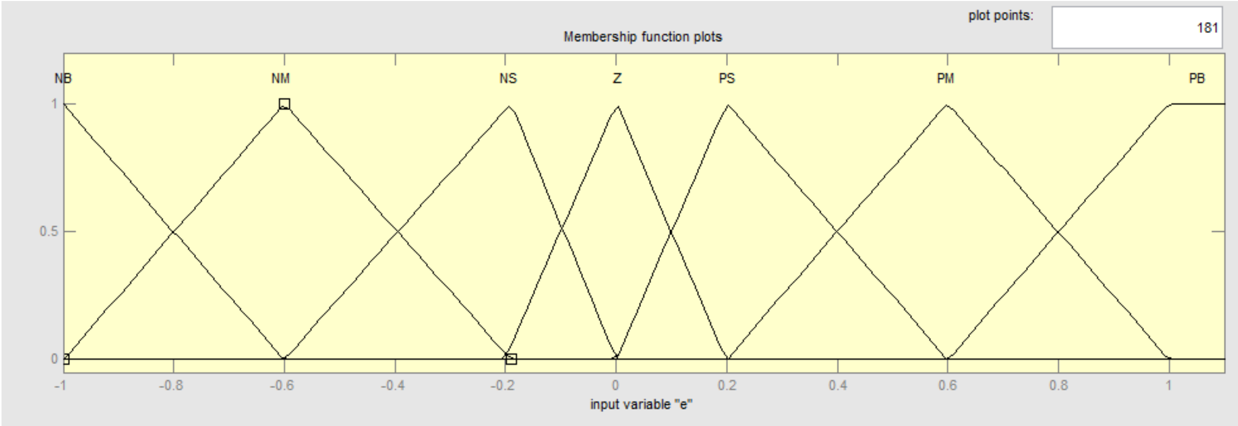

Figure 4.0.2 Input membership functions for frequency error

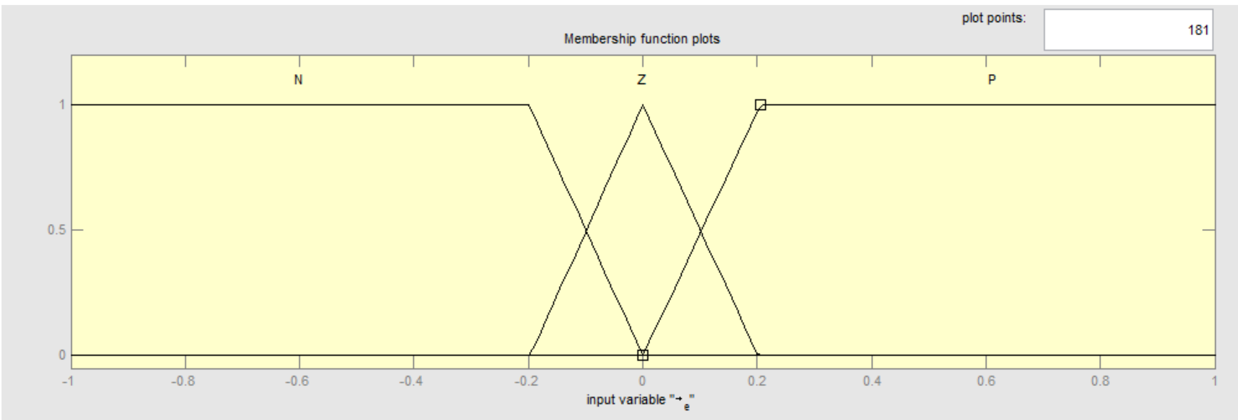

Figure 4.0.3 Input membership functions for change in frequency error

From figure 4.2, NB and PB are trapezoidal type and all the remaining membership functions are triangular type. And from figure 4.3, N and P are trapezoidal type and only Z is triangular type. The universe of discourse of each membership function is shown in the table below 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. The membership functions for frequency error and change in frequency error are made more in number in order to activate only the required actuator valve and to minimize error.

Table 3 Membership function universe of discourse of error

E	Degree of membership						
	NB	NM	NS	Z	PS	PM	PB
-1 to -0.8	0.5 to 1	0.5 to 0	0	0	0	0	0
-0.8 to -0.6	0 to 0.5	1 to 0.5	0	0	0	0	0
-0.6 to -0.4	0	0.5 to 1	0 to 0.5	0	0	0	0
-0.4 to -0.2	0	0 to 0.5	0.5 to 1	0	0	0	0
-0.2 to -0.1	0	0	1 to 0.5	0 to 0.5	0	0	0

-0.1 to 0	0	0	0.5 to 0	0.5 to 1	0	0	0
0 to 0.1	0	0	0	1 to 0.5	0 to 0.5	0	0
0.1 to 0.2	0	0	0	0.5 to 0	0.5 to 1	0	0
0.2 to 0.4	0	0	0	0	1 to 0.5	0 to 0.5	0
0.4 to 0.6	0	0	0	0	0.5 to 0	0.5 to 1	0
0.6 to 0.8	0	0	0	0	0	1 to 0.5	0 to 0.5
0.8 to 1	0	0	0	0	0	0.5 to 0	0.5 to 1
1 to 1.1	0	0	0	0	0	0	1

Table 4 Membership function universe of discourse of change in frequency error

Δe	Degree of membership		
	N	Z	P
-1 to -0.2	1	0	0
-0.2 to -0.1	1 to 0.5	0 to 0.5	0
-0.1 to 0	0.5 to 0	0.5 to 1	0
0 to 0.1	0	1 to 0.5	0 to 0.5
0.1 to 0.2	0	0.5 to 0	0.5 to 1
0.2 to 1	0	0	1

Two subsets, Low (L) and High (H) are used for the input variable Pd. Both this membership functions are trapezoidal types. The input variable the electrical power is normalized to [0, 0.5] and the input scaling factor for Pd are also found by trial and error. The figure and table below shows the shape of the membership function and the universe of discourse of each membership of the input electrical power respectively.

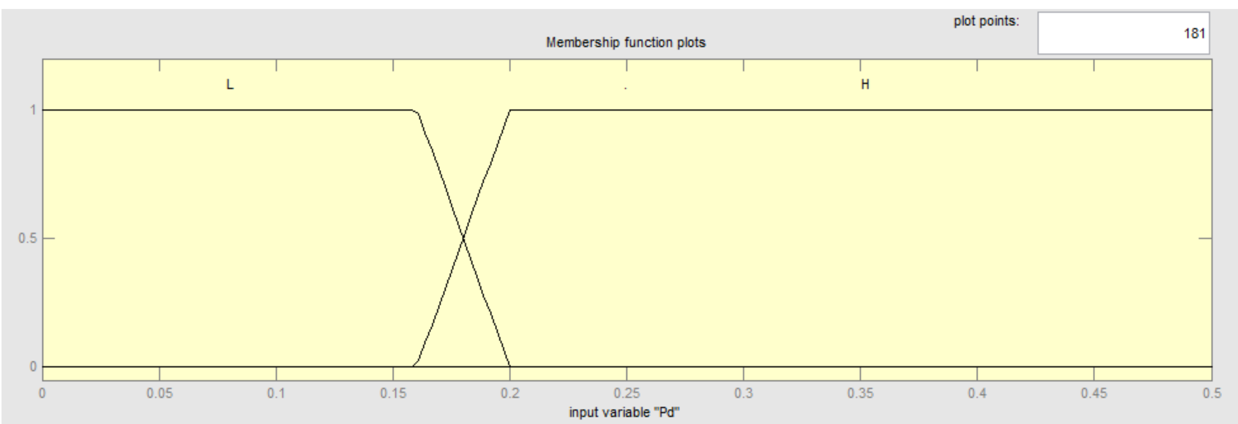

Figure 4.0.4 Input membership functions for demand power

Table 5 Membership function universe of discourse of demand power

Pd	Degree of membership	
	L	H
0 to 0.16	1	0
0.16 to 0.18	1 to 0.5	0 to 0.5
0.18 to 0.2	0.5 to 0	0.5 to 1
0.2 to 0.5	0	1

4.2.2 Rule Base

The rules may use several variables both in the condition and the conclusion of the rules. The controllers can therefore be applied to both multi-input-multi-output (MIMO) problems and single –input-single-output (SISO) problems. Basically a linguistic controller contains rules in the if-then forma, but they can be presented in different formats. Once the membership is found for each of the linguistic labels, a decision can be made onto what the output should be.

The fuzzy controller is created to govern via a servo motor the gate opening of the turbine. It closes the gate opening, not only when the frequency exceeds its nominal value, but also when Pd exceeds the defined limit which is 20% of the nominal turbine power. This task can be summarized by the following rules,

- If e is positive and Pd < Pd limit then Xs is positive
- If e is positive and Pd > Pd limit then Xs is positive
- If e is negative and Pd < Pd limit then Xs is negative
- If e is negative and Pd > Pd limit then Xs is negative
- If e is zero and Pd < Pd limit then Xs is zero
- If e is zero and Pd > Pd limit then Xs is negative

Where e is positive when Fr is less than 50Hz; e is negative when Fr is greater than 50 Hz; e is zero when Fr is equal to 50Hz; Xs positive order to open the gate opening; Xs negative order to close the gate opening; Xs is zero, position of the gate opening remain unchanged.

