Design of Hydro Turbine Management Unit for Standalone Pico Hydro in Rural Area

A thesis submitted in fulfilment of the requirements for the degree of
Master of Engineering (Research)

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ABSTRACT

The exponential increase of greenhouse gas emissions into the atmosphere has resulted in extreme weather events around the globe. Electrical power systems amount for a significant percentage of the global greenhouse gas emissions. Therefore, this alarming increase in greenhouse gas emissions pivoted the interest of the electrical power industry towards renewable energy resources. Hydropower has been used as a primary energy source to generate electricity since the twentieth century. In recent years, small, micro, and Pico hydropower plants were installed which do not require these massive structures to store water, rather they are designed to be run off river hydropower plants. However, there are several challenges that exist pertaining to the efficient operation of small-scale hydropower plants. Considerable research has been conducted to address the limitations of load frequency and turbine intake water flow control. Researchers have investigated the efficacy of flow valve control for turbine intake water flow and electronic load controller for load and frequency control. However, both flow valve control integrated with proportional-integral differential controller and electronic load control fail to overcome existing limitations such as variance in frequency response, insertion of harmonics, and energy dissipated in dump load. Intelligent control with fuzzy logic is a realistic way for achieving ideal control levels and efficiency. An integrated system with an intelligent approach of fuzzy-proportional-integral control and proportional-integral-differential control for load control valve is proposed in this study to improve performance of Pico hydropower plant. The proposed technique is also capable of efficiently handling the non-linearities of the Pico hydropower plant. The proposed technique is implemented in SIMULINK MATLAB and its efficacy is tested against a traditional proportional-integral-differential controller. Results prove that the proposed technique can efficiently control the system's frequency and intake water flow (speed) during load and flow variations. It is evident the proposed integration controller provides an enhanced control of the Pico hydro system during normal operating conditions especially from the aspect of overshooting percentage which is only 0.30% compare to standalone PID controller and Fuzzy PID controller, at 1.70%.

DECLARATION

I hereby declare that this thesis, titled "Design of hydro turbine Management Unit for Standalone Pico Hydro in Rural Area", contains no material that has been accepted for the award of any other degree or diploma, and to the best of my knowledge contains no material previously published or written by another person except where due reference is made in the text of the thesis.

Signature

Name : CHIA YANG KANG

Date : 27/4/2023

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List of Symbols, Abbreviations and Nomenclature

General Notation

Δ_f	Frequency Deviation
V_{rms}	RMS Voltage
V_d, V_q, V_o	Voltages in dq0 reference frame
ω_e	Electrical angular speed of the rotor in per unit
ω_m	Mechanical angular speed of the rotor in per unit
ω_{error}	Wind turbine rotor speed error in per unit
P_{load}	Active load power in per unit
Q	Elementary charge (1.6021x10-19 Coulombs)
C	Capacitor (F)
P_m	Mechanical output power in per unit
T_m	Mechanical torque of wind turbine in per unit

Permanent Magnet Synchronous Generator Parameters

θ_r	Angle between the d-axis and the stationary a-axis
V_{as}, V_{bs}, V_{cs}	three-phase stator voltages
I_{as}, I_{bs}, I_{cs}	instantaneous three-phase stator currents
R_s	stator winding resistance
V_{abc}	Three phase stator voltages
V_{ds}, V_{qs}	instantaneous stator voltages in dq-axes
I_{ds}, I_{qs}	instantaneous stator currents in the dq-axes
L_d , L_q	dq-axis inductances

P_{abc}	Electrical power in abc reference frame
P_{dq}	Electrical power in dq reference frame
T_e	Electromagnetic torque in per unit

Tunnel and Penstock Parameters

Q_r	Discharge water flow rate
T_w	Water starting time of the pipe segment
L	Length of the water tunnel
U_o	Water velocity
G	Gravity constant
H_o	Dynamic water head
Q_o	Water flow at nominal operation

Turbine Parameters

G	Opening of the wicket gates in per unit
P_m	Mechanical output power from the turbine in per unit
H_d	Dynamic head in per unit

Hydraulic Speed Governor Parameters

K_a	Servomotor gain
T_a	Servomotor time constant
R_p	Static gain of hydraulic speed governor
K_p	Proportional gain
K_i	Integral gain

K_d	Derivative gain

Excitation System Parameters

V_{fd}	Exciter voltage
T_r	Stator terminal voltage transducer time constant
K_A	Main regulator gain
K_e	Exciter gain
T_e	Exciter time constant
Ef_{min}	Lower limit of voltage regulator output
Ef_{max}	Upper limit of voltage regulator output

