Addis Ababa University

Addis Ababa Institute of Technology

DESIGN OF SELF-TUNING FUZZY CONTROLLER FOR MICRO HYDROPOWER PLANSTS ON IRRIGATION DAMS

A Thesis Submitted to the School of Graduate Studies, Addis Ababa Institute of Technology in Partial Fulfilment of the Requirements for the Degree of Master of Science in Electrical Engineering

By

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Addis Ababa University

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Declaration

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

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Signature

Addis Ababa, Ethiopia
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Place Date of
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This thesis has been submitted with my approval as a university advisor

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Advisor Name
Signature

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LIST OF SYMBOLS

f	Frequency
po	Number of poles
rev	Revolutions
T_w	Water starting time
ΔP_m	Change in mechanical power
ΔG	Change in gate position
U	Water velocity
G	Gate position
h	Hydraulic head
A_t	Turbine gain
G_o	Initial gate position
G_{fl}	Per unit full load gate position
G_{nl}	Per unit no load gate position
T_a	Accelerating torque
T_m	Mechanical torque
T_e	Electrical torque
J	Moment of inertia
w_m	Angular velocity
t	Time
w_{om}	Rated angular velocity
H	Inertia constant
P_m	Mechanical power

P_e	Electrical power generated
$\overline{P_m}$	Per unit mechanical power
$\overline{P_e}$	Per unit electrical power generated
$\overline{w_r}$	Per unit angular velocity
δ	Angular position of the rotor
$\Delta\overline{w_r}$	Per unit change in rotor speed
$\overline{\Delta G}$	Per unit change in gate position
$\overline{\Delta P_e}$	Per unit change in electrical load power
$\overline{\Delta P_B}$	Per unit change in ballast load
$\Delta\overline{P_D}$	Per unit change in demand power
V_{ll}	Line voltage
R_B	Ballast load resistance
D	Load damping constant
Δf_{ss}	Steady state frequency error

LIST OF ABBREVIATIONS

NB	Negative Big
NM	Negative Medium
NS	Negative Small
Z	Zero
PS	Positive Small
PM	Positive Medium
PB	Positive Big
FLC	Fuzzy Logic Controller
p.u	Per Unit
ELC	Electronic Load Controller
MHPP	Micro Hydro Power Plant
PI	Proportional Integral
EEPCo	Ethiopian Electric Power Corporation

ABSTRACT

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Micro hydro power plants are stand alone renewable energy sources and free from emission of green house gases. It is an appropriate choice for rural electrification where supplying grid electricity is not economical. In Ethiopia, we have several irrigation dams, streams and running rivers which have considerable hydropower potential. Micro hydropower plants can be installed on the existing irrigation dam with less investment and time.

Nowadays, electronic load controller is used to control the frequency of micro hydropower plants. However, electronic load controller wastes big amount of water during low power demand which can be diverted at high head for irrigation purposes. In addition, micro hydropower plants are characterized by parameter variations like damping constants where fixed control does not provide the desired performance under different operating conditions. Thus, development of an appropriate control scheme for micro hydropower seems inevitable to obtain the desired performance under different operating conditions.

This thesis proposes 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. A detail dynamic model of micro hydropower plant is developed to design the proposed controller. Genetic algorithm is used to optimize the membership functions of the fuzzy logic controller. To meet a sudden consumer demand of power, 0.25p.u. power is dissipated on the ballast loads under steady state condition.

It is observed from the simulation results that the average overshoot for 30% load change is 4.6% and the settling time is 7.5 seconds with the proposed fuzzy logic controller while overshoot is 8.9% and 13.5% and settling time is 11 seconds and 29 seconds with PI load control and PI flow control, respectively. Moreover, even for 70% load rejection, overshoot is only 11.6% and the settling time is 11 seconds. It is further observed that the change in energy wasted on ballast load from the desired value is always around zero at steady state conditions.

Key Words: Micro Hydropower, Irrigation Dams, PI Controller, Fuzzy Logic Controller, Genetic Algorithm

Chapter One

INTRODUCTION

1.1 Back Ground

Micro-hydro power plant (MHPP) was one of the earliest small scale renewable energy technologies to be developed, and is still an important source of energy today [1]. It has the potential to produce an important share of power more than solar or wind power with a low price. Generation capacity of micro hydropower plants ranges from 0.2KW to 100KW and are thought to be ideal renewable resources to electrify isolated rural communities, particularly, in developing countries [2].

Most of the rural part of Ethiopia is not yet electrified. Unfortunately, it is not feasible both technically and cost wise to extend the national grid to isolated rural communities. Due to the high potential of micro hydropower in Ethiopia, micro hydropower plants could play a positive role towards accelerating rural electrification process. Moreover, a number of micro – irrigation earth dams have been constructed and planned to be constructed in different parts of the country, especially in rural areas of Tigray and Amhara regional states without taking into consideration the opportunity to integrate them with power generation so as to electrify the surrounding rural community [3].

If a reservoir has already been built for other purposes such as flood control, irrigation network, water abstraction for a big city, recreation area, etc., it is possible to generate electricity [3]. The main problem in utilizing power from irrigation dam is how to harmonize the existing operational plan to the intended power generation.

In addition to the problem of harnessing micro hydropower from irrigation dam, micro hydropower plants are characterized by parameter variation like damping constant of generator with load changes which makes conventional controller with fixed gains inefficient.

1.2 Statement of the Problem

Loads connected to the generator require a uniform and an uninterrupted supply of electrical power. So, MHPP needs to be controlled to maintain an uninterrupted power at rated frequency. For this purpose, two main types of governors are used. The frequency can be maintained constant by action on the gate opening position, by adjusting the water flow with mechanical-hydraulic governors, electro hydraulic governors or mechanical governors, to produce just the necessary power according to the load demand. On the other hand, the electronic load controllers govern the turbine speed by adjusting the electrical load on the generator, thus by balancing the total electrical load torque with the hydraulic input torque from the turbine. Thus, they maintain a constant electrical load on the generator in spite of changing user loads. In this case, the turbine gate opening is kept on the same position in order to use a constant water flow and hence guarantee the same mechanical power at the generator shaft. It permits to use turbine with no flow regulating devices [1, 4, 5].

The electro hydraulic governor takes long time to stabilize the output because of the servomotor which responds slowly [2]. It becomes insufficient in case of large variations on the small grid and the stability of the system could be completely lost. On the other hand, electronic load controller is used to simplify the MHPP control and to limit damages caused by the water hammer effect on the performance of the controller. The stabilizing time is very short even for large variations [6]. However, the controller wastes big quantities of water when little electrical power is required by the users. This is not the concern for MHPP to be installed on flowing water, but for the plant installed on irrigation dam where the primary objective is irrigation, the energy wasted on ballast load is a great loss which can be diverted at high head for irrigation purpose by employing some supervision mechanism. For such a plant we do not need automatic generation control as it increases the capital cost of the plant and make the project economically infeasible.

In Ethiopia, many small irrigation dams were constructed to combat the drought. Only in Tigray regional state, there are forty six fully implemented small irrigation dams [3]. The study on five of these dams shows that they are continuously releasing irrigation water through its bottom outlet from September to August and spills during the rainy season without producing any electric energy. In most cases the time schedule of irrigation does not coincide with the electricity needs for household electrification. Therefore, power can be harnessed from those dams by locating power house at appropriate position [3]. Multipurpose reservoirs to meet the irrigation and energy demand have significant cost factor, which makes micro hydropower plant on irrigation dam economically viable [7]. Moreover, the irrigation takes priority over power generation and thus a method has to be devised to harmonize power generation and irrigation.

In the other hand, designing frequency controllers for MHPP should take into account its parameter variation such as damping constant with operating points [1, 5, 8]. Previous studies have shown that conventional controller could not handle the effect of parameter variation which varies with the operating point. The self tuning mechanism should be employed to handle such a problem.

Hence the thesis aims to combine the advantages of flow control and load control methods to harness the hydropower potential of irrigation dams without affecting much the existing irrigation water supply by applying fuzzy self tuning controller and fuzzy supervisor. First, maintain the frequency constant with a short stabilizing time for any operating conditions, even for large step changes in the power demand by action on the ballast load. Second, save the precious water by managing the opening gate according to the electrical power dissipated on ballast load. When power on ballast load is more than the specified, the supervisor supervises the gate position by controlling the servomotor until power on ballast load is within the specified limit.

1.3 Objectives of the thesis

The primary objective of this thesis is to model standalone MHPP, design and simulate a fuzzy controller for standalone, micro hydropower plants on irrigation dams. The specific objectives are;

- To study different frequency control mechanisms of micro hydropower systems
- To model standalone micro hydropower plant for frequency control
- To optimize the membership function with genetic algorithm for the design of fuzzy logic controller
- To design a fuzzy controller and supervisor to obtain good transient as well as steady state performances for standalone micro hydropower plants
- To simulate the fuzzy control system on the MHPP using MATLAB-SIMULINK

1.4 Methodology

The research methodology of the thesis involves a number of different tasks that are performed to lead towards completion. The first task is to describe the statement of the problem and define the objectives of the research. This is followed by the literature review where all the theoretical information regarding the frequency control of MHPP is gathered. A comparison of previous similar research is also presented. A brief description on the fuzzy control theory and genetic algorithm is then presented. A detail mathematical model of MHPP is presented. For the selected generator and turbine, a PI controller is designed for flow control and load control independently. This is followed by the design of ballast load. Next, rule base is developed for self-tuning PI controller followed by optimization of membership functions with genetic algorithm. The rule tables are constructed with the development of membership functions for supervisory fuzzy logic controller. Using the rule base and membership functions of fuzzy logic controller and fuzzy supervisor are designed. Simulation studies are carried out for different damping constants to show the advantages of the proposed self tuning controller and fuzzy supervisor compared to the conventional frequency controller with load control and flow control. The final stage is the conclusion based on the research findings. A flow chart representing the methodology of the thesis is shown in Figure 1.1.

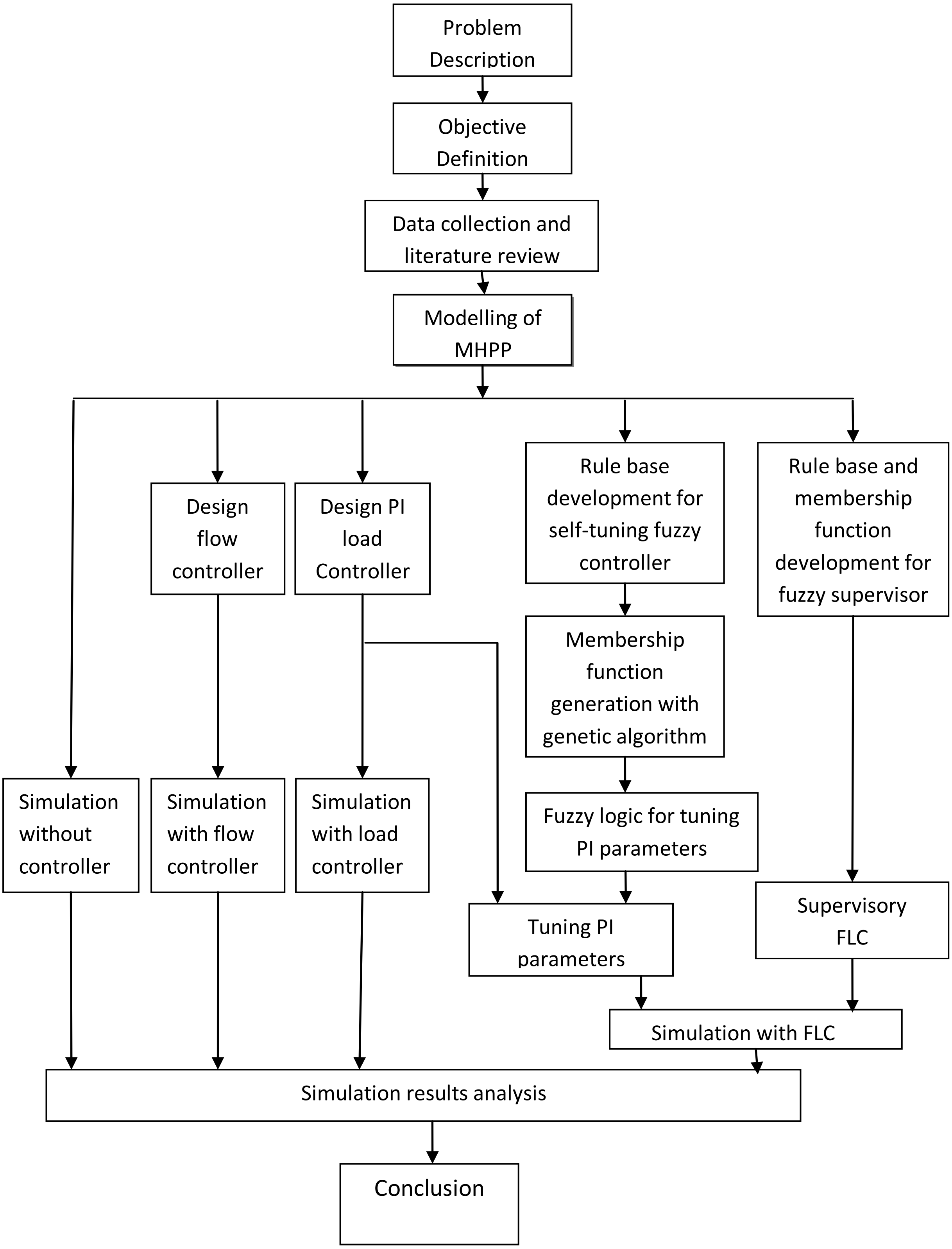

Figure 1.1: Flow chart of the research methodology of the thesis.

1.5 Thesis outline

The thesis is organized into six chapters. Chapter one presents the introduction, statement of the problem, objectives of the study and the methodology leading towards the completion of the thesis.

The second chapter discusses about micro hydropower and its development in Ethiopia, micro earth dam construction in Ethiopia, fuzzy logic controller and genetic algorithm. Finally, related works are discussed in brief.

Chapter three deals with the detailed model of a micro hydropower plant. Modelling of the synchronous generator, turbine and servomotor are described in this chapter. Different ballast load configurations and modelling of the ballast load are also discussed in this chapter.

Chapter four presents the fuzzy logic controller design. The selection of membership functions and the construction of rule tables for both self tuning controller and fuzzy supervisor are also presented in this chapter.

The simulation results obtained using Matlab-Simulink and discussions of the results are presented in chapter five. Chapter six includes conclusions and suggestions for future work.

Chapter Two

LITERATURE REVIEW

This chapter presents review of a micro earth dam construction in Ethiopia, micro hydropower potential as well as development of micro hydropower in Ethiopia. Different mechanisms of controlling the frequency of MHPP are also discussed in this chapter. The basics of fuzzy logic controller, genetic algorithms and related works are also presented in this chapter.

2.1 Small Irrigation Dams and their potential in Ethiopia

Construction of micro-dams for irrigation in Ethiopia started in the late seventies to combat the recurrent drought in the country. Since 1992 the responsibility for the development of small-scale irrigation schemes has been transferred to the regional governments. Only in Tigray and Amhara regional states a total of 48 and 6 small dams were constructed for irrigation. Their storage capacity ranges from 0.1 to 3.1 Mm^3 and 38 similar projects have been studied in Tigray Regional State for consequent implementation [3, 7]. The detail description of these dams in Tigray is found in Table 2.1.

Table 2.1: Fully implemented micro dam irrigation schemes existing in Tigray[3]

S/N	Site Name	Capacity (Mm^3)	Dam Height (m)	Reservoir Area(ha)	Command Area (ha)
1	Mejae	0.3	13.5	6	14
2	Gereb-Mihiz	1.35	17.5	30	80
3	Mai-Gassa	1.3	12.7	42.12	70
4	Mai-Delle	1.77	15	35	90
5	Gum-Sellasa	2.03	11.5	48	110
6	Adi-Kenafiz	0.75	15.5		60
7	Mai-Haidi	0.24	9.2	5.65	9
8	Gra-Shito	0.3	10	6.72	16
9	Fledgling	0.28	14	6.6	20
10	Dur-Anbessa	0.13	18	14	61
11	Gereb-Segen	0.55	14.86	11.7	24
12	Shilant III	0.15	9		7
13	Meskebet	1.34	17.5	52.8	70

14	Mai Gundi	0.8	12.5		46
15	Ruba Feleg	0.9	17.5		80
16	Felaga	0.9	11.92	21.53	75
17	H.W.Cheber		15.5		80
18	Era Quhila				87
19	Haiba	3.1	16	95	100
20	MwL	1.4	19	31	100
21	Adi-Amharay	0.96	14.7	31.5	60
22	Era	1.96	16.7		100
23	Sewhineda	0.36	14.5	7.8	23
24	Teghane	1.08	11	60	
25	Mai-Negus	2.38	24	38	150
26	Laelay-Wukro	0.93	11		50
27	Korir		15	32	100
28	Gereb-Awso	0.11	10.5	2.12	9
29	Adi-Hilo	0.1	11.4	2.5	9
30	Shilanat I	1.61	23		98
31	Gindae	0.73	19.5		53
32	Adi-Shihu	1	10.8	36	40
33	Endazeoy	0.18	12.34	4.05	13
34	Hashenge	2.23	19	38	120
35	Arato	2.59	20	40	120
36	Mai-Serakit	0.49	11		31
37	Adi-Gela	0.51	18		30
38	Embagedo	1.35	22	18.5	100
39	Embagedo	1.78	20	36	80
40	Zamra Diversion				
41	Gereb-Birki	1.01	17.8	17	88
42	Shilanat IV	2.86	24	31.5	171
43	Mai Egam	0.17	13		10
44	Gerb Shegalu	1	20		50
45	Higaetcheber	N.A	15.5		80
46	Lealay Yukro	0.93	11	50	
47	Betiquate	0.61	16	70	
48	Embagedo	1.78	20		80
	Total				3194.5

Small and medium storage irrigation projects are very useful for harnessing small streams and extending irrigation facility to local areas. The projects take less time in planning and execution and give the desired benefits. Therefore, such projects are preferred as effective short term measures to meet the food requirement in limited areas, mobilizing indigenous knowledge and skills at low investment costs. These storage reservoirs have a potential to generate electric power for the local people [7].