The required effect here is to keep the output frequency of the generator at its rated value under varying loads and varying flow rate of water from the injector to the turbine. From this required aim, rules are made for every combination of frequency error, change in frequency error and the electrical power on what the output should be in order to make the frequency become constant. After rule base construction rule evaluation which focuses on operation in the antecedent of the fuzzy rules is done. In antecedent part AND/OR fuzzy operation are used, in this design the AND operation is used.

Out of the seven fuzzy sets NB and PB are made trapezoidal type to accommodate any value beyond the range. The rule base for the controller is developed and furnished in the table below. The rules are framed such that, it can be used for scheduling both Kp and Ki.

Table 6 Fuzzy Rule

$e/_{\Delta e}$	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PM	PM	PS	Z
NM	PB	PM	PM	PM	PS	Z	NS
NS	PB	PM	PS	Z	Z	NS	NM
Z	PB	PM	PS	NS	NS	NM	NM

PS	PM	PS	Z	NS	NS	NM	NB
PM	PS	Z	NS	NM	NM	NM	NB
PB	Z	NS	NM	NB	NB	NB	NB

4.2.3 Fuzzy Inference

The rules reflect the strategy that the control signal should be a combination of the reference error and the change in error. 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.

4.2.4 Defuzzification Design

The controller core is the fuzzy control rules which are mainly obtained from intuitive feeling and experience. The design process of fuzzy control rules involves defining the rules that relate the input variables to the output model properties. After the rules are evaluated, each output membership function will contain a corresponding membership. From these memberships, a numerical (crisp) value was produced. The imprecise fuzzy control action generated from the inference must be transformed into a precise control action in the application. 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 center gravity method is used to defuzzify fuzzy variables into their physical domains. The output defuzzification membership functions for ΔKp, ΔKi and ΔXs are shown in the figures below.

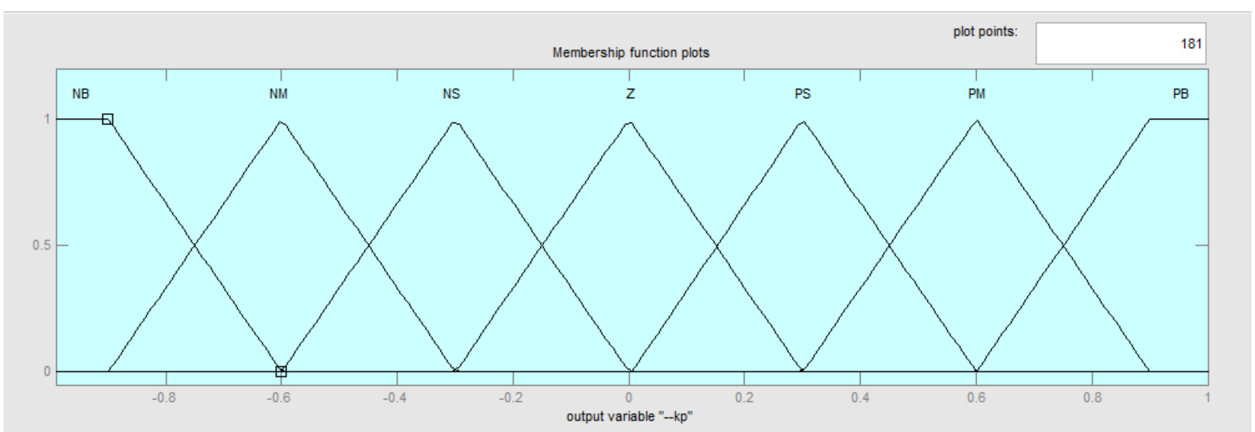

Figure 4.0.5 Output membership functions for ΔKp

Seven fuzzy subsets are selected for the output variable change in proportional gain, which are negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM), and positive big (PB).

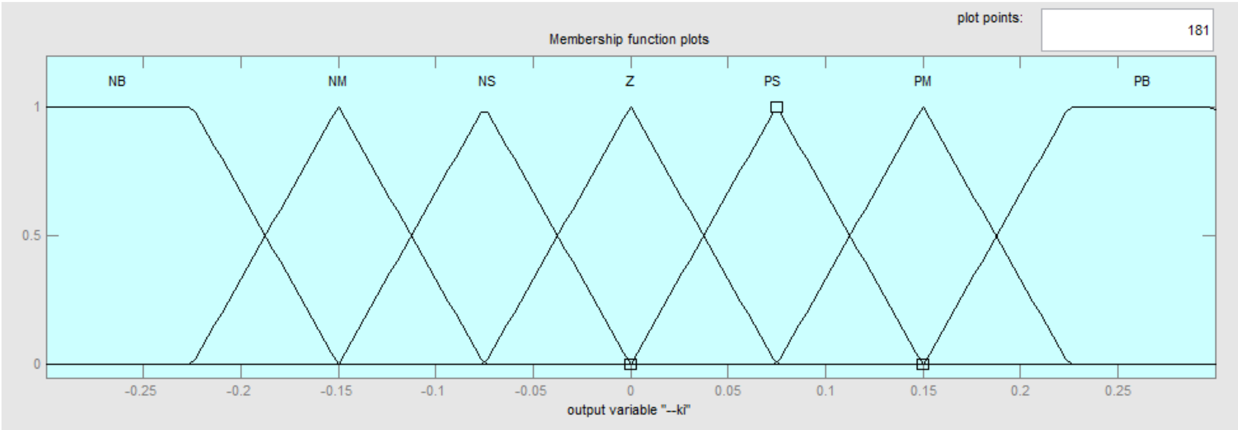

Figure 4.0.6 Output membership function for ΔKi

Also seven fuzzy subsets are selected for the output variable change in integral gain, which are negative big (NB), negative medium (NM), negative small (NS), zero (Z), positive small (PS), positive medium (PM), and positive big (PB).

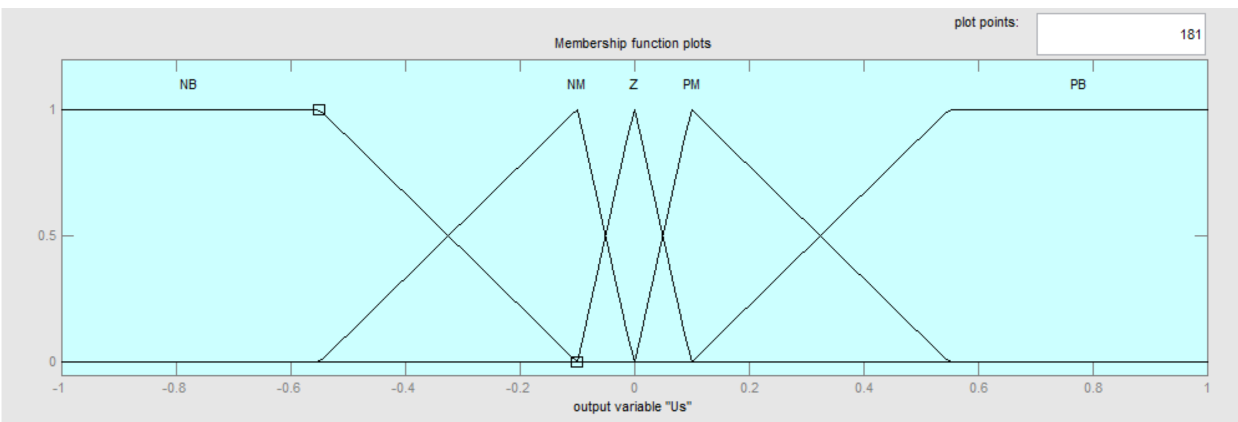

Figure 4.0.7 Output membership functions for ΔXs

Five fuzzy subsets are selected for the output variable ΔXs, which are negative big (NB), negative medium (NM), zero (Z), positive medium (PM), and positive big (PB). The universe of discourse of each membership function is shown in the tables below with degree of membership.