Synchronous Machine Parameters

V	Voltage
I	Current
Φ	Flux
R	Resistance
L	Inductance
T	Time constant
$-d$	Direct axis quantity
$-q$	Quadrature axis quantity
$-R$	Rotor quantity
$-s$	Stator quantity
$-l$	Leakage quantity
$-m$	Magnetizing quantity

$-f$	Field winding quantity
$-k$	Damper winding quantity
$-kq1$	Second damper winding in quadrature axis
$-kq2$	Third damper winding in quadrature axis
$\Delta\omega_m$	Mechanical Speed variation in per unit
H	Inertia constant
T_m	Mechanical torque in per unit
T_e	Electromagnetic torque in per unit
K_d	Damping factor
$\omega_m(t)$	Mechanical speed of the rotor in per unit
ω_o	Synchronous Speed of operation in per unit
p	Pole pairs
F	Friction factor

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CHAPTER 1 : INTRODUCTION

1.1 Project Background

The electrical power system is a complex network that is further subdivided into generating, transmission, and distribution systems. The power system was invented in the 18th century using water as the primary source to generate hydroelectric energy with the primary need to power lights. In the present era the dependence of humans on electricity has increased immensely such that every aspect of their livelihood is dependent on electricity, be it health, energy, heating, appliances, and transportation. Conventionally, the primary sources from which electricity is generated is classified into three categories which are nuclear energy (uranium, thorium, plutonium), fossil fuels (natural gas, coal, and petroleum), and renewable energy sources that have been derived from the earth's natural resources, such as biomass energy (such as ethanol), hydropower, geothermal power, wind energy, and solar energy(Ávila *et al.*, 2021; Benhammane *et al.*, 2021; Henninger *et al.*, 2020; Lai *et al.*, 2021).

Reliance on fossils fuels to generate electricity has made power systems one of the biggest contributors to global warming due to the amount of greenhouse gasses such as carbon dioxide (CO_2) emitted by them. However, as discussed above there are other clean energy sources available therefore, this alarming increase in CO_2 emissions has resulted in a paradigm shift pertaining to power generation industry. Therefore, research on generation of electricity from renewable energy resources (RES) has gained considerable traction in recent years (Boza *et al.*, 2021; Igogo *et al.*, 2021; Meha *et al.*, 2020; Pierri *et al.*, 2021; Sinsel *et al.*, 2020; Steele *et al.*, 2021). One other reason to shift to RES is the exponential rate at which fossil fuel resources are depleting. RES such as hydropower, geothermal, biomass, wind, and solar have recently emerged as viable alternatives for supplying rural regions and communities, particularly for stand-alone applications, making it evident that they have the potential of supplying energy in remote areas. RES not only have proven them cost-effective but they also provide clean, sufficient, and environmentally friendly power supply to the consumers. Furthermore, RES are also characterised as energy resources that are abundant and essentially inexhaustible in their natural surroundings (Lu *et al.*, 2021; Tan *et al.*, 2021; Q. Wu *et al.*, 2017; Zakaria *et al.*, 2021).

The abundance of renewable resources, very low to no greenhouse gas emissions and depletion of fossil fuel resources are the reasons for an increase in demand of generation from RES. Renewable resources not only maintain the natural resources but also contribute to mitigating the risks of environmental disasters such as fuel spills and natural gas leaks. Hydropower is the only renewable resource that has been used for power generation since the 18th century. Hydropower is further divided into waves, tidal, rivers, and canals. Historically only rivers and canals are used for hydropower generation as they maintain constant flow and the power generation is stable. However, in recent years generation from waves and tides have also increased owing to the demand for generation from RES and the technological advances and innovations. Power generation from solar, biomass, geothermal and wind resources has also increased in recent years. Power generated solar photovoltaic (PV), solar thermal and wind turbines hold majority shares in the renewable electricity market (Arens *et al.*, 2021; Colla *et al.*, 2020; Gielen *et al.*, 2019; Gralla *et al.*, 2017; Hannan *et al.*, 2018; Svobodova *et al.*, 2020).