Also in China, the national programme for agricultural development formulated during the 1950s, declared that all water resource projects, which can be utilized for generating electricity, must be corporated with small hydropower stations. From 1950s onwards, many small hydropower plants had therefore been constructed in China in conjunction with water resource projects [7].

Thus, harnessing of the available water stored in irrigation dams will enable to generate electricity in the rural areas of Ethiopia and enhance the development of local economy. Studies have shown that the cost of civil work for micro hydropower is about 20%. But this could be reduced to 4-5 % for projects on irrigation dams [7]. This will have a significant importance on poverty reduction in Ethiopia since it protrudes the development activities. Table 2.2 shows the power generation capacity of the selected irrigation dams in Tigray regional state of Ethiopia.

Table 2.2: Power generation capacity of the selected irrigation dams [13]

Sr. No	Site name	Net head (m)	Live storage (Mcm)	Estimated energy Production (KWH)	Energy loss (5%) KWH	Net energy (KWH)	Generation Capacity KW
1	Haiba	10	3.1	60,822	3041	57,781	19
2	Gum-sellase	7	2.03	27,926	1396	26,530	9
3	Mai-negus	16	2.38	69,978	3499	66,479	22
4	Arato	13	2.59	66,032	3302	62,730	21
5	Shilanat IV	16	2.86	84,039	4202	79,837	26

2.2 Micro Hydro Power Development

Micro hydro systems have been in use for many centuries. They had been used to run milling stones to grind cereals priory to their use for electricity generation. In case of micro hydropower plants, the flowing water is used to rotate the shaft of a turbine which in turn drives a synchronous generator [9, 10].

Micro hydro power can be run-of-river types or small reservoir types [7]. In the run-of-river schemes the turbine generates electricity as and when the water is available and provided by the river. When the river dries up and the flow falls below some predetermined amount (the minimum technical flow of the turbine equipping the plant), generation ceases [10].

The amount of power generated by micro hydropower depends largely on the head and the flow rates available. The actual power produced may vary depending on turbine generator efficiency and pressure losses through the intake and penstock. Mathematically power from micro hydropower plant is given by

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

where η, g, Q and H are overall efficiency, gravitational acceleration, mass flow of water and head respectively.

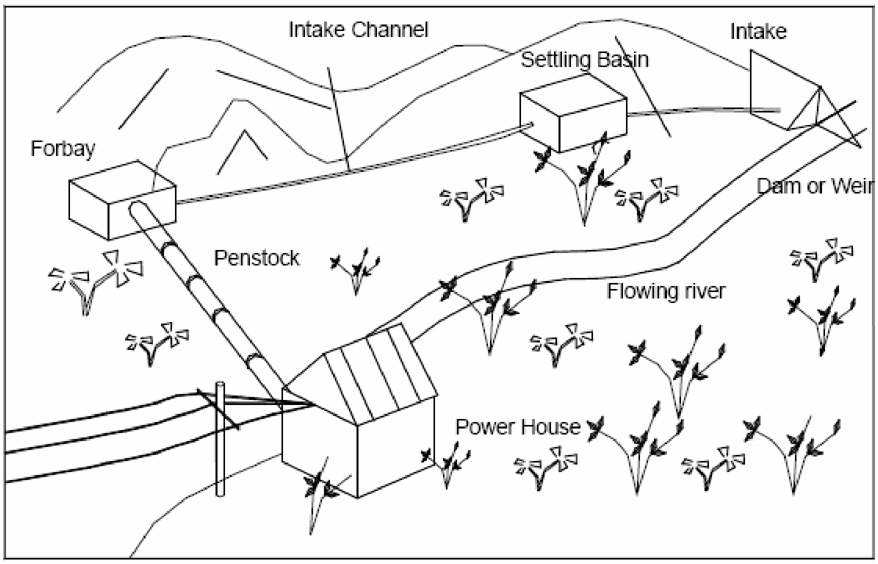

Figure 2.1: Layout of a typical micro hydro power scheme [11]

Development of micro hydropower systems requires the construction of diversion weirs, power canals, fore bays, penstocks and tail races. It also requires selection of the proper turbines and synchronous generators. The components of micro hydropower plant are shown in Figure 2.1. Moreover, the control systems should be designed for micro hydropower plants [9].

2.2.1 Control Systems of Micro Hydropower Plants

In an electric power system, consumers require uninterrupted power at rated frequency and voltage. To maintain these parameters within the prescribed limits, controls are required on the system. Voltage is maintained by the control of excitation of the generator and frequency is maintained by eliminating the mismatch between generation and load demand. This can be achieved in two different ways [4, 9]: automatic generation control and automatic load control.

Automatic generation control systems can be classified as mechanical-hydraulic governors, electro hydraulic governors or mechanical types. Mechanical hydraulic governors are sophisticated devices which are generally used in large hydro power systems. They require heavy maintenance and are expensive to install, making their usage in micro hydro power plants uneconomical. Electro hydraulic governors are complex devices needing precision design and are expensive. Mechanical governors incorporate a massive fly ball arrangement and usually do not provide flow control. They require an elaborate set of complex guide vanes, inlet valves and jet deflectors. Hence conventional governing systems because of their cost and complexity are not ideally suited for installing at the isolated areas [4].

For micro hydropower, two main types of governors are used to control frequency. First, it could remain constant by action on the gate opening position to produce just the necessary power according to the connected load. Second, electronic load controllers (ELC) govern the frequency by adjusting the electrical load connected to the alternator. Therefore, they maintain a constant electrical load on the generator in spite of changing user’s load [1, 4, 5]. In this case, the turbine gate opening is kept in a specific position that guarantees a nominal mechanical power at the generator shaft. It permits to use turbine with no flow regulating devices. The former governor takes long time up to 70 seconds to stabilize the output and it becomes insufficient in case of large load variations where the stability of the system could be completely lost [12]. ELC is used in order to simplify the MHPP control. The stabilizing time is short even for large load variations.

However, ELC waste precious energy that can be used gainfully. Also they do not carry out flow control, implying that the mineral rich water is made to spill away, which could have been diverted at high head for irrigation purposes [1, 12].

In the other hand, there are other effects such as water level in the reservoir that cause fluctuations of the frequency. The level of water on the reservoir might change significantly depending on the season, which would directly affect the MHPP output frequency. Even for a certain level of water, the users might connect machines that require high level of power causing large drop of frequency [12]. Thus, an effective control scheme must be developed to take into account such operating conditions and to insure frequency control.

This thesis is intended to overcome the problem of frequency variation and power loss on the ballast load associated with flow controller and load controller, respectively by incorporating fuzzy controller. Moreover, it will also minimizes the effect of parameter like damping constant variation.

2.3 Fuzzy Logic controller

Fuzzy systems are made of a knowledge base and reasoning mechanism called fuzzy inference engine. A fuzzy inference engine combines fuzzy if-then rules into a mapping from the inputs of the system into its outputs, using fuzzy reasoning methods. Fuzzy systems represents nonlinear mapping accompanied by fuzzy if-then rules from the rule base. Each of these rules describes the local mappings. The rule base can be constructed either from human expert knowledge or designer intuition [13].

The fuzzy controllers are suitable for white-box problems, based on expert knowledge of the system [14]. A fuzzy controller consists of four main components as fuzzification, rule base, inference mechanism and defuzzification.

2.3.1 Fuzzification

In the Fuzzification process, the membership functions defined on the input variables are applied to their actual values if the input variables are crisp. If the sensor is fuzzy, fuzzification refers to finding the intersection of the label's membership function and the distribution for the sensed data. Usually the sensor reading is crisp. The fuzzification sub process turns the measurement into a degree of membership [15]. In the other word fuzzification module converts the crisp values of the control inputs into fuzzy values, so that they are compatible with the fuzzy set representation in the rule base.

According to fuzzy set theory the choice of the shape and width of membership function is subjective, but a few rules of thumb apply [16]

- A term set should be sufficiently wide to allow for noise in the measurement.
- A certain amount of overlap is desirable; otherwise the controller may run into poorly defined states, where it does not return a well defined output.
- Start with triangular sets. All membership functions for a particular input or output should be symmetrical triangles of the same width. The leftmost and the rightmost should be shouldered ramps.
- The overlap should be at least 50%. The widths should initially be chosen so that each value of the universe is a member of at least two sets, except possibly for elements at the extreme ends. If, on the other hand, there is a gap between two sets no rules fire for values in the gap. Consequently the controller function is not defined.

There are at least three advantages to this [16]:

1. The computations are simpler;

2. It is possible to drive the control signal to its extreme values; and

3. It may actually be a more intuitive way to write rules.

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 NB. In fuzzy sets, elements are assigned a grade of member-ship such that the transition from membership to non-membership is gradual rather than abrupt [14]. The output of fuzzification module will be the input to the next module, the fuzzy logic IF-THEN rule base for the control, which requires fuzzy-subset inputs in order to be compatible with the fuzzy logic rules.

2.3.2Rule base

The rule base is essentially the control strategy of the system. It is usually obtained from expert knowledge or heuristics and expressed as a set of IF-THEN rules. The rules are based on the fuzzy inference concept and the antecedents and consequents are associated with linguistic variables [15].

The rules use three variables both in the condition and the conclusion of the rules. To simplify, this section assumes that the control objective is to regulate some process output around a prescribed set point or reference. The presentation is thus limited to single-loop control.

Rule formats: Basically a linguistic controller contains rules in the if-then format, but they can be presented in different formats [16]. In our systems, the rules are presented to the controller in a format similar to the one below;

1. If error is NB and change in error is NB then Δ Ki is PB and Δ Kp is Z

2. If error is NB and change in error is NZ then Δ Ki is PS and Δ KP is NS

3. If error is PM and change in error is PB then Δ Ki is NM and Δ KP is NB

4. If error is Z and change in error is Z then Δ Ki is Z and Δ KP is Z

5. If error is PS and change in error is NS then Δ Ki is NS and Δ KP is PM

6. If error is NM and change in error is NB then Δ Ki is NS and Δ KP is NB

2.3.3 Inference engine

For each rule, the inference engine looks up the membership values in the condition of the rule. It has three operations: - aggregation, activation and accumulation.

Aggregation

The aggregation operation is used when calculating the degree of fulfilment or a firing strength of the condition of a rule. A rule, say rule 1, will generate a fuzzy membership value μ_{e1} coming from the error and a membership value $\mu_{ce\,1}$ coming from the change in error measurement. The aggregation is their combination,

$$\mu_{e1} \text{ and } \mu_{ce\,1}$$

Aggregation is equivalent to fuzzification, when there is only one input to the controller [18]. Aggregation is sometimes also called fulfilment of the rule or firing strength.

Activation

The activation of a rule is the deduction of the conclusion, possibly reduced by its firing strength. Min or product (*) is used as the activation operator. The multiplication scales the membership curves, thus preserving the initial shape, rather than clipping them as the min operation does. Both methods work well in general, although the multiplication results in a slightly smoother control signal [14, 16]. In Figure 2.2, only rule six is fired while in Figure 2.3 rule three and seven are fired.

Accumulation

All activated conclusions are accumulated, using either sum or max operations. On right side figure in Figure 2.3, the bottom shows the results with accumulation, where the blue one is with sum operation and red one is with max operation.

2.3.4 Defuzzification

The defuzzification uses methods such as centre of gravity, maximum and weighted mean to convert from the inference mechanism into the crisp values applied to the actual system. The resulting fuzzy set (Figure 2.2 and Figure 2.3, bottom right) is converted to a number that can be sent to the process as a control signal.

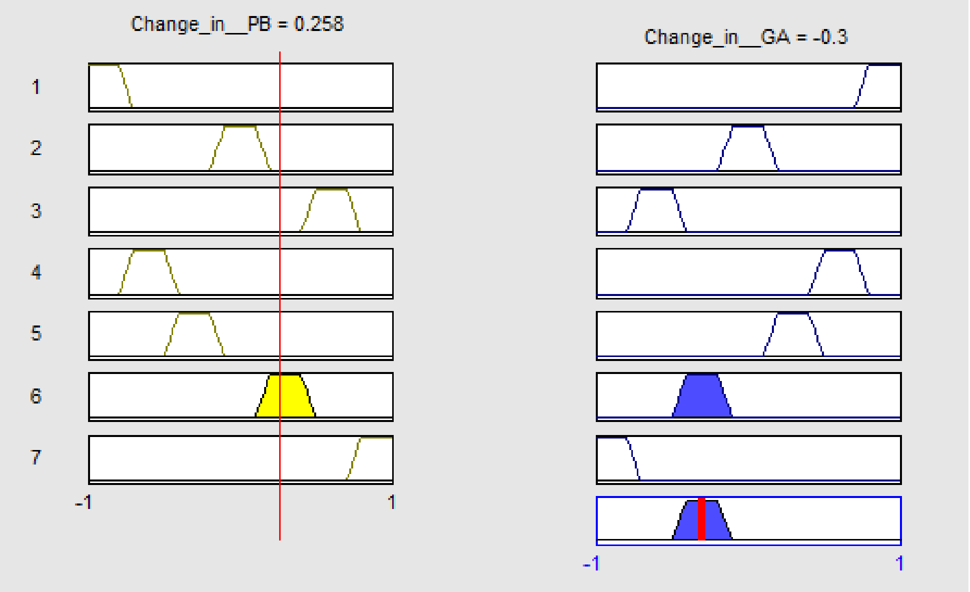

Figure 2.2: Graphical construction of the control signal when single rule is fired

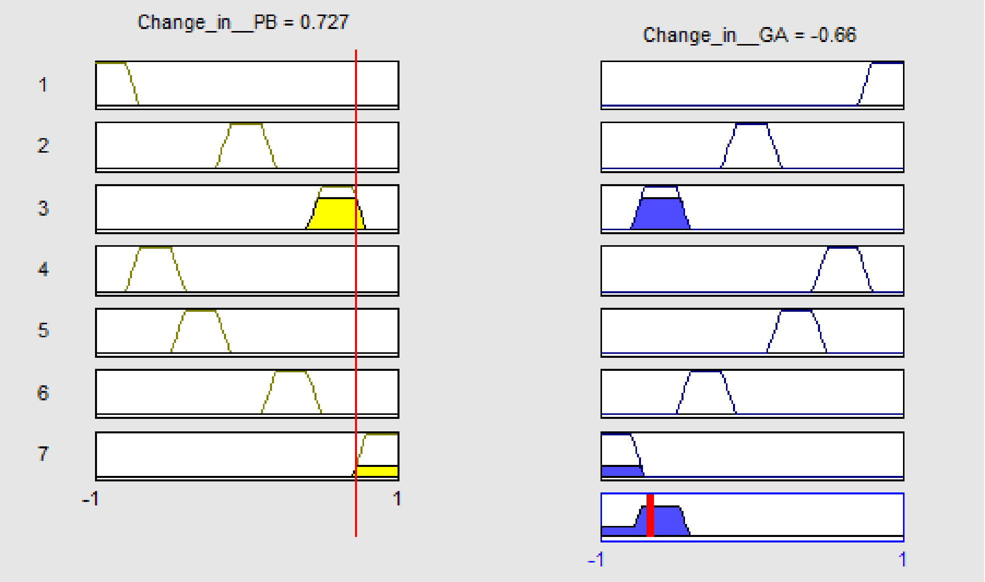

Figure 2.3: Graphical construction of the control signal when two rules are fired

2.4 Self Tuning PI controller

A PI controller is the most commonly used feedback controller. The PI controller calculates an error value as the difference between a measured process variable and a desired set point. The controller attempts to minimize the error by adjusting the process control inputs.

PI controllers are still the most popular controller which is widely used to improve the performance of the actuator in industry, because it's easy to operate and very robust [17]. However, performance specifications of the systems such as rise time overshoot, settling time and error steady state can be improved by tuning value of parameters K_p and K_i of the PI controller, because each component has its own special purposes. Latest PI controller's structure is quite different from the original one and the implementation is based on a digital design. These digital PI include many algorithms to improve their performance, such as anti wind-up, auto-tuning, adaptive, fuzzy fine-tuning and neural networks. However, the basic operations still remain the same [18].

A proportional–integral controller (PI controller) is a generic control loop feedback mechanism (controller) widely used in power system control. The parameters of the conventional PI controllers are not suitable for isolated MHPP because of the parameter variation of MHPP. The automatic selection of the system parameters is significantly necessary for the plant with unpredictable parameter variations. As known, the fuzzy system is a formal methodology for implementing a human's heuristic knowledge obtained from experience about any system [12]. Therefore, self tuning fuzzy PI controller can be designed to reduce the parameter variations and achieve high performance of the control systems.