Table 7 Membership function universe of discourse of change in output proportional gain

ΔKp	Degree of membership						
	NB	NM	NS	Z	PS	PM	PB
-1 to -0.9	1	0	0	0	0	0	0
-0.9 to -0.78	0.5 to 1	0 to 0.5	0	0	0	0	0
-0.78 to -0.6	0 to 0.5	0.5 to 1	0	0	0	0	0
-0.6 to -0.52	0	1 to 0.5	0 to 0.5	0	0	0	0
-0.52 to -0.3	0	0.5 to 0	0.5 to 1	0	0	0	0
-0.3 to -0.18	0	0	1 to 0.5	0 to 0.5	0	0	0

-0.18 to 0	0	0	0.5 to 0	0.5 to 1	0	0	0
0 to 0.18	0	0	0	1 to 0.5	0 to 0.5	0	0
0.18 to 0.3	0	0	0	0.5 to 0	0.5 to 1	0	0
0.3 to 0.52	0	0	0	0	1 to 0.5	0 to 0.5	0
0.52 to 0.6	0	0	0	0	0.5 to 0	0.5 to 1	0
0.6 to 0.78	0	0	0	0	0	1 to 0.5	0 to 0.5
0.78 to 0.9	0	0	0	0	0	0.5 to 0	0.5 to 1
0.9 to 1	0	0	0	0	0	0	1

Table 8 Membership function universe of discourse of change in integral gain

ΔKp	Degree of membership						
	NB	NM	NS	Z	PS	PM	PB
-0.3 to -0.23	1	0	0	0	0	0	0
-0.23 to -0.19	0.5 to 1	0 to 0.5	0	0	0	0	0
-0.19 to -0.15	0 to 0.5	0.5 to 1	0	0	0	0	0
-0.15 to -0.11	0	1 to 0.5	0 to 0.5	0	0	0	0
-0.11 to -0.07	0	0.5 to 0	0.5 to 1	0	0	0	0
-0.07 to -0.04	0	0	1 to 0.5	0 to 0.5	0	0	0
-0.04 to 0	0	0	0.5 to 0	0.5 to 1	0	0	0
0 to 0.04	0	0	0	1 to 0.5	0 to 0.5	0	0
0.04 to 0.07	0	0	0	0.5 to 0	0.5 to 1	0	0
0.07 to 0.11	0	0	0	0	1 to 0.5	0 to 0.5	0
0.11 to 0.15	0	0	0	0	0.5 to 0	0.5 to 1	0
0.15 to 0.19	0	0	0	0	0	1 to 0.5	0 to 0.5
0.19 to 0.23	0	0	0	0	0	0.5 to 0	0.5 to 1
0.23 to 0.3	0	0	0	0	0	0	1

Table 9 Membership function universe of discourse of change in Xs

ΔKp	Degree of membership				
	NB	NM	Z	PM	PB
-1 to -0.58	1	0	0	0	0
-0.58 to -0.37	0.5 to 1	0 to 0.5	0	0	0
-0.37 to -0.1	0 to 0.5	0.5 to 1	0	0	0
-0.1 to -0.05	0	1 to 0.5	0 to 0.5	0	0
-0.05 to 0	0	0.5 to 0	0.5 to 1	0	0
0 to 0.05	0	0	1 to 0.5	0 to 0.5	0
0.05 to 0.1	0	0	0.5 to 0	0.5 to 1	0
0.1 to 0.37	0	0	0	1 to 0.5	0 to 0.5
0.37 to 0.58	0	0	0	0.5 to 0	0.5 to 1
0.58 to 1	0	0	0	0	1

Fuzzy supervisor

The water level on the reservoir might decrease as it might increase depending on the availability of water on the river. Thus, the generated power would vary considerably. Therefore, undesirable situations might be occurred, where the generating unit would be no longer able to feed the consumer loads connected to the mini-grid. To remedy this possible situation, the proposed fuzzy supervisor, is able either to disconnect or connect the less preferred departures, depending on the level of the available water.

The level of water “h” is divided into four sets (H1, H2, H3, H4) while the departures of the grid are three (D1, D2 and D3). D1 is the more preferential departure while D3 is the less preferential. This task, assured by the fuzzy supervisor, can be summarized by the following rules:

- If h is H1 then D1, D2, and D3 are connected.
- If h is H2 then D1 and D2: connected, D3: disconnected.
- If h is H3 then D1 connected, D2 and D3: disconnected.
- if h is H4 then D1, D2, and D3 are disconnected.

Furthermore, the proposed fuzzy supervisor manages the electrical production between the three departures. The division of the mini-grid into different departures will be also used by the proposed supervisor to limit the consumed power "Pe", to make sure that it never exceeds the turbine power. Whenever very large overloads are caused by the users, where the load exceeds the produced power, the fuzzy supervisor disconnects the less preferential departures (D3) to avoid large drop of frequency. If the consumed power still exceeds the turbine power, the supervisor disconnects other less priority departure (D2) and so on. The fuzzy membership functions for the fuzzy supervisor input parameters (h, InpD1, InpD2 and InpD3) and output parameters (D1, D2 and D3) are shown in figure below,

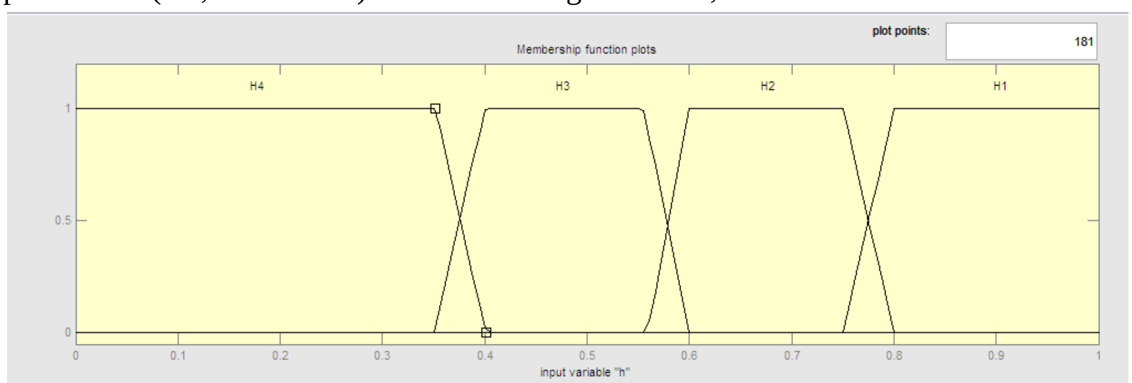

Figure 4.0.8 Input membership function for h

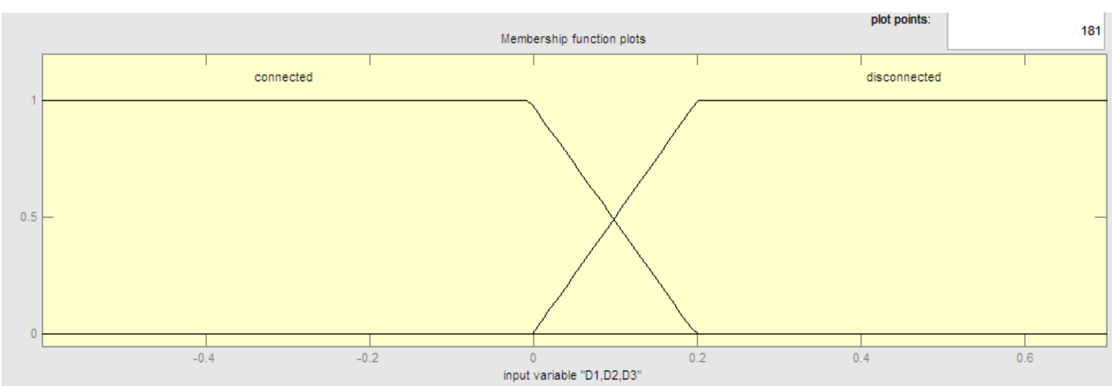

Figure 4.0.9 Input membership function for InpD1, InpD2 and InpD3

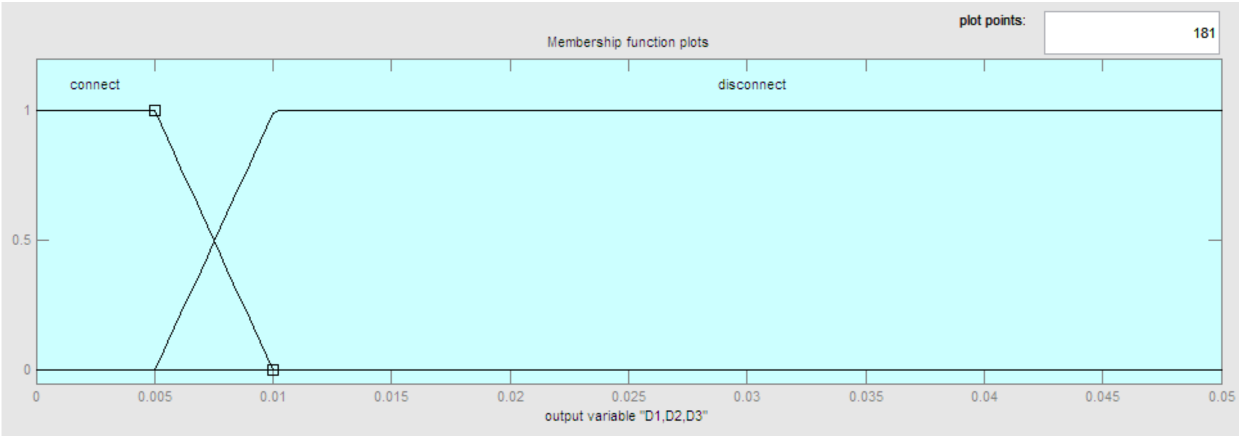

Figure 4.0.10 Output membership function for D1, D2 and D3

The universe of discourse of each membership function is shown in the tables below with degree of membership.