Water covers 70% of the earth's surface, making it the primary resource for hydroelectric energy regeneration. It is often used on a large or small scale, depending on the output and location of the installation (Mandelli *et al.*, 2016; Quaranta *et al.*, 2020). Pico-hydropower is commonly characterised as a hydropower system capable of producing up to 5 kW of energy from a water flow. In practice, the environmental impact of small or Pico hydro plant (PHP) sourced from rivers and streams does is not significant compared to large scale hydropower plant (Kadier *et al.*, 2018; Rotilio *et al.*, 2017). Standalone Pico hydropower is one of the ideal renewable energy sources for providing electrification to communities in a remote part of Borneo, Malaysia, and was considered an economical and ecologically viable mechanism for generating renewable energy in lower capacities of up to 5kW. Pico hydropower operates efficiently in standalone mode and can supply a few households especially in rural areas. It may also be used to drive milling and turning machines using mechanical drives (Chala *et al.*, 2019; Kougias *et al.*, 2019). (Tushaar *et al.*, 2017) proved the credibility of pico hydropower by sustaining uninterrupted power supply to a village Gupathi with 4.5kW power plant and to a village in Arunachal Pradesh with power plant rated at 1.5kW. Furthermore, 10-11% of the capital cost of the PHP installation will be returned by the revenue generation, demonstrating that it is financially sustainable.

A pico-hydro system is a renewable energy source that generates electricity by combining a small generator with hydro turbines to generate electricity(Quaranta *et al.*, 2020; Rotilio *et al.*, 2017). Pico hydro power generation systems have attracted the attention of Malaysian ministry of Energy, Green Technology, and water (KeTTHA) due to its eco-friendly nature and the abundance of water resources in Malaysian Peninsula. KeTTHA developed a strategy in 2010 focus on national electricity supply security and long-term socio-economic growth with objective of increasing integration of RES based electricity power plants to national grid (Awang *et al.*, 2021; Basar *et al.*, 2011). (Kadier *et al.*, 2018) advocated the potential of PHP in leading Malaysia's green energy development initiative. He also discussed the limitations and future perspectives relating to PHP. Despite increase in electricity generation from RES, they have been under constant scrutiny regarding environmental conservation and economic expansion. This was discussed in detail in a review of PHP by (Chala *et al.*, 2019). He also discussed the development of various hydropower facilities and compared them to traditional fossil fuels.

One of the limitation of PHPs identified by researchers is the inadequate control of the water inflow and output frequency of the turbine, following their installation. PHPs are usually installed in rural areas as standalone units, and they are installed the indigenous population is responsible for their maintenance. However, the indigenous population lack the resources and the technical knowledge to run and maintain PHPs, particularly when it comes to frequency regulation. The lack of expertise in distant villages about maintaining a mechanical flow governor has been a severe problem for many years. Standalone controllers cause unbalance between power supply and load demand and thus affected power quality, which is extremely inconvenient for the consumers. Therefore, it is necessary to conduct research into developing an effective integrated controller with the objective of providing stable electricity through frequency and voltage management.

Frequency and voltage management are essential variables for a power system, as it serves as an indicator of the system's energy balance and power quality. Voltage and frequency variations effect the active power of the system. To provide system stability and power balance, standalone controllers such as the Flow Control Valve (FCV) and Electronic Load Controller (ELC) have been developed previously. However, from previous research it is evident that neither FCV nor ELC overcome the limitations of frequency response, insertion of harmonic distortion and energy dissipated in dump load. Harmonic distortion is experienced by power system due to installation of ELC in the system which is caused by regular switching action of dump load, whereas standalone FCV causes variance in terms of frequency response time. These voltage and frequency variations effect the active power of the system.

Conventionally, the Proportional Integral Derivative (PID) controller has been employed for the purpose of PHP management. A PID controller responds to errors and changes in errors. It has been one of the most sophisticated and extensively used in industrial process control applications controller due to simplicity and adaptability. Tuning is a process for a particular operating point. A system works at various operating variables, and retuning is essential for the system to maintain system stability. The settings of the PID are carefully tuned using a variety of tuning methods. The PID constant should be chosen so that the response has a rapid rising time, low overshoot, and a quick settling time. The process of settling these parameters also was called tuning. The PID controller is not capable of providing efficient control under non-linear conditions associated with the PHP (El Hamdaouy *et al.*, 2020).