Fuzzy logic-based self tuning scheme for the conventional PI controllers uses fuzzy computing along with conventional control methods for enhancement of the control performance. The Fuzzy tuned PI controller is expected to reduce the rise time and the settling time and also reduce the overshoot which generally occurs in a conventional PI controller. The structure is easy to understand and is capable of accommodating without much change in the actual system. It works on the same basic principle of a conventional PI controller, but unlike the fixed gain of PI controller, in this controller, the values of the proportional and the integral gains are modified continuously based upon the operating condition. We know that as per the control structure of a conventional PI controller in continuous time domain, the control action is u(t)= K_pe(t) + K_i∫e(t)dt. In the proportional term, control action is proportional to the "product of proportional gain K_p and error value" and in the integral term, it is proportional to "the product of the integral gain K_i and integral of the error". That means the proportional gain provides the control action effectively when the error is more (transient response) and the integral gain delivers efficiently when the system is operating near the set point value [13]. The Figure 2.4 illustrates the basic control structure of the proposed self tuning controller.

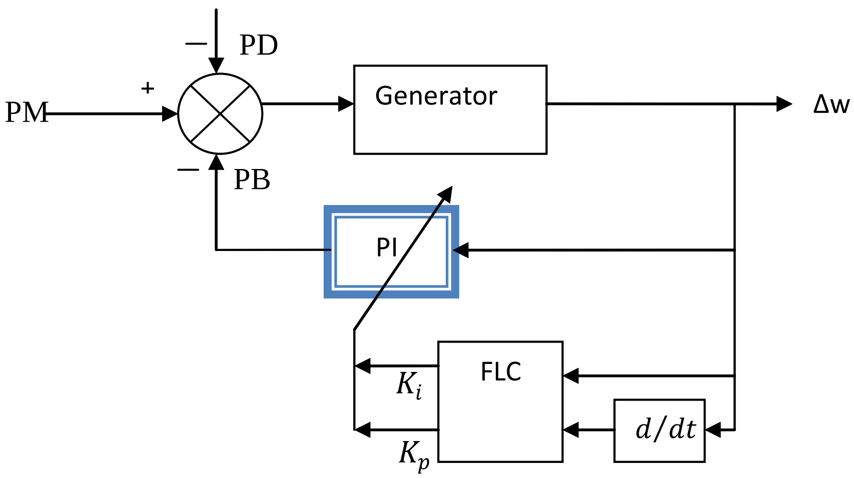

Figure 2.4: The basic structure of the Self tuning controller

Hence the control method follows that when the frequency error is large, the proportional gain must be kept large and when the operating point is near the set point; the integral gain comes to action and reaches the maximum after reaching the steady state value. Fuzzy logic rules are written as per this control strategy such that the proportional gain (K_p) must be maximum when the error is large and should be started varying to the minimum when the system is near the set point. The integral gain (K_i) is varied such that its value will be minimum when the system operates away from the set point and attains maximum value when it operates near to the set point.

2.5 Basics of Genetic Algorithms

Genetic algorithms are useful algorithms for optimising solutions to problems; especially those that are analytically intractable. They are inspired, as the name suggests, by the biological concepts of genetics and evolution [14].

A chromosome is an encoded string of possible values for the parameters to be optimised. These chromosomes can be made up of real-valued or binary strings. The first step in genetic algorithm is initialization of potential solutions called population. Each member of this set is referred to as an individual and they are evaluated by decoding the parameter values from the chromosomes and applying them to the problem to see how well they perform the task at hand (the objective that is to be optimised) [25, 27]. The score that an individual achieves at performing the required task is called its fitness.

After the fitness of each individual has been calculated, a procedure known as selection is performed. Individuals are selected to contribute towards creating the next generation, the probability of selection being related to the individual's fitness [28].

Once selection has occurred, crossover takes place between pairs of selected individuals. The strings of two individuals are mixed. In this way, new individuals are created that contain characteristics that come from different individuals relatively successful individuals [28]. Figure 2.5 shows how crossover is performed between two individuals.

Before crossover	**After crossover**
Parent1: 1010111**000**	Child 1: 1010111**010**
Parent2: 0111011**010**	Child 2: 0111011**000**

Figure 2.5: Crossover in genetic algorithm

A third operation that occurs is mutation, the random changing of bits in the chromosome. It is generally performed with a relatively low probability. Mutation ensures that the probability of searching a given part of the solution space is never zero [28]. Illustration of a simple mutation operation is shown in Figure 2.6.

Before crossover	**After crossover**
Parent1: 1010111000	Child 1: 1010101000
Parent2: 0111011010	Child 2: 0011011010

Figure 2.6: Mutation in genetic algorithm

A simple genetic algorithm procedure is presented as follows;

Produce an initial population of individuals

Evaluate the fitness of all individuals

While termination condition not met **do**

Select fitter individuals for reproduction

Recombine between individuals

Mutate individuals

Evaluate the fitness of the modified individuals

Generate a new population

End while

Genetic algorithms can be used to compute membership functions [14]. Given some functional mapping for a system, some membership functions and their shapes are assumed for the various fuzzy variables defined for a problem. These membership functions are then coded as bit strings that are then concatenated. An evaluation (fitness) function is used to evaluate the fitness of each set of membership functions (parameters that define the functional mapping).

2.6 Previous Works on Frequency Control of Micro Hydropower Plant

For the last few decades studies have been made on MHPP's and their control systems. Different papers [1][8][9][12][19] have considered different aspects in improving the controller structure.

In [9] a dual mode frequency controller for stand alone, micro and mini hydropower plant is developed. Load control mode is developed for micro hydropower and flow control mode is designed for mini hydropower plants. 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. The problem with load control mode is that during minimum demand of power a lot of energy is wasted on ballast load. The cited reference [9] didn't consider micro hydropower that can be installed on irrigation dams where the irrigation has a high priority over power. In flow control mode, the controller controls the position of a spear valve using a stepper motor so that the flow of water into the turbine, and consequently the frequency is controlled [9].

The papers [1, 12] proposed fuzzy controller for micro hydropower that 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 also controls the servomotor in order to close or open the gate opening.

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

A significant number of researchers have applied genetic algorithms to optimise fuzzy logic controllers. Many different approaches to this task have been taken. Genetic algorithm is applied to optimise a rule-base of a fuzzy logic controller for which the membership functions have already been created [25]. Genetic algorithm is also used to determine the number of membership functions, the number of fuzzy rules and the rule-base [26]. In both of these cases, the genetic algorithm is implemented using real-valued encodings.

In this thesis, fuzzy logic controller is proposed to tune the parameters of PI controller and supervise the energy dissipated on the ballast loads for micro hydropower plant. Genetic algorithm is used to optimize the membership functions of fuzzy logic controller.

Chapter Three

MICRO HYDRO POWER SYSTEM MODELLING

The first step in the analysis and design of the control system of a micro hydropower plants is modelling of the different components. The transfer function model of the system is used in designing control systems. After proper assumptions and approximations are made to linearise the differential equations describing the components of MHPP, transfer functions representing each component are obtained. Thus, transfer function model of a micro hydropower plant is developed for load control and flow control. The block diagram in Figure 3.1 shows different component of a micro hydropower plants.

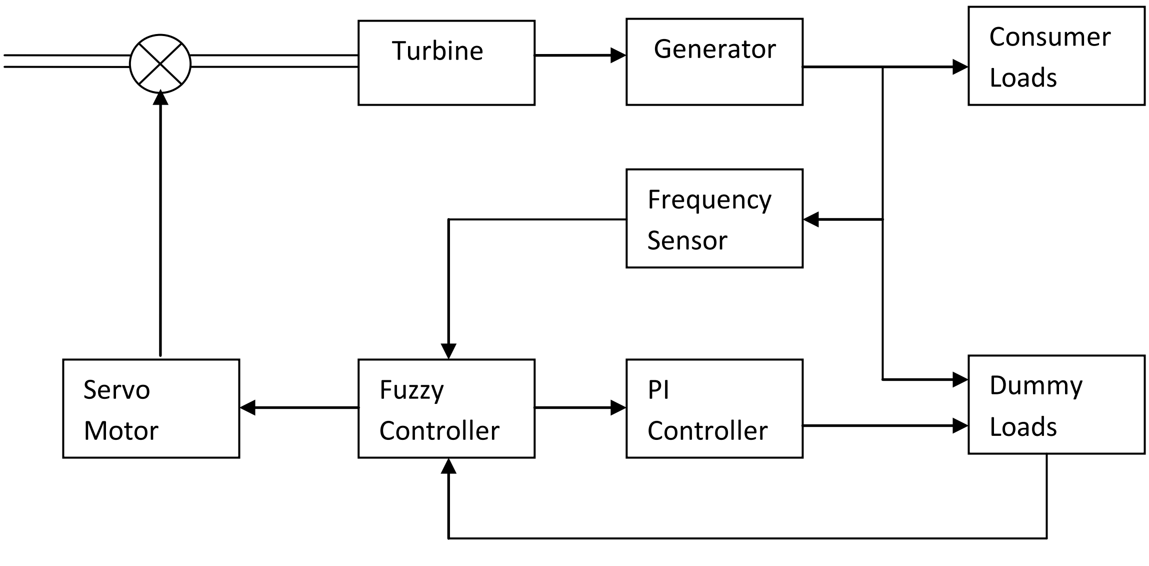

Figure 3.1: Components of a Micro Hydropower Plant

3.1 Servo motor modelling

An electric servo motor is a precision electric motor whose function is to cause motion in the form of rotation or linear motion in proportion to a supplied electrical command signal. Here the controlled variable is the turbine power. The electric servo motors are preferable for the flow control of micro hydro power systems as they have a simple design, require less maintenance and are less expensive than conventional governors [4].

In the proposed control system an electric servomotor will be used as an actuator which acts on the gate opening to control the flow of the water. The servomotor actuates the gate valve to open more when the dump load becomes less than the minimum required damp load and the change in frequency is negative. It closes the gate when the ballast load is higher than the maximum load we want keep on ballast load at steady state and the change in frequency is positive.

The approximate transfer function for the servo motor with driver is considered for the analysis and is given by [4]

$$G(s) = \frac{1}{(1 + sT_1)} * \frac{1}{(1 + sT_2)} \quad (3.1)$$

$where, T_1 =$ mechanical time constant and $T_1 =$ electrical time constant of motor

3.2 Turbine modelling

A turbine converts the hydraulic power in pressurised water into mechanical power in the form of a rotating shaft. There are many varieties of turbine, each with its own benefits and drawbacks. However, the Pelton and crossflow turbines are the most widely used for micro-hydro power in the developing world [6]. Crossflow turbine is a reaction turbine unlike impulse turbines, which are the standard for larger scale hydro-power, they don't require expensive pressurised casings and intricately machined blade profiles.

For large hydropower plants, manufacturers offer complete sets of turbines and generators, in which the runners are directly coupled to the generator and therefore designed to run at the speed of the generator. It is generally more important to use less costly, standardised runners rather than custom-designed runners for MHPP systems. Consequently, the various components such as turbine, coupling, and generator are considered separately [20].

Crucial design criteria for the turbine are:

- available net head
- flow speed
- required speed for coupling to a generator

A turbine is characterised by its power-speed- and efficiency-speed- characteristics. This means that for a particular head, a turbine runs most efficiently at a particular speed and therefore requires a particular flow. Under the given conditions in Ethiopia which mostly provide low to high heads, cross flow, pelton and to some extent francis turbines are most suitable. Compared to reaction turbines like the francis, impulse turbines like cross flow and pelton offer the following advantages which make them more convenient for application under Ethiopia conditions [20]:

- They are tolerant of sand and other particles in the water
- They allow better access to working parts
- They are easier to fabricate and maintain; crossflow turbines up to about 250kW can be fabricated locally
- They are usually cheaper than reaction turbines because pressure casing and carefully engineered clearances are not needed
- They are less subject to cavitation, although at high heads, high velocities can cause cavitation in nozzles or on the blades or buckets.
- They offer flatter efficiency curves, especially if additional flow control devices are built in like for example variable cross section nozzles, spear valves, guide vanes, and devices to vary the number of jets or partition the flow.

Compared to pelton turbines, which generally require casting facilities, crossflow turbines merely require simple fabrication techniques. In addition, the crossflow design is suitable for a wide range of heads and power ratings, because the shape of the turbine blades allows the runner length to be increased to any value without, in theory, changing the hydraulic characteristics.

To find out, which type of turbine is appropriate under the given site conditions, meaning available head and runoff speed, the turbine selection diagram shown in Figure 3.2 can be used.

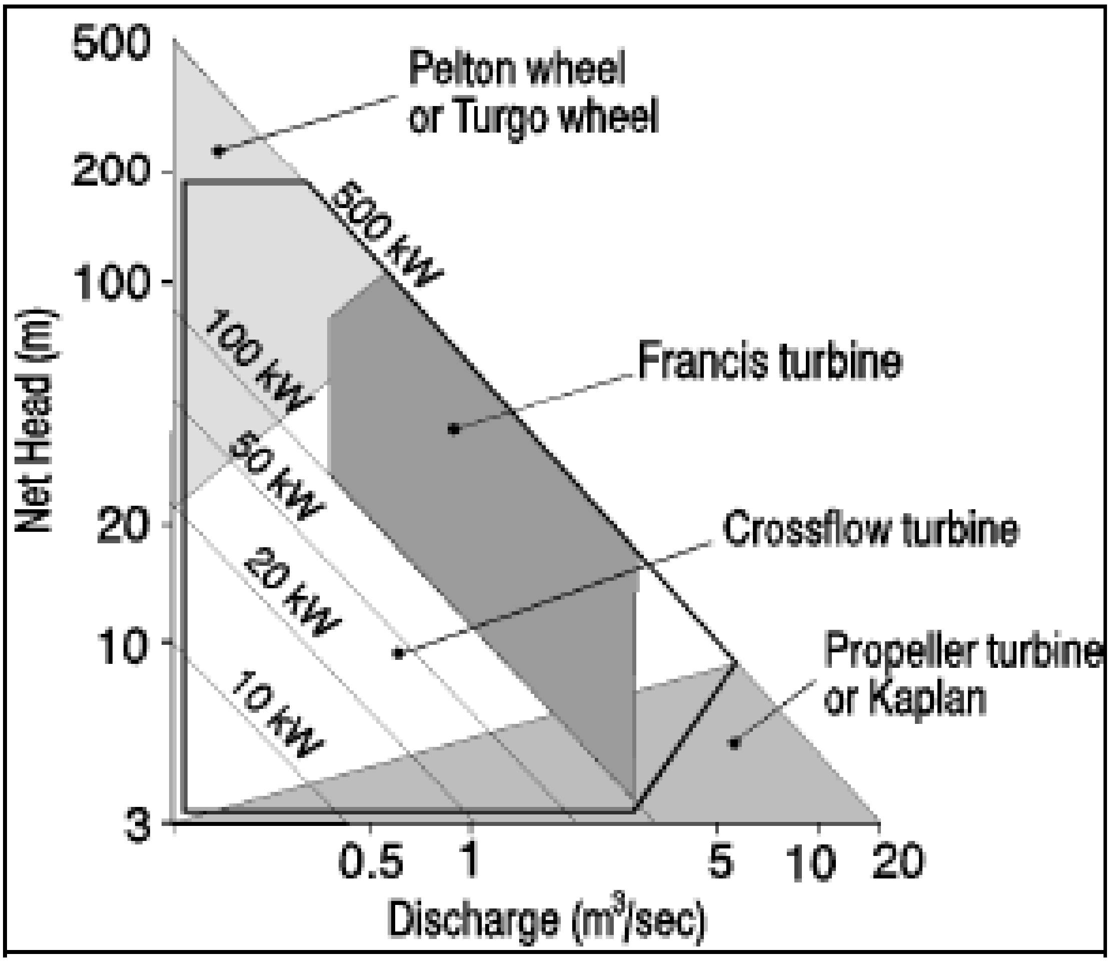

Figure 3.2: Turbine selection diagram [6]

For analysis purpose we choose shilanat 4 irrigation dam with head of 16m and flow speed of $0.3m^3/sec$, crossflow turbine is the most convenient one.

The local availability of cross flow turbines allows the users to insist on a guarantee and ensures reasonable access to repair and maintenance specialists [6]. These are crucial arguments in favour of crossflow turbines. Considering these arguments, the cross flow turbine is the most suitable for MHHP in Ethiopia where the rural community need low cost of installation and maintenance [6].

Once an appropriate turbine is selected, its speed should be reconciled with the speed of the generator, or with any other machine that is mechanically driven by the turbine. If the turbine and generator speeds are different, gearing, or a belt or chain drive between turbine and generator is required. The generator speed [rpm] is calculated according to:

$$rev = \frac{120 * f}{po} \tag{3.2}$$

where

$$rev = revolutions\ per\ minute[rpm]$$
$$f = frequency[Hz]$$
$$po = number\ of\ poles$$

For a commonly used alternator, for 50 Hz and with 4 poles, a speed of 1,500 rpm is calculated.

There are two types of turbine models

1. Linear turbine model
2. Nonlinear turbine model

3.2.1 Linear Turbine modelling

The linear modelling of the hydraulic turbine and water column is usually based on the following assumption [21].

1. The hydraulic resistance is negligible
2. The penstock pipe is inelastic and water is in compressible.
3. The velocity of water varies directly with the gate opening and with the square root of the net head
4. The turbine output power is proportion to the product of head and volume flow.