Table 10 Membership function universe of discourse of h

h	Degree of membership			
	H4	H3	H2	H1
0 to 0.35	1	0	0	0
0.35 to 0.4	0.5 to 1	0 to 0.5	0	0
0.4 to 0.55	0 to 0.5	0.5 to 1	0	0
0.55 to 0.6	0	1 to 0.5	0 to 0.5	0
0.6 to 0.75	0	0.5 to 0	0.5 to 1	0
0.75 to 0.8	0	0	1 to 0.5	0 to 0.5
0.8 to 1	0	0	0.5 to 0	0.5 to 1

Table 11 Membership function universe of discourse of InpD1, InpD2 and InpD3

Input D1, D2, D3	Degree of membership	
	connected	disconnected
-0.6 to 0	1	0
0 to 0.1	1 to 0.5	0 to 0.5
0.1 to 0.2	0.5 to 0	0.5 to 1
0.2 to 0.7	0	1

Table 12 Membership function universe of discourse of output variable D1,D2 and D3

Output D1, D2, D3	Degree of membership	
	connected	disconnected
0 to 0.005	1	0
0.005 to 0.00625	1 to 0.5	0 to 0.5
0.00625 to 0.01	0.5 to 0	0.5 to 1
0.01 to 1	0	1

4.4 Simulink Model

All the components of MHPP are modeled to design the controller and to analyze the simulation results. The Overall Simulink model of the MHPP control system are shown in the figure below,

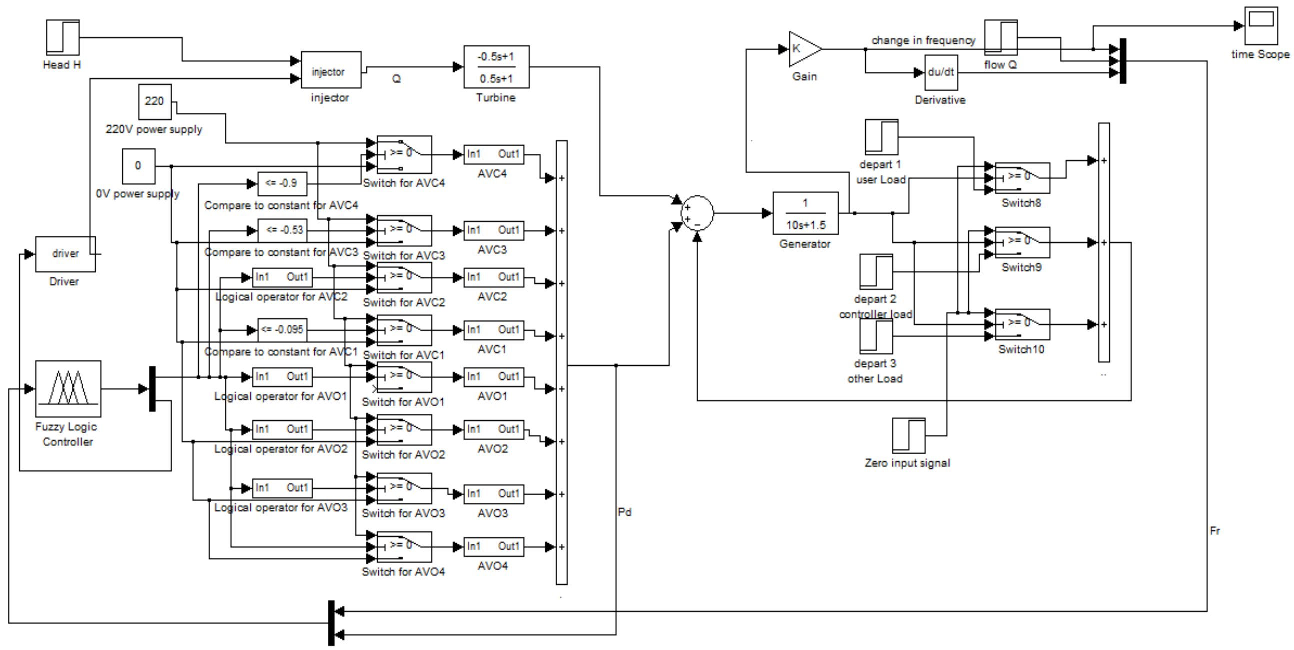

Figure 4.0.11 the overall Simulink Simulation model

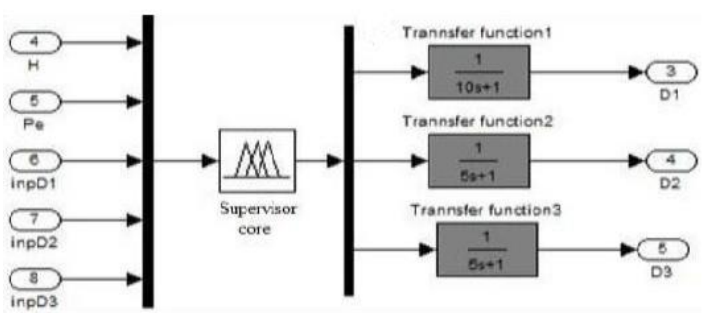

Figure 4.0.12 the proposed fuzzy supervisor

CHAPTER 5
SIMULATION RESULT & DISCUSSION

5.1 Introduction

After modeling the Micro Hydro-power Plant, it is simulated in the software Mat Lab Simulink. The Simulink model shows the simulation of the turbine mechanical power, electromagnetic power, rotor angular velocity, stator output current, and stator output voltage, the performance of the MHPP with PI controller and finally the performance of the MHPP with the proposed Fuzzy Logic Controller. Also the result of the FPGA is discussed.

5.2 Simulation Result

The simulation results are presented when load is added and rejected. To see the effect of load variation on the system the response of the system is tested for load addition of 15% and 75% as well as load removed of 15% and 75%. The frequency deviation of the MHPP without controller and with fuzzy controller for 75% load addition and 75 % load removed is shown in the figure 5.1 and figure 5.2 respectively. The results are obtained assuming the damping constant of the generator equal to 1 up to 2 and flow rate of water 0.2 m^3/sec.. The results are revised in table 5.1 below.

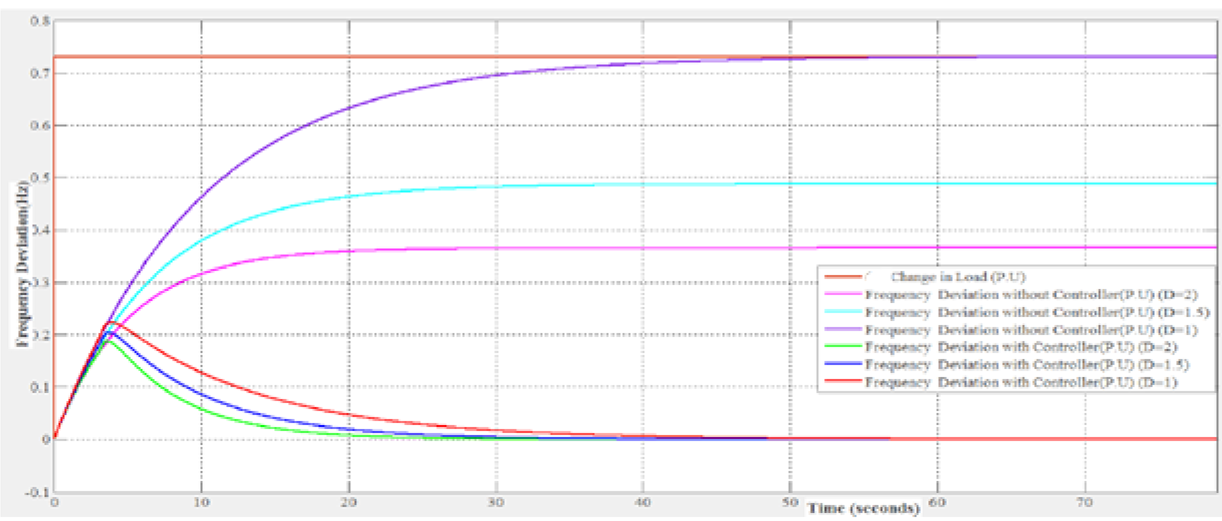

Figure 5.0.1 frequency responses for 0.75 P.U load rejection

When the load is rejected from the system the feedback gets back to the power plant the load can drop suddenly and inversely the frequency increases beyond the nominal set point. The figure above shows this. The reverse is true, when the load is added the frequency deviation decrease. It is shown in the figure below.

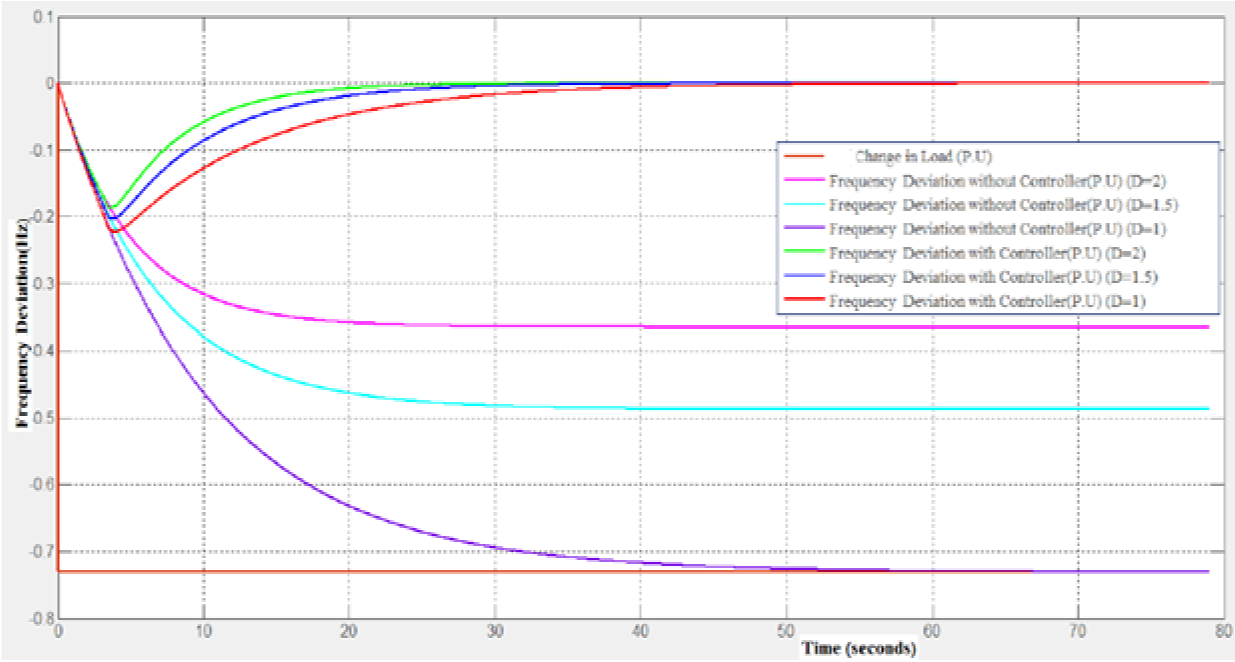

Figure 5.0.2 frequency response for 0.75 P.U load addition

From the above figure we can see that the frequency decreases when the load is added. This is because the power source is an AC generator, in this case the load is sufficiently high as compared then it will causes the frequency to decrease, as it will take more energy for the generator to be able to cope with the newly increased load, causing the generator rpm to drop and eventually the frequency drops. The deviations are brought under control by the fuzzy logic control to ensure quality power to the customers.

The simulation result is recapped with the table below,

Table 13 steady state and transient performance of frequency controller for 75% load changes

75% load changes	Without controller D=1	Without controller D=1.5	Without controller D=2	With controller D=1	With controller D=1.5	With controller D=2
Steady state (P.U)	0.731	0.437	0.316	0	0	0
Overshoot	13.15%	8.7%	6.28%	3.46%	3.04%	2.74%
Settling time	Never settled	Never settled	Never settled	39.82 sec	27.65 sec	20.87 sec

The frequency deviation of the MHPP without controller and with fuzzy controller for 15% load addition and 15% load remover is shown in the figure 5.5 and figure 5.6 respectively. The results are obtained by taking the same assumption taken for the 75% load changes.

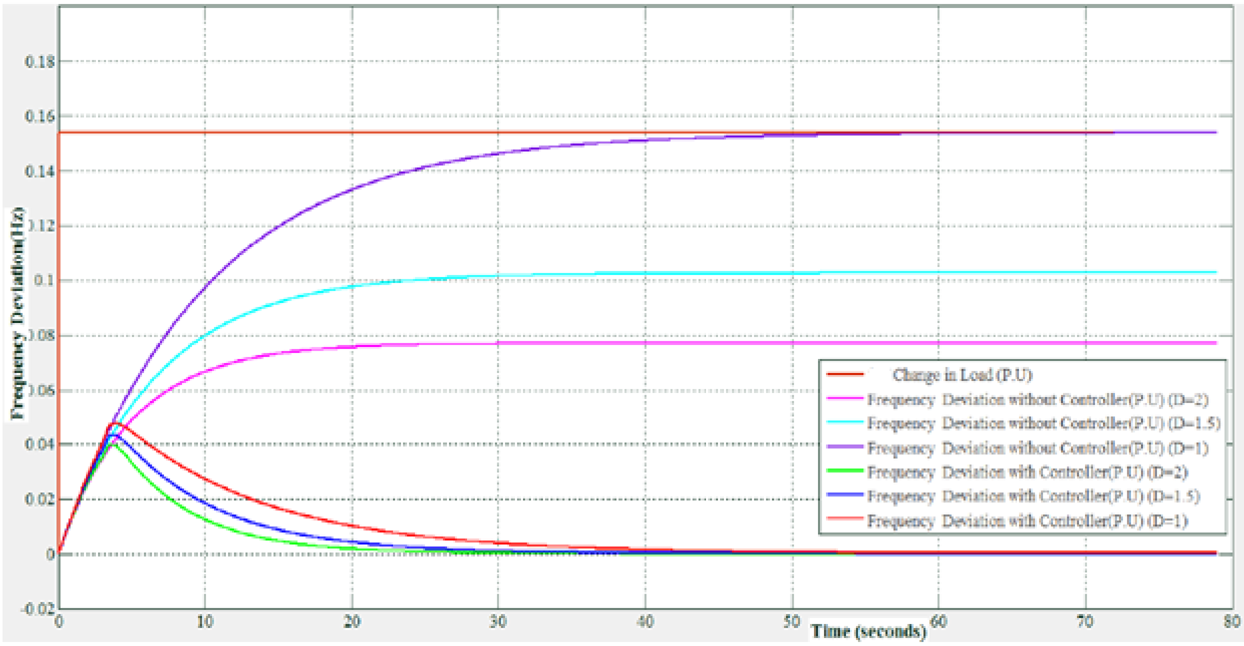

Figure 5.0.3 frequency responses for 0.15 P.U load rejection

Figure 5.5 frequency responses for 0.15 P.U load rejection

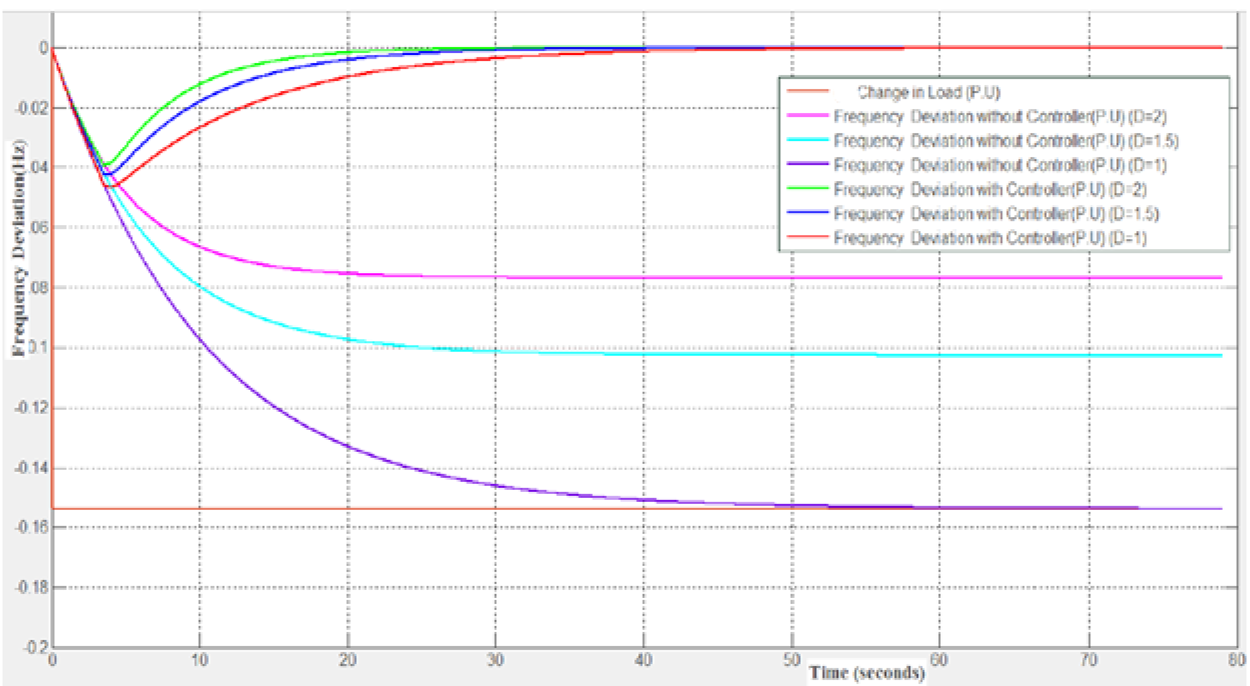

Figure 5.0.4 frequency response for 0.15 P.U load addition

The results for 15% load change are revised in table 4.3 below.