In micro hydropower systems, hydraulic turbines are used to derive synchronous generators. These hydraulic turbines convert the energy of flowing water into mechanical energy which in turn is converted into electrical energy. The hydraulic turbine is already modelled in different literatures. The transfer function between change in gate position of the wicket gate and the change in mechanical output power of the turbine is given by [21]

$$\frac{\Delta P_m}{\Delta GA} = \frac{1 - T_w s}{1 + 0.5T_w s} \tag{3.3}$$

where $T_w = {}^{LU_o}/_{(gh_o)}$

$\Delta P_m = change\ in\ mechanical\ power$
$\Delta GA = change\ in\ gate\ position$

The velocity of water in the penstock is given by [21]

$$U = K_u G\sqrt{h} \tag{3.4}$$

where

U= water velocity
G=gate position
h=hydraulic head at the gate
$K_u = a\ constant\ of\ proportionality$

The water starting time (T_w) is the time required for a head H_o to accelerate the water in the penstock from standstill to the velocity U_o. It varies with load and at full load it lies between 0.5 and 4.0 seconds [9]. For load controlled micro hydropower systems, the water starting time remains constant. L is the length of the penstock and g is acceleration due to gravity.

Thus, the block diagram of the turbine is represented as

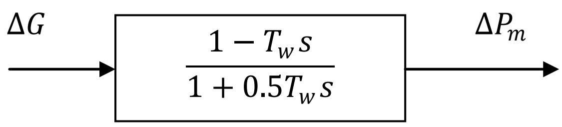

Figure 3.3: Linear turbine model

3.2.2 Non Linear Turbine modelling

Nonlinear turbine model is developed assuming inelastic water column. The model is constructed assuming an incompressible fluid and a rigid conduit. The transfer function between change in gate position of the wicket gate and the change in mechanical output power of the turbine is given by [8, 12].

$$\frac{\Delta P_m}{\Delta G} = \frac{1 - G_o T_w s}{1 + 0.5 G_o T_w s} A_t \quad (3.5)$$

where $A_t = Turbine\ gain$

$$A_t = \frac{1}{\overline{G_{fl}} - \overline{G_{nl}}} * \frac{Turbine\ rating}{Generator\ rating}$$

$where\ \ G_o = per\ unit\ initial\ gate\ position$

$\overline{G_{fl}} = per\ unit\ full\ load\ gate\ position$

$\overline{G_{nl}} = per\ unit\ no\ load\ gate\ position$

Figure 3.4: Nonlinear turbine model

3.3 Generator modelling

A generator is an electrical component which converts mechanical energy of the prime mover to electrical energy which has different rating. The rating of a generator is based on some characteristics concerning the electricity supply process. The consumer loads in an electrical system can be subdivided into resistive and inductive loads. Resistive appliances are heaters, ordinary light bulbs, meaning incandescent filament lights etc., whereas partially inductive loads are induction motors, appliances incorporating motors, transformers like cassette recorders and TVs, fluorescent lights, etc.. The second group of loads cause current to lag behind voltage because of circuit inductance. This phenomenon is expressed by the power factor, characterising the relation of real power and apparent power.

Synchronous Generators (Alternators) use permanent magnet or electro-magnets to create the magnetic field required to generate a current in the output coil. Therefore, excitation of synchronous generators is not grid dependent, making them ideal for standalone power generation systems. In the case of off-grid use, a voltage regulator (usually built in) maintains a constant voltage irrespective of consumer load variations [6]. The frequency generated by synchronous generators is directly proportional to the shaft speed, meaning that synchronous generators are easier to regulate.

The model of the synchronous generator is derived from the swing equation. The swing equation states that the net torque, which causes acceleration or deceleration of the rotor of the synchronous generator, is the difference between the electromagnetic torque and mechanical torque applied to the generator [21].

When there is unbalance between the torques acting on the rotor, the net torque causing acceleration or deceleration is given by [21]

$$T_a = T_m - T_e \tag{3.6}$$

where

T_a = accelerating torque in N.m

T_m = mechanical torque in N.m

T_e = electromagnetic torque in N.m

The combined inertia of the generator and prime mover is accelerated by the unbalance in the applied torques. Hence the equation of motion is [21]

$$J\frac{dw_m}{dt} = T_a = T_m - T_e \tag{3.7}$$

where

J= combined moment of inertia of generator and turbine, Kg.m^2

$w_m = angular\ velocity\ of\ the\ rotor, mech. {}^{rad}/_{s}$

$t = time, s$

The per unit inertia constant H, defined as the kinetic energy in watt-seconds at rated speed divided by the VA base. Using the w_{om} to denote rated angular velocity of rotor in mechanical radians per second, the inertia constant is

$$H = \frac{1}{2}\frac{J{w_{om}}^2}{VA_{base}} \tag{3.8}$$

The moment of inertia J in terms of H is

$$J = \frac{2H}{{w_{om}}^2}VA_{base} \tag{3.9}$$

Substituting Equation (3.9) in Equation (3.7) we get

$$\frac{2H}{{w_{om}}^2}VA_{base}\,\frac{dw_m}{dt} = T_m - T_e \tag{3.10}$$

Rearranging yields

$$2H\frac{d}{dt}\left(\frac{w_m}{w_{om}}\right) = \frac{T_m - T_e}{VA_{base}/w_{om}}$$

$$2H\frac{d}{dt}\left(\frac{w_m}{w_{om}}\right) = \frac{T_m w_{om} - T_e w_{om}}{VA_{base}}$$

$$2H\frac{d}{dt}\left(\frac{w_m}{w_{om}}\right) = \frac{P_m - P_e}{VA_{base}} \tag{3.11}$$

where $P_m = T_m w_{om}$ is the mechanical input power to the synchronous generator and $P_e = T_e w_{om}$ is the electrical power generated by the generator.

In per unit the above equation can be rewritten as

$$2H\frac{d}{dt}\overline{w_m} = \overline{P_m} - \overline{P_e} \tag{3.12}$$

$$\overline{w_r} = \frac{w_m}{w_{om}} = \frac{w_r/p_f}{w_o/p_f} = \overline{w_m}$$

where $w_r = angular\ velocity\ of\ the\ rotor, electrical\ .{}^{rad}/_{s}$

$w_{om} = rated\ angular\ velocity\ of\ the\ rotor, electrical\ .{}^{rad}/_{s}$

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

$$\delta = w_r t - w_o t + \delta_o \tag{3.13}$$

Taking the time derivative,

$$\frac{d\delta}{dt} = w_r - w_o = \Delta w_r$$

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

$$= w_o \frac{d\overline{w_r}}{dt} = w_o \frac{d\Delta\overline{w_r}}{dt}$$

From which

$$\frac{d\overline{w_r}}{dt} = \frac{d\Delta\overline{w_r}}{dt} = \frac{d\overline{w_m}}{dt} \tag{3.14}$$

Substituting Equation (3.14) in Equation (3.12),

$$2H\frac{d}{dt}\Delta\overline{w_r} = \overline{\Delta P_m} - \Delta\overline{P_e} \tag{3.15}$$

With the Laplace transformation,

$$2Hs\Delta\overline{w_r} = \overline{\Delta P_m}(s) - \overline{\Delta P_e}(s) \tag{3.16}$$

$$\Delta\overline{w_r} = \frac{\overline{\Delta P_m}(s) - \overline{\Delta P_e}(s)}{2Hs} \tag{3.17}$$

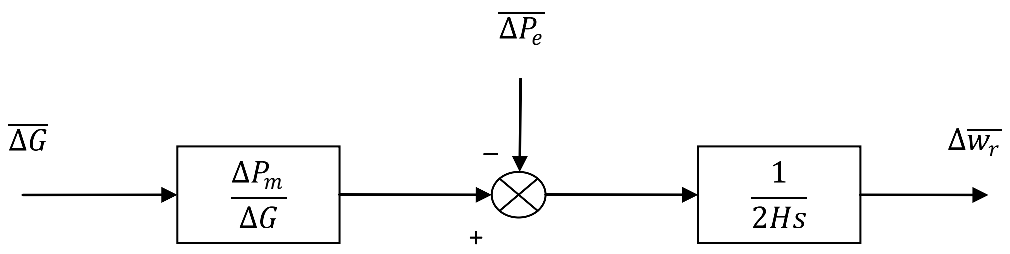

Figure 3.5: Generator model coupled with turbine

3.4 Load modelling

The electrical load connected to the synchronous generator is of two types: consumer load and ballast load. The change in the total electrical load is due to changes in both the consumer and ballast load.

$$\Delta\overline{p_e} = \overline{\Delta P_B} + \Delta\overline{P_D} \qquad (3.18)$$

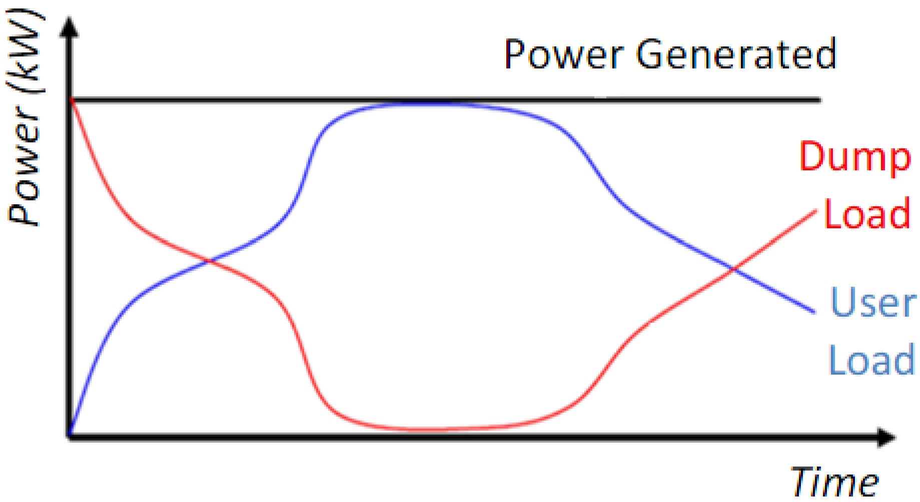

Figure 3.6: Power Generated = User load + Ballast load [6]

3.4.1 Ballast load modelling

The ballast load is a low priority, resistive load that accepts the surplus energy generated. Its primary purpose is to counteract the change in the consumer load. When certain amount of load is removed from the consumer load, the same amount of load must be accepted in the ballast load and vice versa.

The capacity of the ballast load is determined by taking into consideration the ideal condition that the consumer load is zero at some instant. When the entire consumer load is suddenly out, all the output of the synchronous generator should be accepted by the ballast load. At this condition

$$P_{e-\text{rated}} = P_B$$

$$where\ P_{e-rated} = \text{rated } generator \text{ output } power$$

The value of total ballast resistor is given by

$$R_B = \frac{{V_{ll}}^2}{P_{e-rated}} \tag{3.19}$$

3.4.2 Load response to frequency deviation

In general power system loads are a composite of a variety of electrical devices. For resistive loads, such as lighting and heating loads, the electrical power is independent of frequency. In the case of motor loads, such as fans and pumps, the electrical power changes with frequency due to changes in motor speed. How a load is sensitive to frequency depends on the composite of the speed-load characteristics of all the driven devices [21]. The overall frequency-dependent characteristics of a composite load can be expressed as

$$\Delta\overline{p_D} = \overline{\Delta P_l} + D\Delta\overline{w_r} \tag{3.20}$$

where

ΔP_l is the non frequency sensitive consumer load changes

$D\Delta\overline{w_r}$ is frequency sensitive load changes.

The load damping constant is expressed as percent change in load for one percent change in frequency. Typical values of D are 1 to 2 percent. A value of D=2 means that change in divided by percent change in frequency [21].

The system block diagram including the effect of the load damping is shown below

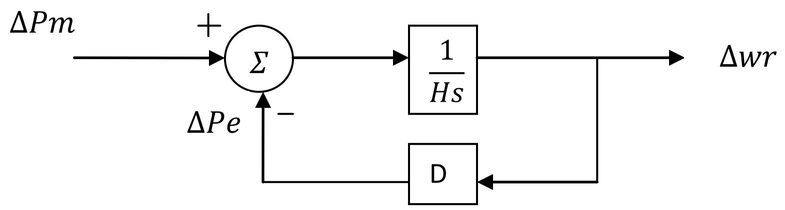

Figure 3.7: Generator with load damping effect

Ballast load is a pure resistive load; hence the effect of damping is neglected for ballast load. The change in electrical load can be rewritten as

$$\Delta\overline{p_e} = \overline{\Delta P_B} + \overline{\Delta P_l} + D\Delta\overline{w_r} \tag{3.21}$$

Substituting Equation (3.21) in Equation (3.16),

$$2Hs\Delta\overline{w_r}(s) = \overline{\Delta P_m}(s) - \overline{\Delta P_B}(s) - \overline{\Delta P_l}(s) - D\Delta\overline{w_r}(s) \tag{3.22}$$

Equation (3.22) can be simplified as

$$\Delta\overline{w_r}(s) = \frac{1}{2Hs + D}\left(\overline{\Delta P_m}(s) - \overline{\Delta P_B}(s) - \overline{\Delta P_l}(s)\right) \tag{3.23}$$

Equation (3.23) is represented in block diagram as

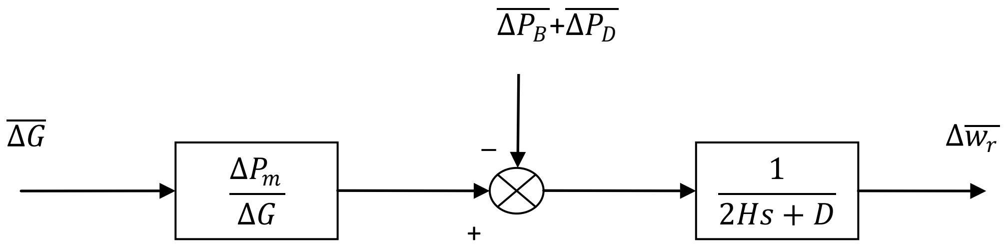

Figure 3.8: Turbine, load and generator block diagram

3.5 Electronic load controller modelling

The ELC is a turbine governor, which indirectly keeps the turbine speed constant, by means of an additional "dump" load, which absorbs any surplus available energy. The ELC ensures that the generator runs at constant frequency, and thus speeds, by keeping constant the total resistive load. The most common type is a water-cooled dump load, which can in addition be a source of water heating. The ELC should provide a sufficient load on the generator such that when the user load is off, and the turbine is providing full power to meet the maximum expected demand, all the power can be safely absorbed by the dump load without the turbine and generator increasing speed. The ELC senses frequency variations to activate the dump load. Figure 3.7 shows the overall action of electronic load controller.

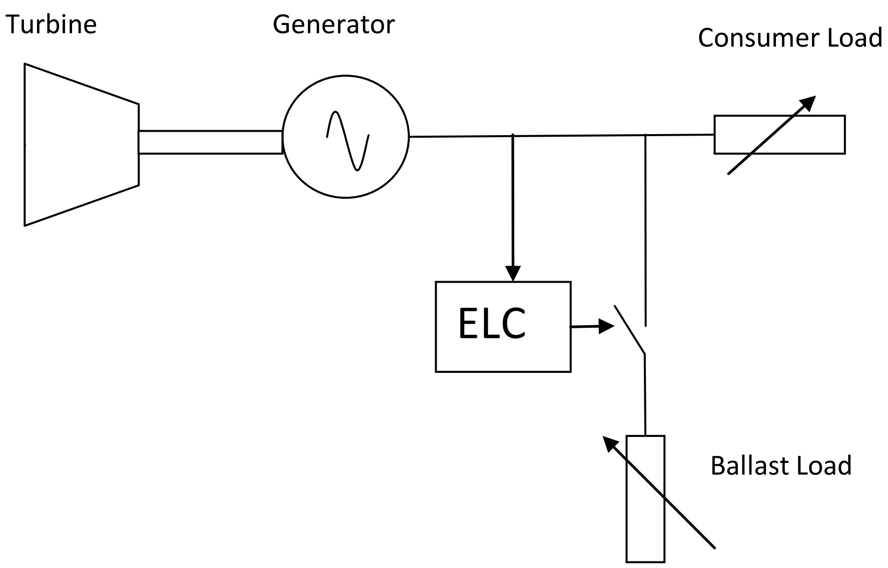

Figure 3.9: ELC load governing principle

The load controller is modelled in the same way the governors of medium and large scale hydropower systems are modelled [9]. Therefore, understanding the principle of operation of mechanical or electronic hydraulic governors is crucial.

The governing system for large power plants in block diagram is shown below [21]

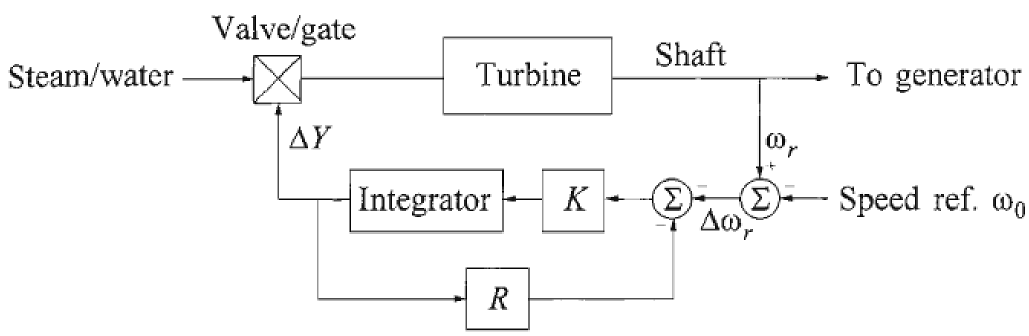

Figure 3.10: Block diagram of speed governor for large power plants [21]

The increase in pe causes the frequency to decay at a rate determined by the inertia of rotor. As the speed drops, the turbine mechanical power begins to increase. This in turn causes a reduction in the rate of decrease of speed and then an increase in speed when the turbine power is in excess of the load power. The speed will ultimately return to its reference value and the steady state turbine power increases by an amount equal to additional load.