Table 14 steady state and transient performance of frequency controller for 15% load changes

15% load changes	Without controller D=1	Without controller D=1.5	Without controller D=2	With controller D=1	With controller D=1.5	With controller D=2
Steady state (P.U)	0.114	0.063	0.037	0	0	0
Overshoot	2.82%	1.55%	0.925%	0.17%	0.05%	0.025%
Settling time	Never settled	Never settled	Never settled	38.12	26.08	19.25

The fuzzy supervisor manages to use the available water based on consumer demand. Even for random and large load variations, the proposed control system keeps good dynamics as shown in the figure below,

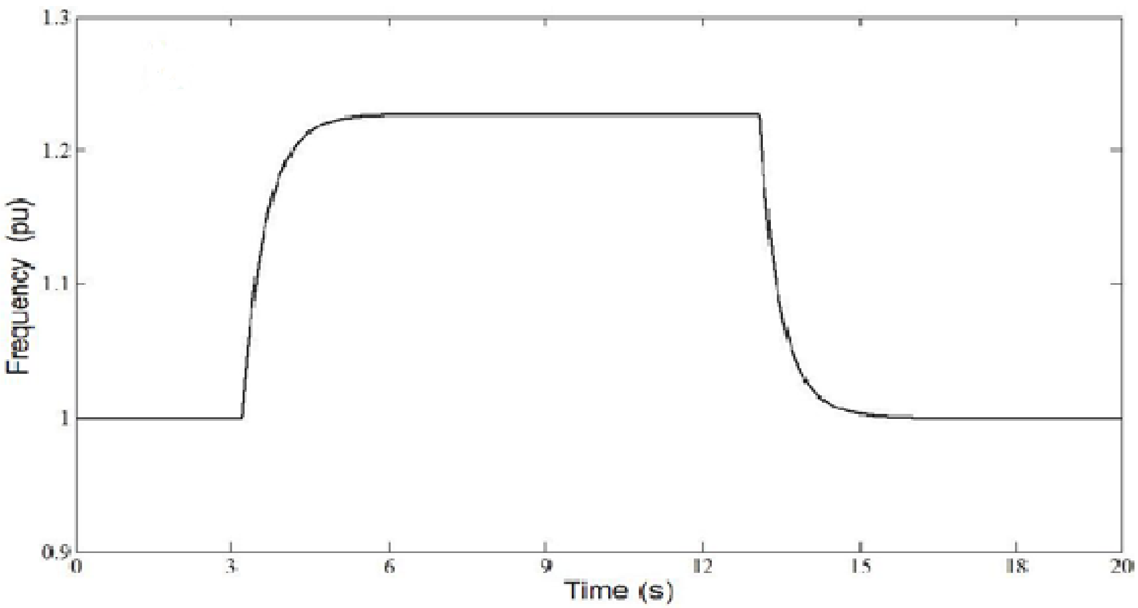

Figure 5.0.5 frequency response for random and large load

The comparison of frequency response of the micro hydropower system with PI controller and fuzzy controller for a 15% and 75% load rejection is shown in the two figures below. The results are obtained taking the same assumption for the generator damping constant and the flow rate of water.

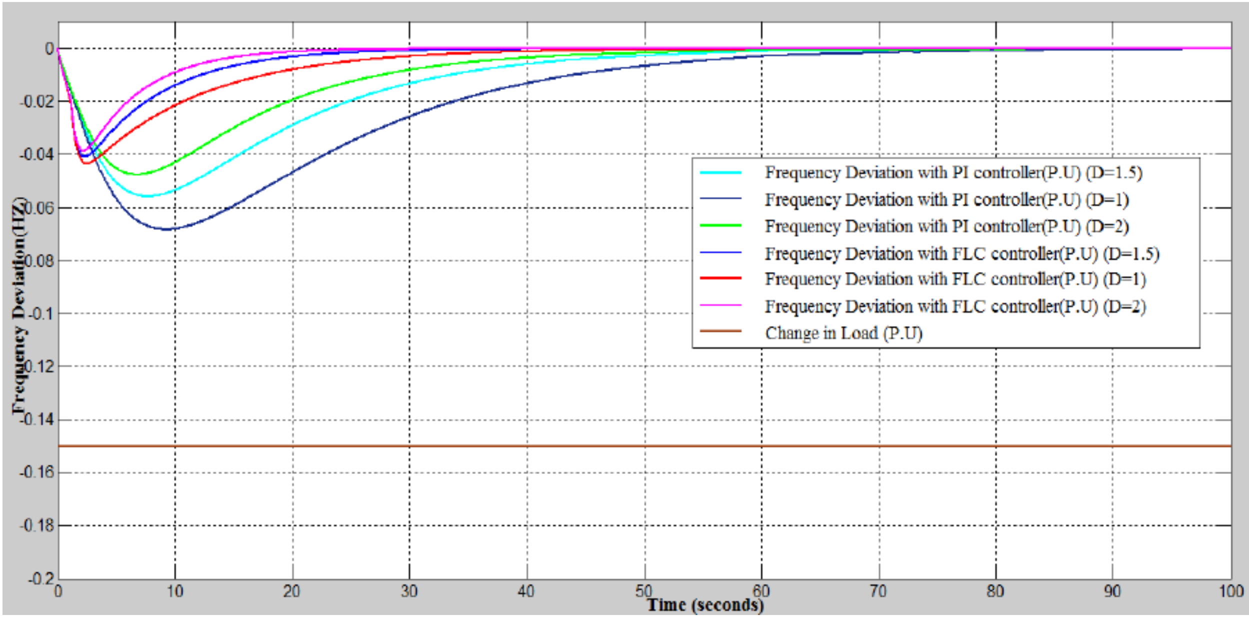

Figure 5.0.6 frequency response for 0.15 P.U load change

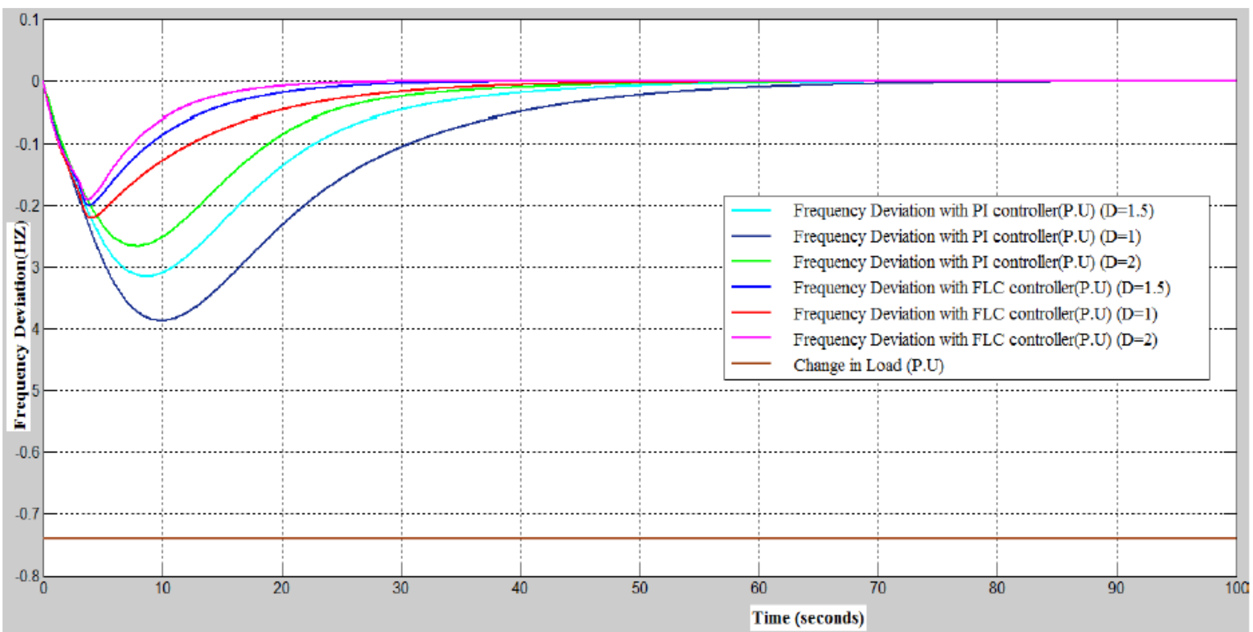

Figure 5.0.7 frequency response for 0.75 P.U load change

Simulation results for the PI controller and fuzzy controller are revised in the table below. As can be observed, the settling time and overshoots with the PI controller and the proposed fuzzy controller are given from the simulation result.

Table 15 Comparison between PI and Fuzzy for 75% load change

Parameter	PI controller			Fuzzy controller		
	D=1	D=1.5	D=2	D=1	D=1.5	D=2
Steady state (P.U)	0	0	0	0	0	0
Settling Time	69.8	58.7	47.6	39.82	27.65	20.87
Overshoot	6.82%	5.43%	4.42%	3.46%	3.04%	2.74%

Table 16 Comparison between PI and Fuzzy for 15% load change

Parameter	PI controller			Fuzzy controller		
	D=1	D=1.5	D=2	D=1	D=1.5	D=2
Steady state (P.U)	0	0	0	0	0	0
Settling Time	45.7	56.3	67.2	38.1	26.08	19.25
Overshoot	0.72%	0.45%	0.23%	0.175%	0.05%	0.025%

From these results, we can see that the fuzzy logic controller has a better performance compared to the PI controller.

In the FPGA realization of FLC, upon successful completion of the VHDL coding functional simulation is performed to verify the correct functionality and to determine the deviation or tolerance parameters of the fuzzy logic frequency controller using generated test bench which is the ModelSim-ALTERA.

A set of stimuli as inputs (functional vectors that changes with at fixed time duration) is fed into the test bench. The waveform in figure 4.15 shows the values of the inputs and the corresponding output in hex form at the various instances determined by the stimuli in the test bench.

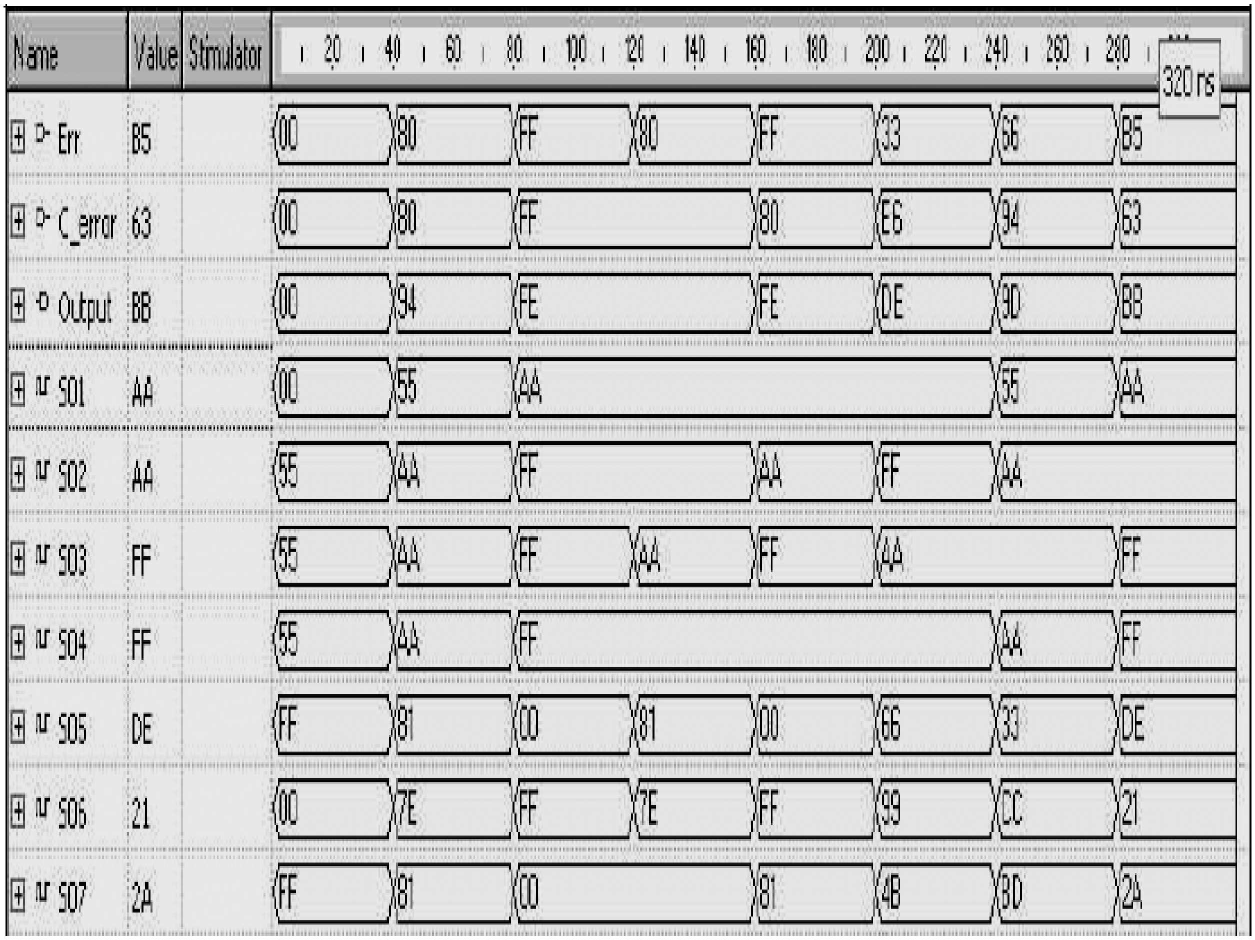

Figure 5.0.8 Waveform of functional simulation of the FLFC

The same test stimuli are used for timing simulation taking into account the propagation delay. In addition, the simulation at this stage is performed upon nodes that are synthesizable. Slice of the timing waveform is shown in the figure below,

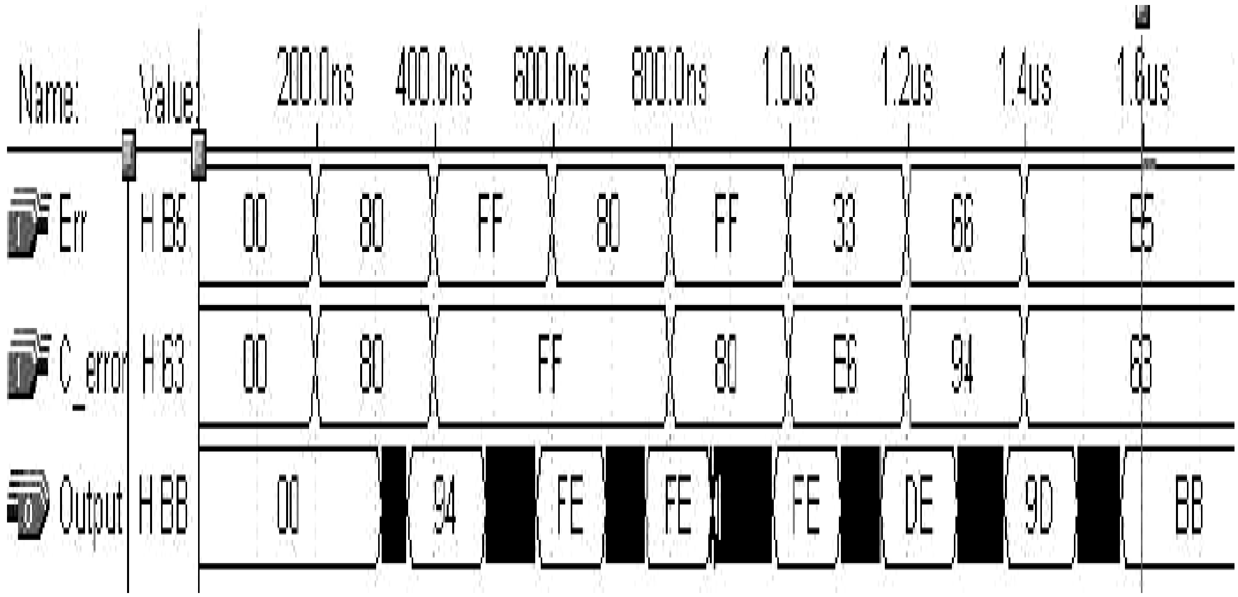

Figure 5.0.9 Waveform of Timing Simulation of the FLFC

It is important to note that, the outputs are exactly the same for both functional and timing simulation. The difference between these two simulations is that there is a noticeable time delay before the output is available upon the assertion of a set of input. Notice also that the output requires a period before its value stabilizes.

5.3 Discussion

This section present the discussion on the tests performed on the micro hydro-power plant. The tests performed on the frequency controller of MHPP were to analyze its performance for load change.

As it can be seen from figure 5.1 to figure 5.6, the frequency return to its steady state in a short time. From figure 5.7 and figure 5.8, the frequency returns to its steady state in a very short time using fuzzy controller rather than PI controller. This demonstrates the capability and effectiveness of the proposed fuzzy controller for frequency control of micro hydro-power plants.

The tests performed on the controller was to see how the FLC 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 other test performed on the controller is, to design the controller using VHDL. This is done due to the controller can be modified to engage different algorithm for further improvements in the performance of the micro hydro-power plants. The main objective here is, the cost benefit of MHPP with the proposed controller is analyzed in detail with FPGA. FPGA is better than microcontroller because it has not been configured to have a particular function during fabrication. Also FPGA is very flexible, reusable and quicker to acquire.

CHAPTER 6
CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

6.1 Conclusion

In rural areas of Ethiopia, there are rivers which are used for only agricultural purpose but these rivers can be used for small hydro generation. In our country, there are rural communities still live without electricity. So these rivers are useful for the generation of small hydro generation. This thesis worked to develop a cost effective controller for micro hydro generation to rural areas by using available hydropower resources. When there is load variation, the frequency regulation of MHPP was a problem. The proposed Fuzzy logic controller is used to improve and maintain MHPP frequency regulation. The proposed controller can be used for MHPP with different power output and head by varying the size of the actuator valve. Good transient and steady state responses for different operating points of the processes can be achieved by increasing the number of membership functions.