The value of regulation(R) determines the steady-state speed versus load characteristics of the generating unit. The ratio of speed variation or frequency variation to change in valve/gate position or power ΔP is equal to R. The parameter R is referred to as speed regulation [21].

The change in position of the gate opening in other word is the change in hydraulic input power. We can adapt the change in hydraulic power as the change in ballast load for micro hydro power plants.

For large hydro power plants the change in hydraulic power required when there is change in electrical load is given by

$$\Delta P = -\frac{K_i}{s}\Delta w(s) - K_p \Delta w(s) \tag{3.24}$$

For micro hydro power plants the change in ballast load required for change in demand power is given by

$$\Delta P_B = -\frac{K_i}{s}\Delta w(s) - K_p \Delta w(s) \tag{3.25}$$

The compensator given above has the form of simple PI controller. Hence the frequency controller can be modelled as PI controller.

3.5.1 Types of electronic load controller

The two most commonly employed techniques used for load governing are the phase delay load configuration and binary load configuration

In phase delay load configuration, the ballast load comprises a permanently connected single resistive load circuit of magnitude equal to (or slightly greater than) the full load rated output of the generator. As a result of the detection of a change in the consumer load, the firing angle of a power electronic switching device, such as a triac, is adjusted, thus altering the average voltage applied to, and hence the power dissipated by, the ballast load [9].

As with all power electronic switching of this nature, this technique introduces harmonics onto the electrical system. It is worthwhile to note that these harmonics are continuously present to some extent as long as the ballast load is energised.

The presence of these harmonics will cause overheating of electrical equipment connected to the system and of the generator; this is usually counteracted by derating of the generating plant [22].

In binary load action, the ballast load is made up from a switched combination of a binary arrangement of separate resistive loads. The load proportion carried by each step is in the ratio 1:2:4 and when switched in sequence, the ballast load exhibits a stepped characteristic, as shown in Figure. The summation of all of the ballast load steps is equal to (or slightly greater than) the rated output power of the generator.

In response to a change in the consumer load, a switching selection is made to connect the appropriate combination of load steps. This switching operation occurs during the transient period only, thereafter full system voltage is applied to the new fraction of the ballast load and hence harmonics are not produced at all by this method in the steady-state. In addition, it is usually the practice to adopt solid state switching relays which include a zero-voltage switching circuit that reduces the harmonic distortion associated with the transient switching period [22].

3.6 Fuzzy Controller

The fuzzy controller consists of four main components as fuzzification, rule base, inference mechanism and defuzzification. The overview of the fuzzy controller operation step is shown in Figure 3.12.

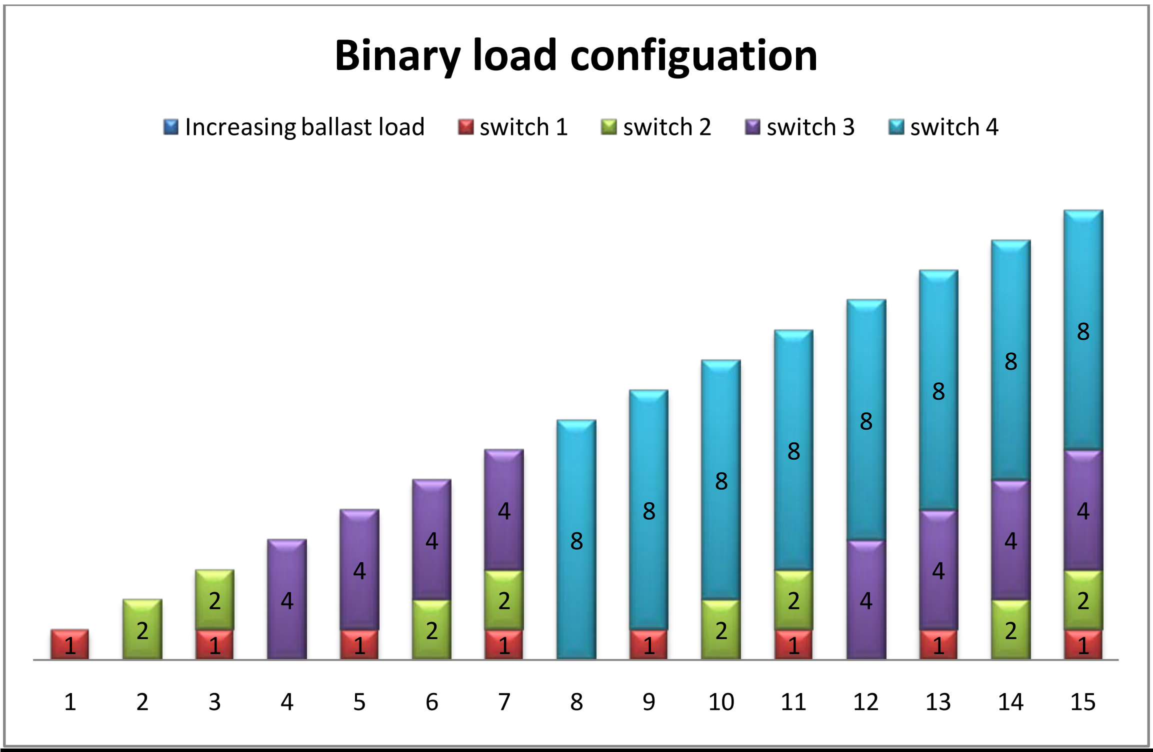

Figure 3.11: Binary load configuration

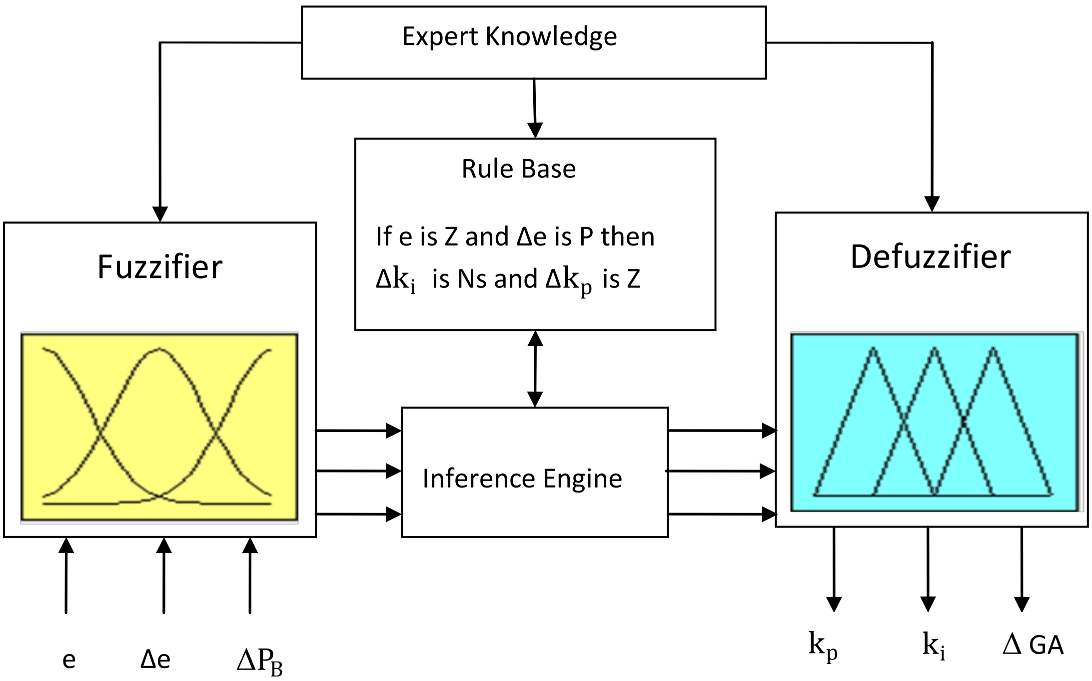

Figure 3.12: Over view of fuzzy controller step

Chapter Four

DESIGN OF FUZZY LOGIC CONTROLLER

The proposed fuzzy logic controller tunes the parameters of PI controller to control the frequency of micro hydropower plant and supervises the energy dissipated on the ballast load. This chapter presents the design and analysis of the proposed control system for micro hydropower plant. The parameters of the generator are given in appendix A.

4.1 PI controller design

The initial gains k_{po} and k_{io} are tuned using Ziegler-Nichols methods for the generator parameters given in appendix. It is the most common method in industry and is found to be efficient [21].

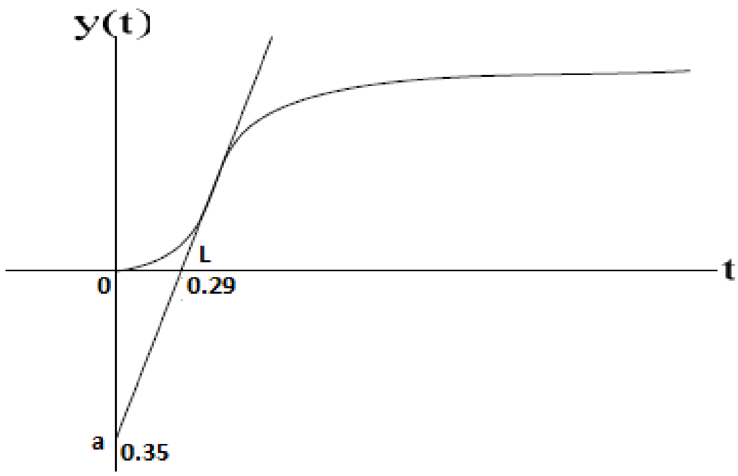

Figure 4.1: Ziegler-Nichols tuning using step response of the generator

The steps followed in ZN PI controller design are [21, 23]:

1. Obtain the plant step response.
2. Draw the steepest straight-line tangent to the step response curve at inflection point.
3. Obtain a and L as shown in Figure 4.1

4. k_p = 0.9/a and k_i = 3L

For the generator with H = 3.75 and D = 1.5 given by the manufacturer, the step response of generator is obtained. And the corresponding values are found to be k_p= 2.53 and k_i=0.87.

4.2 Designing the ballast load

The change in control power ΔPB can be calculated using the values of k_p and k_i of the PI controller as

$$\Delta PB(s) = \left(k_p + \frac{k_i}{s}\right)\Delta w(s) \quad (4.1)$$

Assuming a step non-frequency sensitive consumer load change, the change in electrical power in s-domain is given by

$$\Delta P_E(s) = -\frac{\Delta P_D}{s} - \left(k_p + \frac{k_i}{s}\right)\Delta w(s) \quad (4.2)$$

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

$$\Delta P_{Ess}(s) = \lim_{s\to 0}\left[-\frac{\Delta P_D}{s} - \left(Kp + \frac{Ki}{s}\right)\Delta w(s)\right] \quad (4.3)$$

The steady-state power error is zero, and simplifying Equation (4.3) an equation that relates steady-state frequency error and change in non-frequency sensitive load becomes

$$\Delta P_D = -K_{io}\Delta w_{ss} \quad (4.4)$$

In per-unit, angular frequency and frequency are equal; and moreover, at steady-state change in ballast load should be balanced by change in mechanical power. Thus, the following expression is obtained.

$$\Delta PB = K_{io}\Delta f_{ss} \quad (4.5)$$

Therefore, at steady-state, the relationship between change in ballast load and change in frequency is a linear one. Since $K_{io} = 0.87$, the change in the control power is given by

$$\Delta PB = 0.87\ \Delta f_{ss} \tag{4.6}$$

Practically, the steady-state frequency error cannot be zero. For the sake of design, the acceptable frequency error can be taken to be 1 Hz (0.02 p.u). Thus, the allowable maximum steady-state power error is 0.0175 per unit.

To meet steady-state performance in binary load configuration, only the minimum load should be determined. The rest are simply multiples of two. The minimum resistive load is already found to be 0.0175 per unit. Then, the i^{th} ballast load is given by

$$\Delta P_B(i) = P_B(i-1) + \Delta P_B(i) \tag{4.7}$$

Assuming there are seven electronic switches in the ballast load, Table 4.1 summarizes the binary load configuration.

Table 4.1: Look up table of the binary load configuration

Switch No.	Per unit dummy load
1	0.0175
2	0.035
3	0.07
4	0.14
5	0.28
6	0.56
7	1.12

According to our design, the total ballast load capacity is 2.222 per unit. The ballast loads were designed for each electronic switch based on their needed capacity to limit steady state error as specified. Ballast loads are designed for the already available irrigation dam Shilanat IV with installed capacity of 26KW found in Tigray regional state.

The power dissipation capacity of each resistance and the resistor values connected to each electronic switch is determined by using the following equations:

$$P_s = per\ unit\ ballast\ load * P_{rated} \tag{4.8}$$

$$R_s = 3\frac{{V_{ln}}^2}{P_s} \tag{4.9}$$

where P_s is power dissipation capacity of switch S and R_s is the resistor connected to switch S.

Table 4.2 shows the dissipation capacity of electronic switches and the resistor values connected to each switch.

Table 4.2: Electronic switches dissipation capacity and resistor values

Switch No.	Ballast load (p.u)	Ballast load (KW)	Resistor values (ohms)
1	0.0175	0.455	320
2	0.035	0.91	160
3	0.07	1.82	80
4	0.14	3.64	40
5	0.28	7.28	20
6	0.56	14.56	10
7	1.12	29.12	5

4.3 Genetic algorithm based tuning of membership functions

The optimal membership functions of the FLC are found by genetic algorithm. To start with genetic algorithm, certain parameters need to be defined. These include population size, bit length of chromosome, number of iterations, selection, and crossover and mutation types.

Selection of these parameters decides, to a great extend, the ability of the designed controller. The matlab code for optimization of membership function is shown in appendix B.

Initializing values are detailed as follows

Population type: binary

Crossover type: Single point crossover

Mutation type: Uniform mutation

Number of bits in each parameter = 8

Number of optimized parameters = 16

Population size = 100

Chromosome size = 128

Crossover rate = 0.3

Mutation rate = 0.001

Stopping criteria (maximum number of iterations) = 500 iterations

In each generation, the genetic operators are applied to selected individuals from the current population in order to create a new population. Three main genetic operators: reproduction, crossover and mutation are employed. Different probabilities are applied to these operators.

A part of the new population is created by simply copying without change the selected individuals from the old population. Some individuals are created as offspring of two parents (i.e., crossover being a binary operator). One crossover points are selected at random within the chromosome of each parent, at the same place in each. The parts delimited by the crossover points are then interchanged between the parents. The individuals resulting in this way are the offspring's. A new individual is also created by making modifications to one selected individual. The modifications are done by changing one value in the representation.

4.4 Fuzzy controller Design

The structure of the overall fuzzy controller to supervise the power generated and to control the frequency of the load is shown in the Figure 4.2.

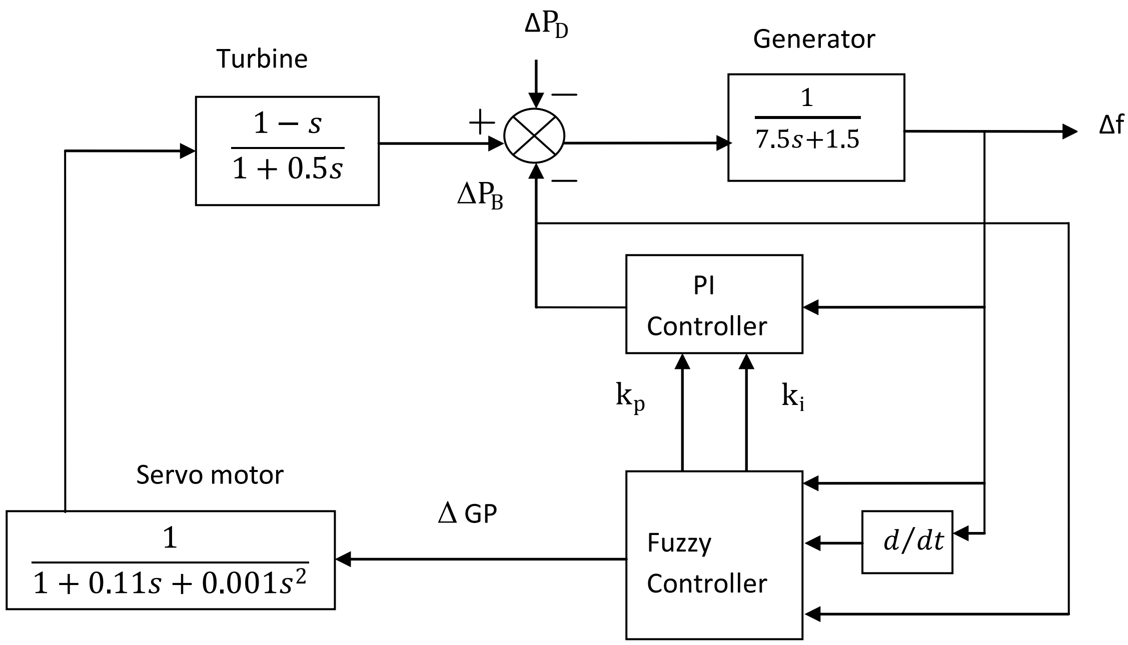

Figure 4.2: Control strategies of the proposed fuzzy controller

The Fuzzy controller consists: fuzzification, rule base, inference engine and defuzzification stages and appropriate design of each stage is crucial to design fuzzy controller.