The thesis focused on the cost effectiveness of the system, for this Induction Generator is used over Synchronous Generator. The advantages are price, robustness simpler starting and control. The controller was realized using VHDL (ModelSim-Altera), implementing the controller on FPGA was found cost effective.

A mathematical model of MHPP was expanded and tested through simulation using Matlab Simulink and ModelSim-Altera. It is observed from the simulation results that the overshoot of the fuzzy controller for 75% load change and 0.2 m^3/s flow rate is 2.74%, 3.04% and 3.46% and the settling times are 20.87, 27.65 and 39.82 seconds respectively. Moreover, the comparison of fuzzy logic controller and PI controller is observed. From the simulation results for 75 % load change the overshoot of the PI controller is 6.82%, 5.43% and 4.42% ant the settling time is 69.8,58.7 and 47.6 seconds respectively.

The controller has been coded, compiled and simulated in VHDL using ModelSim-Altera. At present the system inferred maximum operating frequency is 5 MHz with a critical path of 199.3 ns. This could take advantage of the high speeds achievable using hardware, and as a result would be a beneficial and economic investment for designs requiring fuzzy logic.

Simulation results show the feasibility of the proposed fuzzy control system. Even for random and large load variations, the control system keeps good dynamics as expected. So that the proposed 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.

6.2 Recommendation

Even though hydro-power is a main electric generation in Ethiopia, there are almost no micro hydro power generation in the country. As a recommendation, considering the situation where many villages still live without electricity, especially those in mountains, but still have the resource for micro hydro-power generation; the government should give attention for the exploitation of MHPP.

6.3 Future Work

Only MHPP is considered in this thesis, though there are different renewable energies which may be relevant for rural electrification. Such as solar and wind energy generation. Therefore the performances of fuzzy logic controller can be investigated on this type of energy generation.

The cost benefit of micro hydro-power plant with the proposed controller can be analyzed in is analyzed using VHDL. But it is not implemented, so as a future work, the implementation of the hardware of this proposed controller can be implemented on the FPGA. In addition, the 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 using FPGA can be developed for micro hydro-power plants on this river.

Reference

[1]Hydropower of Ethiopia: status, Potential and Prospects, http://www.ethiopians.com/Engineering/hydropower_of_ethiopia.htmpotential, accessed on 2018.

[2] Alex Jose and Dr. Jayaprakash P., "Power Electronic Control of Induction Generator used in Small Hydro Power System," IJEET copy right IAEME, Volume 5, Issue 12, December (2014), pp. 76-83

[3] SuhasV.Kamble, D.P.Kadam, "Design of Fuzzy controller and supervisor for load Frequency control of Micro Hydro Power Plant", International Journal of Scientific and Research Publications, Volume 4, Issue 1, January 2014

[4] "Micro Hydro in the fight against poverty", tve.org. TVE/ITDG. November 2004. Achieved from the original on 30 July 2007. Retrieved 14 January 2017

[5] http://www.nationmaster.com/country/et-ethiopia/ene-energy, accessed on 2018.

[6] Aklilu Dalelo (PHD), "Rural Electrification in Ethiopia: Opportunities and Bottlenecks", Flensburger Regional Studien, Flensburg 2001

[7] DOE's office of Energy Efficiency and Renewable Energy, "Typical micro hydro setup", 2010

[8]Twidell, J and T weir, "Renewable Energy Resources", 2nd edition, Ontario, Aztex Press, 2005

[9] https://en.wikipedia.org/wiki/Water_turbine#/media/File:Water_turbine_(en_2).svg, "Kaplan turbine and electrical generator cut-away view." accessed on 2018.

[10] https://en.wikipedia.org/wiki/Micro_hydro, "Micro hydro: Turbine types." accessed on 2018.

[11] Haiyan, B., Y. Jiandong and F. Liang, "Study on Nonlinear Dynamical Model and Control Strategy of Transient Process in Hydropower Station with Francis Turbine", in Power and Energy Engineering Conference, 2009, APPEEC 2009.

[12] Strah, B., O. Kuljaca, and Z. Vukic, "Speed and active power control of hydro turbine unit energy Conversion", IEEE Transactions on, 2005. 20(2): p. 424-434.

[13] Weber, H., V. Fustik, F. Prillwitz, A. Iliev.Practically oriented simulation model for theHydroPower Plant "Vrutok" in Macedonia.2nd BalkanPower Conference, 19.-21.06. 2002, Belgrade,Yugoslavia

[14] P. C. Krause. 0. Wasynczuk. S. D. Sudhoff, “Ana1ysis of electric Machinery and drivesystems”, IEEE Press Power Engineering Series, 2002, l41-l87.

[15] Yunus A. Çengel, John M. Cimbala, **“**Fluid Mechanics: Fundamentals and Applications.”, 1st ed., McGraw-Hill

[16] John F. Douglas, **“**Fluid Mechanics.”, 5th ed., Pearson.

[17] Upadhayay, S., “Evaluating the effectiveness of micro-hydropower project in Nepal” San Jose State University, SHSU Scholar Works, 2009.

[18] D. New, “Introduction to Hydropower, Part 1: systems overview”, Home Power 103/October and November 2004.

[19] Kundur P., Neal J.B., and Mark G.L., “Power System Stability and Control”, McGraw-Hill, 1994.

[20] Y. Wang, T. Megil, and M. Haghgooie, “Modeling and control of Electromechanical Valve Actuator”, Ford Motor company, copyright © 2002 Society of Automotive Engineers, Inc.

[21] Alexander Sadiku, “Fundamentals of Electric circuits”, McGraw-Hill, 2007.

[22] C.Nordling, J. Ä Osterman, "Physics Handbook for Science and Engineering", 1999.

[23] R.A.Serway, J.W.Jewett. "Physics for Scientists and Engineers with Modern Physics", 6th Edition, 2004.

[24]] I. Guler, A. Tunca, E. Gulbandilar, “Detection of Traumatic Brain Injuries Using Fuzzy Logic Algorithm”, Expert Systems with Applications, Vol. 34, pp. 13121317, 2008.

[25] A.S. Kannan, R. Kayalvizhi, “A Novel Design of a Fuzzy Coordinated SSSC Controller for Integrated Power Systems”, International Journal on Technical andPhysical Problems of Engineering (IJTPE), Issue 8, Vol. 3, No. 3, pp. 6-16, September 2011.

[26] A. Barati, S.J. Dastgheib, A. Movaghar, I. Attarzadeh, “An Effective Fuzzy Based Algorithm to Detect Faulty Readings in Long Thin Wireless Sensor”, International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 10, Vol. 4, No.1, pp. 5258, March 2012.

[27] Ross T.J., HASSANEIN H., ALI A.N.,: Fuzzy logic with engineering applications: design and stability analysis. 3rd ed. Chichester (RoyaumeUni): Wiley, 2010, xxvii, 275 p. ISBN 978-047-0748-510.

[28] Fullér R., HASSANEIN H., ALI A.N.,: Neural fuzzy systems: towards IMT-advanced networks. Åbo: Åboakademi, 1996, xxvii, 275 p. ISBN 95-165-0624-0.

[29] Kaehler S.D.,: Fuzzy Logic Tutorial. Seattle Robotics Society [online]. 1998. ed. [cit. 2012-08-22]. Avaible at: http://www.seattlerobotics.org/encoder/mar98/fuz/flindex.html

[30] HilmiZenk, HilmiZenk, AdemSefaAkpinar, "Two Different Power Control System Load-Frequency Analysis Using Fuzzy Logic Controller" IEEE 2011, Page no 465-469.

[31] MichaelMcKenna and Bogdan M. Wilamowski, "Implementing a Fuzzy System on a Field Programmable Gate Array", IEEE International Joint Conference on Neural Networks, 2001. Proceedings. IJCNN '01, ISBN: 0-7803-7044-9, Volume: 1, p.189-194, 2001.

[32] https://en.eikipedia.org/wiki/VHDL "VHDL", accessed on 2018.

[33] "Handbook of Digital Techniques for High-Speed Design", Pearson Education India, 01-Sep-2007.

[34] "Digital Hardware Design", Laxim Publications, Ltd., 01-Sep-2008.

[35] https://www.rfideas.com/solutions/industries/manufacturing , accessesd on 2018.

[36] https://www.alibaba.com/product-detail/Electronic-Load-Controller-ELC-_116357027.html , accessed on 2018.

[37] Salman Mohagheghi, Ganesh K. Venayagamoorthy, Satish Rajagopalan,and Ronald G. Harley, "Hardware Implementation of a Mamdani Fuzzy Logic Controller for a Static Compensator in a Multimachine Power System", IEEE Transactions on industry applications, VOL. 45, NO. 4, July/August 2009.