4.4.1 Fuzzifier Design

The frequency error and change in frequency error are normalized to [-1, 1], the change in dump load is normalized to [0, 1]. The input scaling factor for error and change in error are found by trial and error to make the range of frequency error and change in frequency error normalized and found to be 10 and 50, respectively.

The input membership functions for error and change in error of frequency is optimized with genetic algorithm and shown in Figure 4.3. The shape of the membership functions and the universe of discourse for each function is found by trial and error for the change in ballast load and is shown in Figure 4.4. 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.

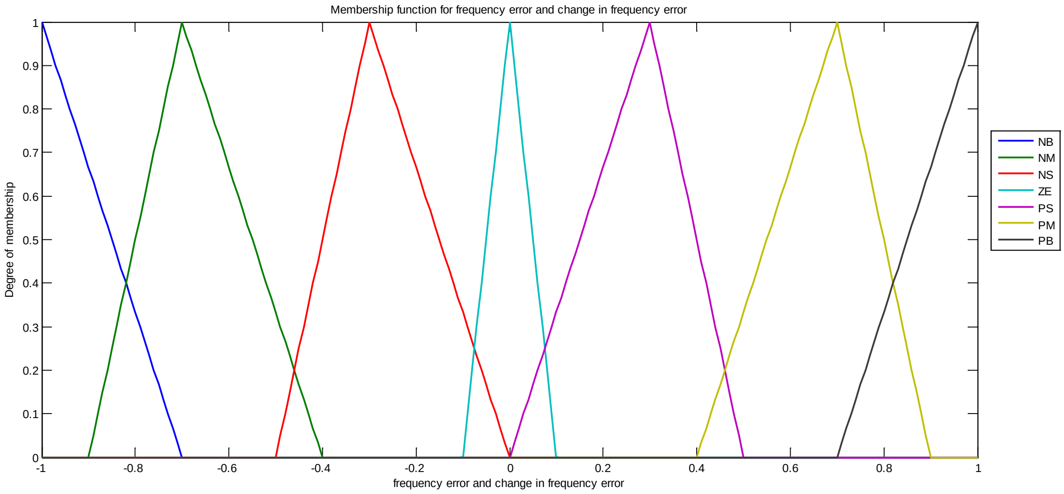

Figure 4.3: Input member ship function for error in frequency and change in error

Figure 4.3 is a graph of the frequency error and change in frequency error fuzzy membership functions. It assigns a crisp value's degree of membership to seven fuzzy linguistic values -- NB, NM, NS, Z, PS, PM, and PB. The fuzzy input membership functions used for error in frequency and change of error in frequency are trapezoidal type for PB and NB and are triangular type for NM, NS Z, PS, and PM. The universe of discourse of each membership function is shown in Table 4.3 with degree of membership.

Table 4.3: Membership function universe of discourse of error and change of error in frequency

e /Δe	Degree of membership						
	NB	NM	NS	Z	PS	PM	PB
-1 to -.7	1 to 0	0	0	0	0	0	0
-.9 to .7	0	0 to 1	0	0	0	0	0
-.7 to -.4	0	1 to 0	0	0	0	0	0
-.5 to -.3	0	0	0 to 1	0	0	0	0
-.3 to 0	0	0	1 to 0	0	0	0	0
-.1 to 0	0	0	0	0 to 1	0	0	0
0 to .1	0	0	0	1 to 0	0	0	0
0 to .3	0	0	0	0	0 to 1	0	0
.3 to 5	0	0	0	0	1 to 0	0	0
.4 to .7	0	0	0	0	0	0 to 1	0
.7 to .9	0	0	0	0	0	1 to 0	0
.7 to 1	0	0	0	0	0	0	0 to 1

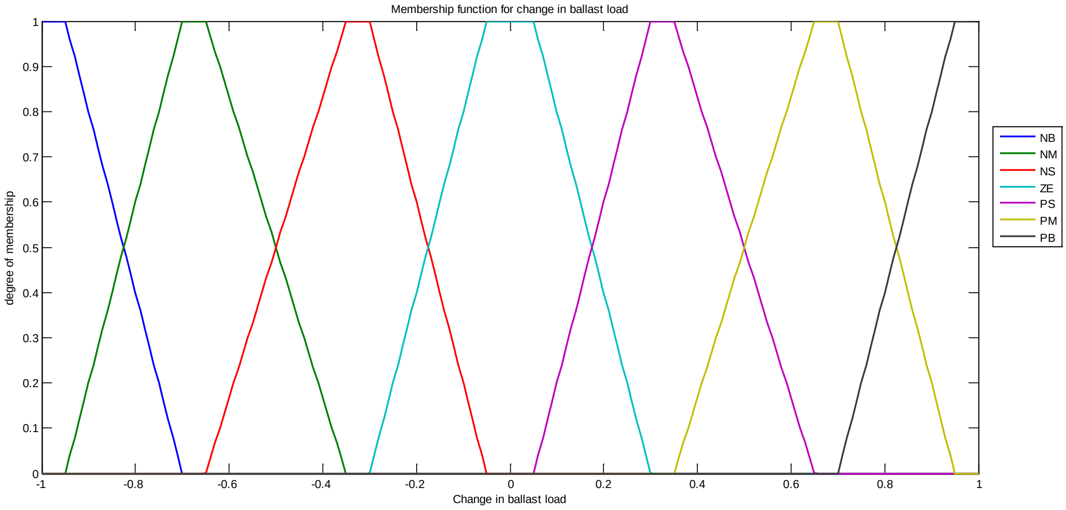

Figure 4.4: Input member ship function for change in ballast load

Figure 4.4 is a graph of the change in ballast load fuzzy membership functions. It assigns a crisp value's degree of membership to seven fuzzy linguistic values -- NB, NM, NS, Z, PS, PM, and PB. The fuzzy input membership functions used for change in ballast load are of trapezoidal types for all functions. The universe of discourse of each membership function is shown in Table 4.4 with degree of membership.

Table 4.4: Membership function universe of discourse of change in ballast load

ΔPB	Degree of membership						
	NB	NM	NS	Z	PS	PM	PB
-1 to -.95	1	0	0	0	0	0	0
-.95 to -.7	1 to 0	0 to 1	0	0	0	0	0
-.7 to -.65	0	1	0	0	0	0	0
-.65 to -.35	0	1 to 0	0 to 1	0	0	0	0
-.35 to -.3	0	0	1	0	0	0	0
-.3 to -.05	0	0	1 to 0	0 to 1	0	0	0
-.05 to .05	0	0	0	1	0	0	0
.05 to .3	0	0	0	1 to 0	0 to 1	0	0
.3 to .35	0	0	0	0	1	0	0
.35 to .65	0	0	0	0	1 to 0	0 to 1	0
.65 to .7	0	0	0	0	0	1	0
.7 to .95	0	0	0	0	0	1 to 0	0 to 1
.95 to 1	0	0	0	0	0	0	1

4.4.2 Rule base construction

Rule formats: Basically a linguistic controller contains rules in the if-then format, but they can be presented in different formats. In our systems, the rules are presented to the controller in a format similar to the one below.

1. If error is NB and change in error is NB then Δk_p is PB and Δk_i is NB
2. If error is Z and change in error is NS then Δk_p is PS and Δk_i is NS
3. If error is PM and change in error is NM then Δk_p is Z and Δk_i is Z
4. If change in dump load is PM then GA is NM
5. If change in dump load is PS then GA is NS

The rule tables for Δk_p, Δk_i and ΔPB are shown in Table 4.5, 4.6 and 4.7 respectively.

Table 4.5: Rule table for k_p

Error(e)	Error Derivative(Δe)						
	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PM	PM	PS	Z	Z
NM	PB	PB	PM	PS	PS	Z	NS
NS	PM	PM	PM	PS	Z	NS	NS
Z	PM	PM	PS	Z	NS	NM	NM
PS	PS	PS	Z	NS	NS	NM	NM
PM	PS	Z	NS	NM	NM	NM	NB
PB	Z	Z	NM	NM	NM	NB	NB

Table 4.6: Rule table for k_i

Error(e)	Error Derivative(Δe)						
	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NM	NM	NS	Z	Z
NM	NB	NB	NM	NS	NS	Z	Z
NS	NB	NM	NS	NS	Z	PS	PS
Z	NM	NM	NS	Z	PS	PM	PM

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

Table 4.7: Rule table for ΔGA

ΔPB	ΔGA
NB	PB
NM	PM
NS	PS
Z	Z
PS	NS
PM	PM
PB	PB

4.4.3 Defuzzification Design

We used the Centroid de-fuzzification method to convert from the inference mechanism into the crisp values applied to the actual system. The output of the fuzzy controller is multiplied by output scaling factors to get the final parameters and control signal. The output defuzzification membership functions for Δk_p , Δk_i and GA are shown in Figures 4.5 and 4.6.

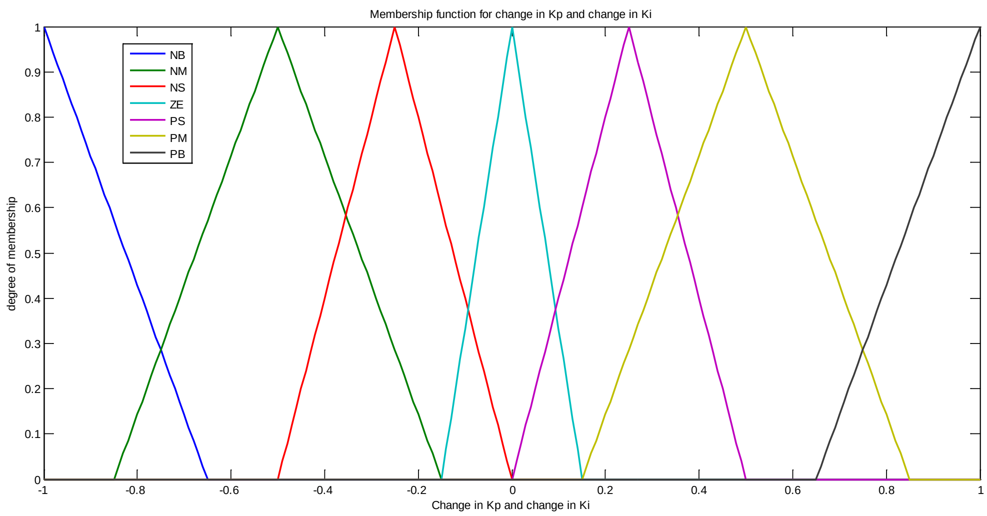

Figure 4.5: Output member ship function for change in k_p and k_i

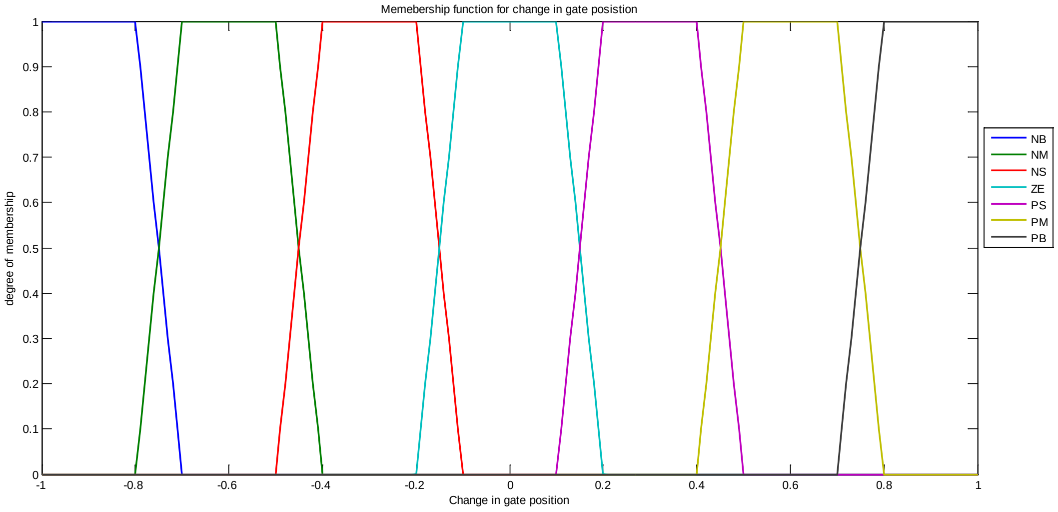

Figure 4.6: Output member ship function for change in GA

Table 4.8: Membership function universe of discourse of change in k_p and k_i

$\Delta k_p/\Delta k_i$	Degree of member ship						
	NB	NM	NS	Z	PS	PM	PB
-1 to -.9	1	0	0	0	0	0	0
-.9 to -.75	1 to 0	0	0	0	0	0	0
-.8 to -.6	0	0 to 1	0	0	0	0	0
-.6 to -.4	0	1 to 0	0	0	0	0	0
-.45 to -.25	0	0	0 to 1	0	0	0	0
-.25 to -.05	0	0	1 to 0	0	0	0	0
-.15 to 0	0	0	0	0 to 1	0	0	0
0 to .15	0	0	0	1 to 0	0	0	0
.05 to .25	0	0	0	0	0 to 1	0	0
.25 to .45	0	0	0	0	1 to 0	0	0
.4 to .6	0	0	0	0	0	0 to 1	0
.6 to .8	0	0	0	0	0	1 to 0	0
0.75 to 0.9	0	0	0	0	0	0	0 to 1
0.9 to 1	0	0	0	0	0	0	1

Table 4.9: Membership function universe of discourse of change in gate position

ΔGp	Degree of membership function						
	NB	NM	NS	Z	PS	PM	PB
-1 to -0.8	1	0	0	0	0	0	0
-0.8 to-.7	1 to 0	0 to 1	0	0	0	0	0
-0.7 to -0.5	0	1	0	0	0	0	0

-0.5 to -0.4	0	1 to 0	0 to 1	0	0	0	0
-0.4 to -0.2	0	0	1	0	0	0	0
-0.2 to -0.1	0	0	1 to 0	0 to 1	0	0	0
-0.1 to 0.1	0	0	0	1	0	0	0
0.1 to 0.2	0	0	0	1 to 0	0 to 1	0	0
0.2 to 0.4	0	0	0		1	0	0
0.4 to 0.5	0	0	0		1 to 0	0 to 1	0
0.5 to 0.7	0	0	0	0	0	1	0
0.7 to 0.8	0	0	0	0	0	1 to 0	0 to 1
0.8 to 1	0	0	0	0	0		1

4.5 Digital Control

As a digital frequency controller is being used, the PI controllers should be transformed into their discrete form. The discrete PI controllers are formulated directly from their corresponding Laplace transforms. For our system the control signal is change in ballast load and it is given by:

$$\Delta P_B(s) = \Delta f(s) * \left(K_p + \frac{K_i}{s}\right) \tag{4.10}$$

Now, applying bilinear transformation to get an equivalent discrete PI controller, the expression in Equation (4.11) is obtained

$$\Delta P_B(z) = \Delta f(z) * \left(K_p + \frac{K_i * z}{1 - z}\right) \tag{4.11}$$

Transforming Equation (4.11) into discrete time domain and taking the sampling time as one second,

$$\Delta P_B(n) = \Delta P_B(n-1) + K_p[\Delta f(n) \quad - \Delta f(n-1)] + K_i \Delta f(n) \tag{4.12}$$

The n^{th} ballast load is, $P_B(n) = P_B(n-1) + \Delta P_B(n)$. The ballast loads are either turned ON or OFF based on this value.

The transfer functions of the generator, turbine and servomotor are converted to their discrete equivalent for simulation studies.

4.6 Simulink Model of MHPP for Frequency Controller

All the components of MHPP are modelled to design the controller and to analyse the simulation results. The overall Simulink model of the MHPP and control system is shown in Figure 4.7.

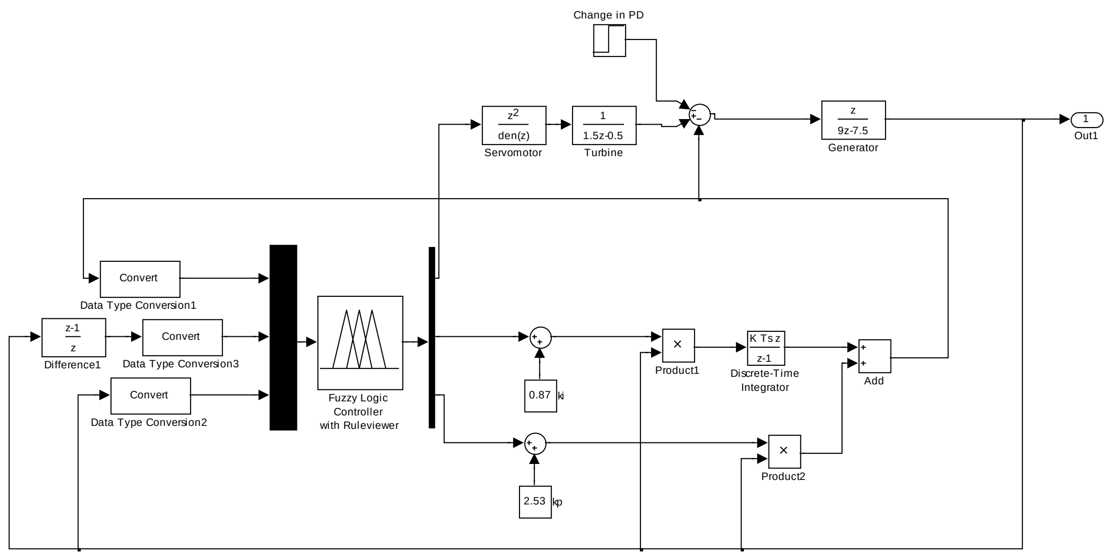

Figure 4.7: Overall Simulink Simulation Model

Chapter Five

SIMULATION RESULTS AND DISCUSSIONS

This chapter presents simulation results obtained from tests performed on the micro hydropower plant using Matlab Simulink with and without fuzzy controller. The Simulink model shown in Figure 4.7 is used to carry out simulation studies and analyse the performance of fuzzy controller under different operating conditions.

5.1 Simulation Results

The response of the system is tested for varying damping constant of the generator. The frequency deviation of the micro hydropower system without controller, with PI load control, with PI flow control and with self tuning fuzzy controller for a 30% load rejection are shown in Figure 5.1. The results are obtained assuming the damping constant of the generator equal to 1.5. It is observed that without controller there is a frequency deviation of 0.2 p.u under steady state condition which is harmful for electrical loads and should be eliminated. It is also seen that with PI flow controller there is an overshoot of 13% and settling time is 30 seconds whereas with PI load controller, the overshoot reduces to 8.9% and the settling time is 11 seconds.

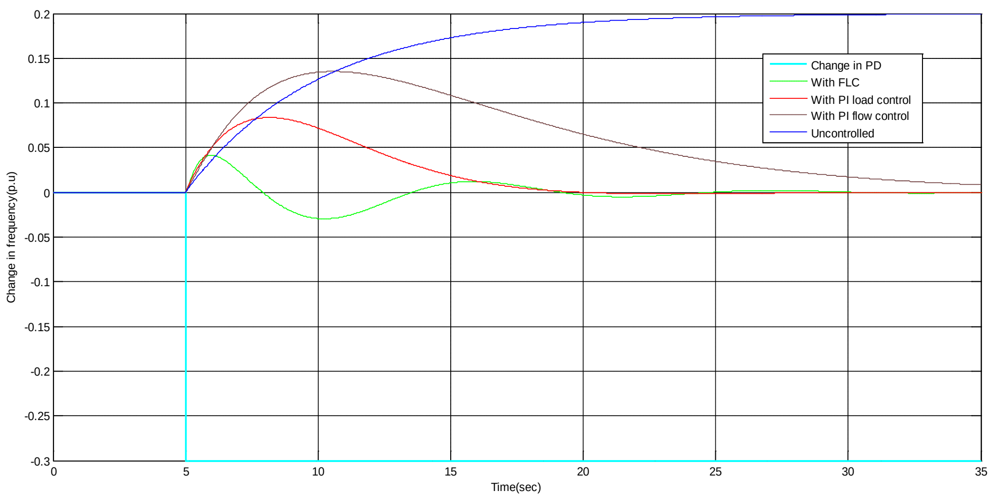

Figure 5.1: Frequency response for 0.3 p.u load rejection (D=1.5)

It is further observed that that the fuzzy self tuning controller reduces the overshoot to 4.6% and the settling time to 8.3 seconds with zero steady state error. Though the micro hydro power plant is stable with all controllers, a good transient and steady state performance is achieved when we employ a fuzzy self tuning controller.

The damping constants of the generators for micro hydropower plant may vary from 1 to 2 depending on the load and internal damping of the generator [24]. Thus, to see the effect of varying damping constant of the generator, simulation results are obtained for damping constants of 1.1 and 1.9 and are shown in Figure 5.2 and 5.3, respectively. Table 5.1 summarizes the transient performances of the micro hydropower plant with different controllers under different operating conditions. It is concluded from Figure 5.1, 5.2, 5.3 and Table 5.1, that both the transient and steady state performance are improved with fuzzy self tuning controller under all operating conditions as compared to those with any another controller.

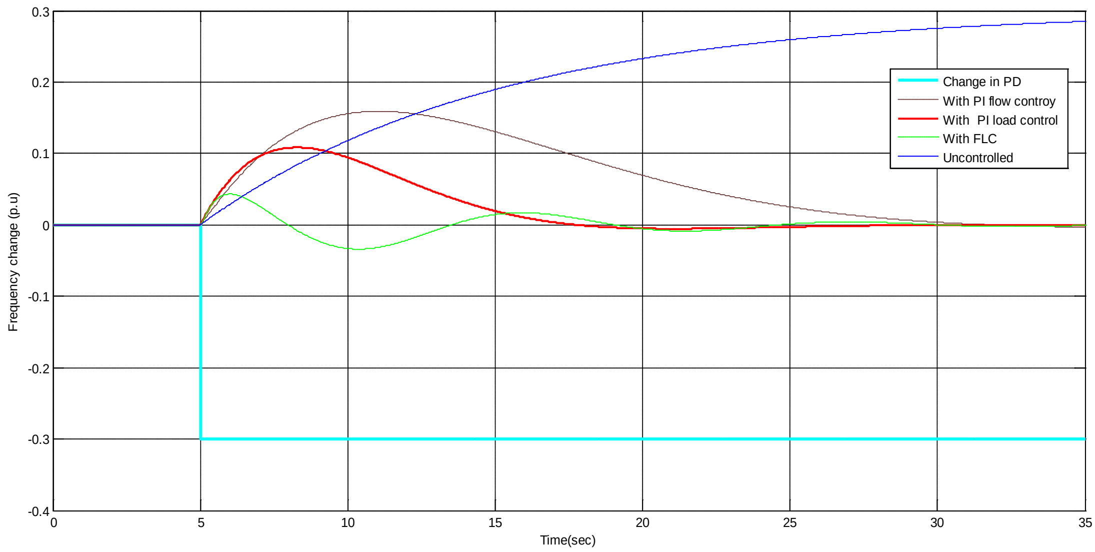

Figure 5.2: Frequency response for 0.3 p.u load rejection (D=1.1)

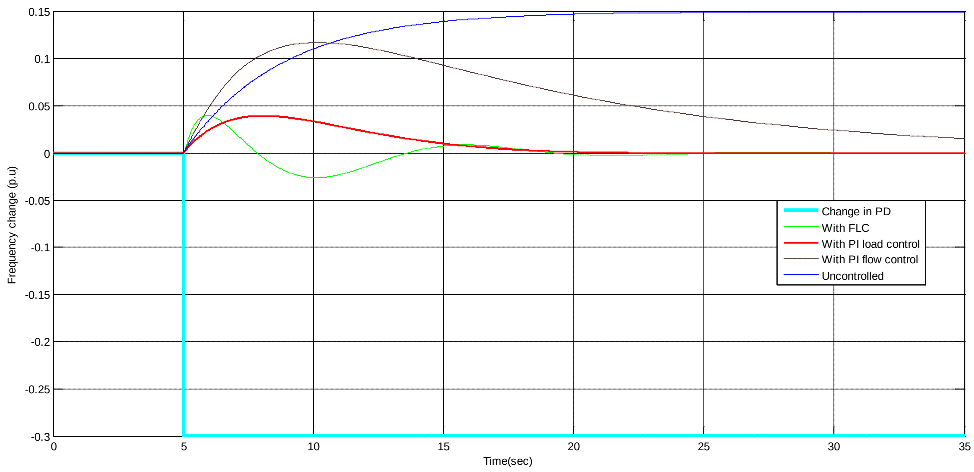

Figure 5.3: Frequency response for 0.3 p.u load rejection (D=1.9)

Table 5.1: Transient and steady state performance with different controllers for different damping constants and sudden 30% load rejection

Controller	Overshoot	Settling time	Steady state frequency error
	Damping constant D=1.1		
Uncontrolled	27%	Not settled	27%
With PI flow control	16%	25 sec	0
With PI load control	10.5%	11 sec	0
With FLC	5.5%	7 sec	0
	Damping constant D=1.5		
Uncontrolled	20%	Not settled	20%
With PI flow control	13.5%	29 sec	0
With PI load control	8.9%	11 sec	0
With FLC	4.6%	8.3 sec	0

	Damping constant D=1.9		
Uncontrolled	15.6%	Not settled	15.6%
With PI flow control	11.7%	33 sec	0
With PI load control	7.3%	14.7 sec	0
With FLC	4.1%	9.8 sec	0

In order to test the robustness, stability and effectiveness of the proposed fuzzy logic controller, different operating conditions like load acceptance, small as well as severe load rejections were taken into account in simulation studies. Figure 5.4 shows the results of simulation for 30 % load acceptance, as well as 15% and for 70% load rejection. It is seen from Figure 5.4 that even for 70% load rejection which is a dangerous load rejection, the settling time is 11 seconds which is small even though the overshoot is 12%. This shows the capability of the fuzzy self tuning controller to perform satisfactorily over a wide range of operating conditions.

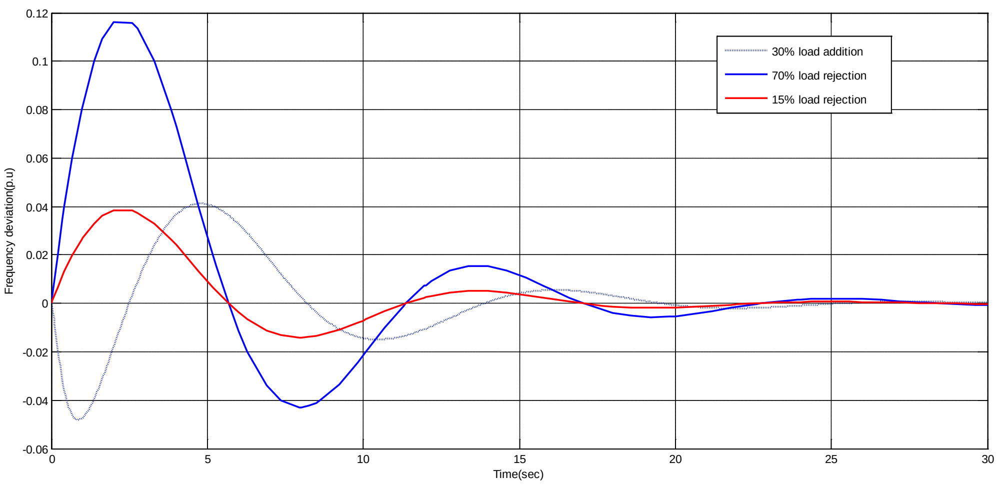

Figure 5.4: Frequency response with fuzzy logic controller under different loading conditions

The capability of the fuzzy logic controller (to supervise energy dissipated on ballast load) is evaluated for different values of load rejection and load addition. Figure 5.5 and 5.6 shows the supervision capability of fuzzy logic controller for 30% and 75% sudden load rejection, respectively. It is observed that when we employee PI load controller for 30% and 75% sudden load rejection, the power on the ballast load is increased by 30% and 75% respectively. It is further seen that when fuzzy logic controller is used to supervise the power dissipated on the ballast load for 30% and 75% load rejection, the power on the ballast load increases initially but it drops to zero after 25 seconds and 43 seconds respectively. This is achieved as a result of fuzzy logic controller acting on gate position to close by 30% and 75% for the corresponding load rejection.

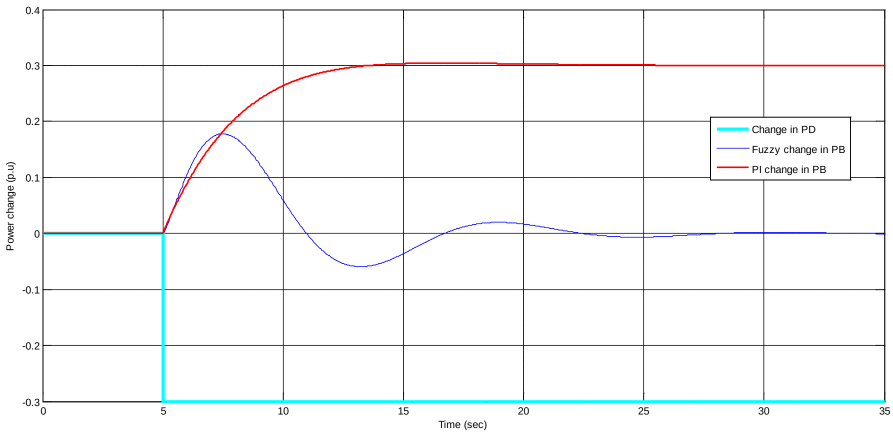

Figure 5.5 (a): Change in ballast load with different controllers for sudden 0.3 p.u load rejection

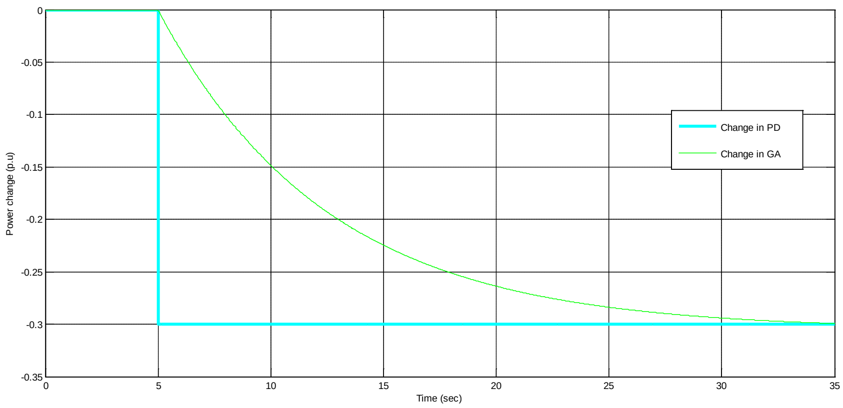

Figure 5.5(b): Change in gate position with FLC for sudden 0.3 p.u load rejection

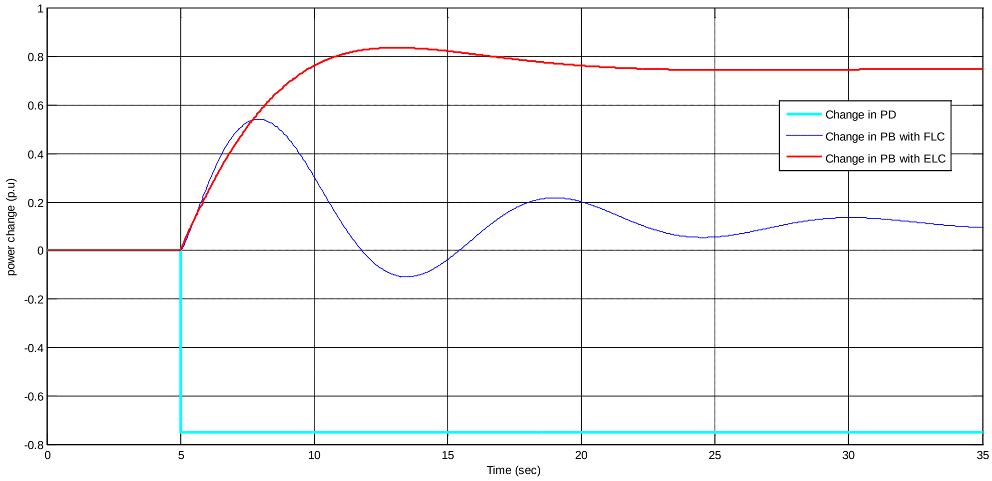

Figure 5.6(a): Change in ballast load with PI different controllers for sudden 0.75 p.u load rejection

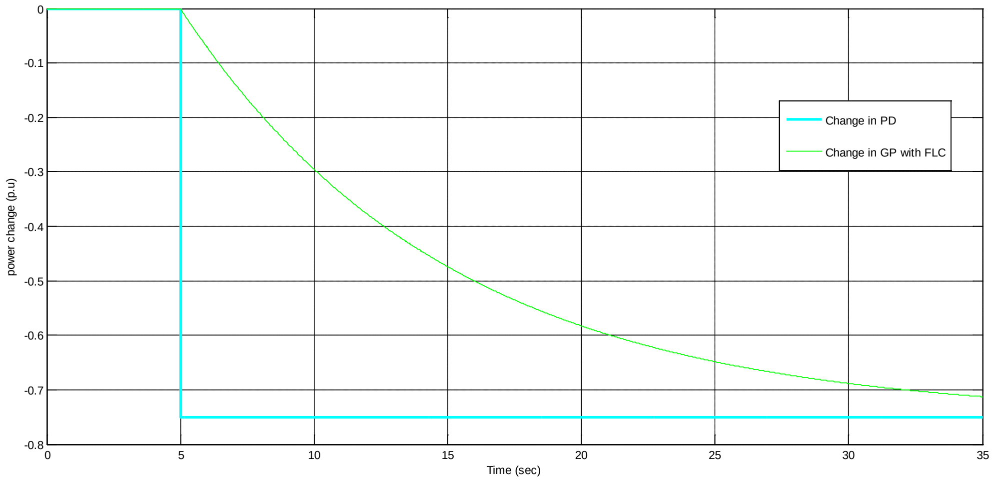

Figure 5.6(b): Change in gate position with FLC for sudden 0.75 p.u load rejection

It is seen from Figure 5.7(a) and 5.7(b) that for 30% load addition, there is a decrease of ballast load by 30% when PI load controller is used to control the frequency whereas with the fuzzy logic controller, the ballast load decreases initially but it comes to zero after 30 seconds and the gate position opens more by 30%.

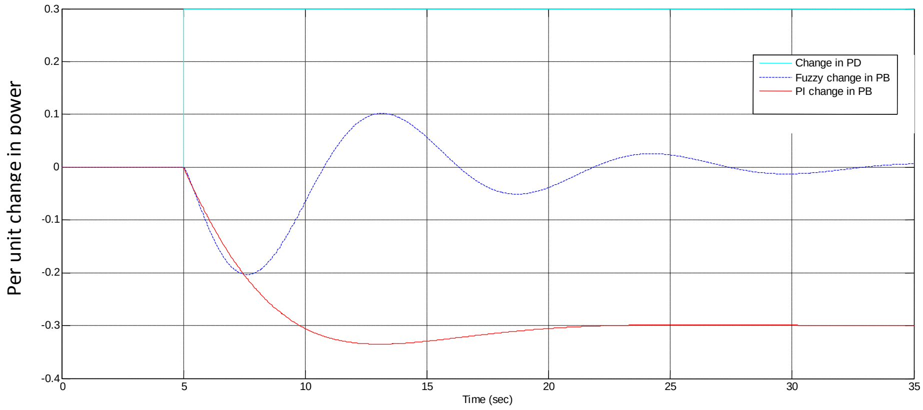

Figure 5.7(a): Change in gate position with FLC for sudden 0.3 p.u load addition

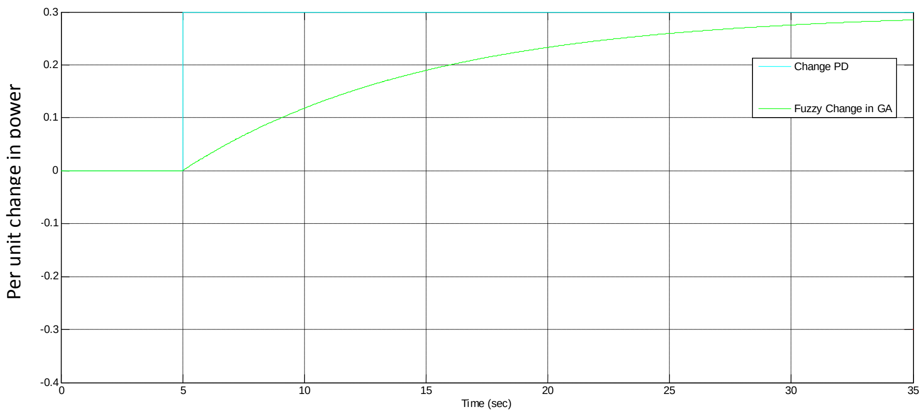

Figure 5.7(b): Change in ballast load with different controllers for sudden 0.3 p.u load addition

5.2 Discussions

The first objective of the tests performed on the MHPP was to analyse its performance with three different controllers; namely- PI flow control, PI load control and fuzzy self tuning PI controller for different damping constants of the generators. Figure 5.1, Figure 5.2, Figure 5.3 and Table 5.1 depict the performance of the proposed controller with step change in demand power and varying damping constant. The response of the system is slow when the conventional PI controller is applied on the system. On the other hand, when the self-tuning fuzzy PI controller is used, the system response improves significantly. This illustrates the capability and effectiveness of the proposed fuzzy controller for frequency control of micro hydropower plants.

Table 5.2 summarises the supervision capability of fuzzy logic controller to manage the power dissipated on ballast loads.

Table 5.2: Energy saving capability of different controllers for different load changes

Controller	Energy wasted on ballast load (p.u)
After sudden 30% load rejection	
FLC	0.25
Load control	0.6
Flow control	0
After sudden 75% load rejection	
FLC	0.5
Load control	1.05
Flow control	0
After sudden 30% load addition	
FLC	0.25
Load control	0
Flow control	0

The second objective of the tests performed on the MHPP was to see how the fuzzy logic controller performs to supervise energy dissipated on the ballast load while keeping the frequency within the acceptable range for different values of load rejection and load addition. It is seen from Figure 5.4 that for any change in demand power, the fuzzy logic controller guaranties the stability of the plant by returning frequency to its steady state in a very short time. Moreover, while controlling the frequency, the fuzzy controller commands the servomotor to close the gate opening position to produce less energy and decreases the dissipated power on the ballast load to its acceptable value (around 25% of the nominal value). Thus, it also saves water on the dam when there is load rejection as shown in Figure 5.5(b) and Figure 5.6(b). When there is a sudden increase in load demand, the fuzzy controller controls the servomotor to increase the gate opening as shown in Figure 5.7(b). This increases the dissipated power on ballast load to its acceptable value while regulating the frequency as shown in Figure 5.7(a) and Figure 5.4, respectively.

Chapter Six

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

6.1 Conclusions

In this thesis, a fuzzy logic controller is proposed 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. Both the transient and steady state performances of micro hydropower plant are improved by increasing the number of membership functions.

A model that represents the complete micro hydropower plant including generator, turbine and servomotor was developed. The performance of the proposed fuzzy logic controller is tested through simulation studies using Matlab/Simulink. It is observed from the simulation results that the average overshoot for 30% load change is 4.6% and the settling time is 7.5 seconds with the proposed fuzzy logic controller while overshoot is 8.9% and 13.5% and settling time is 11 seconds and 29 seconds with PI load control and PI flow control, respectively. Moreover, even for 70% load rejection, overshoot is only 11.6% and the settling time is 11 seconds. It is further observed that the change in energy wasted on ballast load from the desired value is always around zero under steady state condition.

The proposed fuzzy controller is able to maintain the frequency of a micro hydropower plant within tolerable limits in spite of the damping constant variation and load variations. Furthermore, it minimizes the waste of energy by limiting the dissipated power on the ballast load and thereby manages the available water on the irrigation dam.

The shape and distribution of the membership functions used in the design of fuzzy controller should be chosen with care to achieve system stability and robustness. The scaling factor used for the input and output variables also have significant impact on the performance of the fuzzy controller and need to be chosen properly. Incorrect scaling factors can lead the system output to oscillate around the set points.

In Ethiopia, there are many small dams primarily built for irrigation purpose. The research carried out in this thesis reveals the possibility of exploiting the irrigation dams for power generation without affecting irrigation which takes priority over power generation.

6.2 Suggestions for Future Work

The performance of the plant can be investigated with a nonlinear turbine model. Furthermore, input scaling factor and rule base can be optimized with genetic algorithm for further improvements in the performance of the micro hydropower plants. Moreover, the hardware of self-tuning fuzzy logic controller and fuzzy supervisor can be developed for micro hydropower plants on irrigation dams. In addition, the cost benefit of micro hydropower plants on irrigation dams with the proposed controller can be analysed in detail.

REFERENCES

[1] I. Salhi, S. Doubabi, "Fuzzy Controller for Frequency Regulation and Water Energy Save on Micro-Hydro Electrical Power Plants," International Renewable Energy Congress, Tunisia, November 2009.

[2] M.A. Wazed, Shamsuddin A., "A feasibility study of micro hydroelectric power generation at sapchari waterfall, Kharachari ", Journal of Applied science, pp 372-376, 2009.

[3] Tiruneh M., "Reservoir Operational Planning of Irrigation Dams for Micro Hydropower Development", M.Sc. Thesis, Civil Engineering Department, AAU, November 2005.

[4] Himani Goyal and M.Hanmandlu, "An Artificial Intelligence based Control for Micro Hydro Power Plants", IJEIT Vol. 1, No. 1, Oct. 2009.

[5] M. Hanmandlu, H. Goyal, D.P. Kothari, "An Advanced Control Scheme for Micro Hydro Power Plants", International Conference on Power Electronics, Drives and Energy Systems, December 2006.

[6] S. Mbabazi and J. Leary, "Analysis and Design of Electronic Load Controllers for Micro-Hydro Systems in the Developing World", E-Futures, University of Sheffield, March 2010.

[7] Michael Abebe, "Irrigation Dams for Micro Hydropower Development in the Context of Rural Electrification", Symposium on Renewable Energies in Ethiopia, Addis Ababa, April 2004.

[8] Ebru Özbay and Muhsin Tunay Gençoğlu, "Load Frequency Control for Small Hydro Power Plants Using Adaptive Fuzzy Controller",

[9] Ayele Nigussie, "Development of a Dual Mode Frequency Controller for Standalone, Micro and Mini Hydropower Systems," M.Sc. Thesis, Electrical and Computer Engineering Department, AAiT, July 2010.

[10] Celso Penche, "Layman's Handbook on How to Develop a Small Hydro Site", Brussels, June 1998

[11] T. Bimrew, "Comparative Analysis of Feasibility of Solar PV, Wind and Micro Hydro Power Generation for Rural Electrification in the Selected Sites of Ethiopia", M.Sc. Thesis, Mechanical Engineering Department, AAU, July 2007.

[12] I. Salhi, S. Doubabi, N. Essounbouli, "Fuzzy Control of Micro Hydro Power Plants", The 5th IET International Conference on Power Electronics, Machines and Drives (PEMD2010), Brighton (UK), April 2010.

[13] Manoj Kumar Pandey, "Analysis of Self Tuning Fuzzy PID Internal Model Control", MSC Thesis, Thapar University, Patiala, July 2010.

[14] Timothy J. Ross, "Fuzzy Logic with Engineering Applications", John Wiley & Sons Ltd, England, 2004.

[15] Leonid Reznik, "Fuzzy Controllers", Linacre House, Jordan Hill, Oxford, 1997.

[16] Jan Jantzen, "Design of Fuzzy Controllers", Technical University of Denmark, Department of Automation, Denmark, Aug 1998.

[17] Zulfatman and M. F. Rahmat, "Application of Self-Tuning Fuzzy PID Controller on Industrial Hydraulic Actuator Using System Identification Approach", International Journal on Smart Sensing and Intelligent Systems, Vol. 2, No. 2, June 2009.

[18] Seema Chopra, R. Mitra and Vijay Kumar, "Auto Tuning of Fuzzy PI Type Controller Using Fuzzy Logic", International Journal of Computational Cognition, Vol. 6, No. 1, March 2008.

[19] Ebru Özbay, Muhsin Tunay Gençoğlu, "Self-Tuning Fuzzy PI Controlled System Model for Small Hydro Power Plants", 10th International Conference on Clean Energy (ICCE-2010), Cyprus, September 2010.

[20] Dipl.-Geogr. Hedi Feibel, "An Interdisciplinary Approach to the Dissemination of Mini and Micro Hydropower - The Case of Ethiopia", PhD dissertation, Darmstadt University of Technology, 2003.

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

[22] D. S. Henderson and W Pearson, "An Improved Control Algorithm for an Electronic Load Governor", Napier University, Edinburgh, UK.

[23] Jinghua Zhong, " PID Controller Tuning", Mechanical Engineering Department, Purdue University, 2006.

[24] Goran Andersson, "Dynamics and Control of Electric Power Systems", Swiss Federal Institute of Technology, Zurich, 2010.

[25] Herrera, F., Lozano, M., Verdegay, J. L., "Tuning Fuzzy Logic Controllers by Genetic Algorithms", International Journal of Approximate Reasoning 1995; pp.299-315

[26] Lee, M.A., Takagi, "Integrating Design Stages of Fuzzy Systems Using Genetic Algorithms", Proc. 2nd IEEE Int. Conf. Fuzzy Systems, San Francisco, 1993; 612-617

[27] Joseph Foran, "Optimisation of a Fuzzy Logic Controller Using Genetic Algorithms", M.Eng Project Report, Dublin City University, 2002

[28] Mini hydro turbine generators, http://www.alibaba.com/showroom/hydro-turbine-generator.html, accessed on December 2010.

APPENDICES

Appendix A: Raw data for design, analysis and simulation

Appendix Table 1: Specifications of FU-DXJ14-0.3DCT4-Z Synchronous Generator [28]

Parameter	Value
Power rating	30KW
Voltage rating	400V
Speed	1500rpm
Moment of inertia	0.54 Kgm^2
Damping constant	1.5

Appendix B: MATLAB codes

```
% written by Jemal Hayato, June 2011.
% Addis Ababa Institute of Technonlogy
%INITIALISATION
nbits=8; % number of bits in each parameter
npar=16; % number of optimized parameters
popsize = 100; %population size
L = 128; %chromosome size
selection = 0.7; %fraction of population kept
mutrate= 0.001; %mutation rate
maxit=500; % max number of iterations
%initialse the GA population
keep=floor(selection*popsize); % number of population members that survive
parent=round(rand(popsize,L));
x=[0:0.1:1];
for it=1:maxit
  %______________________________________________________
  % convert binary to decimal and scale it
  for i=1:popsize
    para1(i)=1/256*bin2dec(parent(i,1:8));
    para2(i)=1/256*bin2dec(parent(i,9:16));
    para3(i)=1/256*bin2dec(parent(i,17:24));
    para4(i)=1/256*bin2dec(parent(i,25:32));
    para5(i)=1/256*bin2dec(parent(i,33:40));
    para6(i)=1/256*bin2dec(parent(i,41:48));
    para7(i)=1/256*bin2dec(parent(i,49:56));
    para8(i)=1/256*bin2dec(parent(i,57:64));
    para9(i)=1/256*bin2dec(parent(i,65:72));
    para10(i)=1/256*bin2dec(parent(i,73:80));
    para11(i)=1/256*bin2dec(parent(i,81:88));
    para12(i)=1/256*bin2dec(parent(i,89:96));
```

```
    para13(i)=1/256*bin2dec(parent(i,97:104));
    para14(i)=1/256*bin2dec(parent(i,105:112));
    para15(i)=1/256*bin2dec(parent(i,113:120));
    para16(i)=1/256*bin2dec(parent(i,121:128));
  end
  % evaluate the fitness of the individual parents
 for j=1:popsize
   for i=1:11
     if x(i)<=para1(j)
     zi(j)=(-1/para1(j))*x(i)+1;
     elseif para2(j)<=x(i)<=para3(j)
     PSi1(j)=1/(para3(j)-para2(j))*(x(i)-para2(j));
     elseif para3(j)<=x(i)<=para4(j)
     PSi2(j)=1/(para3(j)-para4(j))*(x(i)-para3(j))+1;
     elseif para5(j)<=x(i)<=para6(j)
     PMi1(j)=1/(para6(j)-para5(j))*(x(i)-para5(j));
     elseif para6(j)<=x(i)<=para7(j)
     PMi2(j)=1/(para6(j)-para7(j))*(x(i)-para6(j))+1;
     elseif para8(j)<=x(i)<=1
     PBi(j)=1/(1-para8)*(x(i)-1)+1;
     else
       zi(j)=0;
       PSi1(j)=0;
       PSi2(j)=0;
       PMi1(j)=0;
       PMi2(j)=0;
       PBi(j)=0;
     end
%_______________ input output relation_______________
    for k=1:11
      if x(k)<=para9(j)
```

```
        zo(j)=(-1/para9(j))*x(k)+1;
        elseif para10(j)<=x(k)<=para11(j)
        PSo1(j)=1/(para11(j)-para10(j))*(x(k)-para10(k));
        elseif para11(j)<=x(k)<=para12(j)
        PSo2(j)=1/(para11(j)-para12(j))*(x(k)-para11(j))+1;
        elseif para13(j)<=x(i)<=para14(j)
        PMo1(j)=1/(para14(j)-para13(j))*(x(k)-para13(j));
        elseif para14(j)<=x(k)<=para15(j)
        PMo2(j)=1/(para14(j)-para15(j))*(x(k)-para14(j))+1;
        elseif para16(j)<=x(k)<=1
        PBo(j)=1/(1-para16)*(x(k)-1)+1;
        else
          zo(j)=0;
          PSo1(j)=0;
          PSo2(j)=0;
          PMo1(j)=0;
          PMo2(j)=0;
          PBo(j)=0;
        end
      end

%______________   evaluate fitness____________________________
      cost1(j)=0;
       cost2(j)=0;
        cost3(j)=0;
         cost4(j)=0;
      for o=1:11
         cost1(j)=cost1(j)+( zo(o)-zi(0));
          cost2(j)=cost2(j)+( pso(o)- psi(0));
           cost3(j)=cost3(j)+( pmo(o)- pmi(0));
            cost4(j)=cost4(j)+( pbo(o)- pbi(0));
```

```
 end
 cost(j)= cost1(j)+cost2(j)+cost3(j)+cost4(j);
end

rank = sort(cost(j));

for h=1:80;
    fitparent=parent(:,1:80);
%________________  Pair and mate_________________________________
NM=ceil((popsize-keep)/2); % number of matings
prob=flipud([1:keep]'/sum([1:keep]));% weights chromosomes based upon position in list
probd=[0 cumsum(prob(1:keep))']; % probability distribution function
pick1=rand(1,NM); % mate #1
pick2=rand(1,NM); % mate #2
% ma and pa contain the indicies of the chromosomes that will mate
ic=1;
while ic<=NM
for id=2:keep+1
if pick1(ic)<=probd(id) && pick1(ic)>probd(id-1)
ma(ic)=id-1;
end
if pick2(ic)<=probd(id) && pick2(ic)>probd(id-1)
pa(ic)=id-1;
end
end
ic=ic+1;
end
%__________________ Performs mating using single point crossover_____________

ix=1:2:keep; % index of mate #1
xp=ceil(rand(1,NM)*(L-1)); % crossover point
```

```
fitparent(keep+ix,:)=[fitparent(ma,1:xp) fitparent(pa,xp+1:L)]; % first offspring
fitparent(keep+ix+1,:)=[fitparent(pa,1:xp) fitparent(ma,xp+1:L)]; % second offspring
%______________ Mutate the population_____________________________

nmut=ceil((popsize-1)*L*mutrate); % total number of mutations
mrow=ceil(rand(1,nmut)*(popsize-1))+1; % row to mutate
mcol=ceil(rand(1,nmut)*L); % column to mutate
for ii=1:nmut
parent(mrow(ii),mcol(ii))=abs(parent(mrow(ii),mcol(ii))-1);% toggles bits
end

    end
  end
  %_________________display the output ___
  disp([cost(newparent((1,:)))])
end
```