Artificial Intelligence (AI) algorithms integrated with the PID controller has been proposed by researchers to provide efficient control of non-linear systems such as PHPs. A neuron fuzzy controller based on ANFIS algorithm was proposed by (Dhanalakshmi *et al.*, 2012) for the load frequency control of a wind-micro hydro-diesel hybrid power system. Two ANFIS fuzzy controllers were installed; one with the speed governor for the hydro power unit and one with the pitch controller of the wind turbine. Results exhibited that ANFIS fuzzy controller provided better dynamic frequency control as compared to a PI controller. (Sahoo *et al.*, 2018) proposed an improved grey wolf optimization based fuzzy aided PID controller for frequency control. The improved grey wolf algorithm was implemented to optimize the constants of the PID controller to maintain frequency of the system. The proposed system provided improved frequency management over the existing automatic generation control techniques. An improved firefly-pattern search algorithm was employed to optimize fuzzy aided PID controller by (Rajesh *et al.*, 2019). The proposed hybrid controller is able to provide satisfactory control for diverse set of generation sources. (Kang *et al.*, 2021) designed a fuzzy logic-based controller for battery energy storage system (BESS) integrated with PHP. The objective of integrating BESS with PHP is to provide stable power during peak load demand. The proposed controller efficiently maintained load demand during peak time.

It is evident from the discussed literature that non-linear controller is essential for a pico PHP to maintain stable supply to the consumers. Several researchers have proposed AI and AI integrated with PID controllers as a feasible solution to this control problem. It can be observed from the literature, that to ensure efficient control of PHP dedicated controllers are needed at the water flow of the turbine, at the load supply side of the generator along with a battery management system. A hydro turbine management unit with separate integrated controllers has not been designed to prevent unwanted equipment downtime and maintenance expenses in this study.

1.2 Problems Statement

In conventional stand-alone pico hydro application, the Proportional Integral Derivative (PID) load controllers were used, as a standard control method to maintain a stable frequency response between load generation and load demand. Moreover, the frequency is also affected by the water inflow of the turbine. The turbine needs to maintain a constant round per minute (rpm) for the generator to maintain its frequency and voltage. A control scheme investigating the integration of dedicated controllers for water flow (speed) and load curtailment is yet to be explored. The problems explored in this study are as follows:

1.2.1 Problem With maintain constant water inflow of PHP

Maintaining a constant water inflow on PHP is difficult as they are usually run off river. Therefore, the system is always unstable when supplying power supply. This non-linearity of the system causes numerous power quality issues to the consumers. For this type of operation, a variety of control approaches have been applied. PID is the most widely used control technique for renewable energy resources that were adopted in the early stages of invention. The control method is based on the amount of the error (proportional), the persistence of the error (integral), and the variation of error (differential) which has referred to these terms as derivatives. The PID controller is non-linear and this non-linearity of the system and quick change of the parameters on pico hydro affect the PID controller which is unable to react to these sudden changes. This is the reason why standalone PID load controller is not suitable for pico hydro system. Therefore, design a hydro turbine management unit with integration controller to control the flow of water and consumer load to PHP yet to investigated.

1.2.2 Problem with load control of PHP

A mini-grid scheme feature of hydropower often causes energy power demand unbalance. This imbalance is caused due to variations in water flow and fluctuations in load demand which is high during the day and low during the night leads to poor power quality in terms of the load factor of the system. The economic viability of such a system was considered low, thus, affecting the number of households that access a stable power supply. Therefore, a dedicated load controller integrated with an intelligent water inflow (speed) controller is yet to explored.

1.3 Research Objective

a) To **design a** hydro turbine management unit with integration control using intelligent approach fuzzy-PID flow (speed) control and PID load controller.
b) To **evaluate** the performance of frequency response with load reduction.
c) To **analyse** system operation with sudden load reduction and three phase faults.

1.4 Expected Outcome of the Study

a) By using an intelligent control, both controllers can be integrated. Fuzzy-PID control on the turbine side (valve) and PID control on the generator side (load) will provide an efficient system and enhanced frequency response performance in terms of minimizing overshoot time, transient performance, and steady-state deviation by at minimum 1%.

1.5 Limitation of the Study

This research was associated with the following limitations:

a) The research is focused on a domestic water distribution system.

b) The modelling of power electronic and mechanical circuits is beyond the scope of this study.
c) The design of new turbine, or generator technology was not considered, due to the availability of various technologies changing from time to time in the market.
d) The actual water flow rate is not considered in this research, due to limitation on the system modelling block.

Pico Hydro requires control system to ensure that electricity has been always delivered at the rated frequency. When the grid load has altered, it causes fluctuations in the load and turbine power output. Furthermore, the output frequency is affected by the speed.

When instantaneous high load is experienced by the system, the frequency drops significantly. The proposed fuzzy controller system is designed to maintain the frequency of the Pico Hydro Power Plant approximately constant, and the fuzzy-PID controller is an optimum way to ensure that system remains under control. In addition, as compared to traditional frequency governors, the suggested controller provided superior output performance.

1.6 Thesis Overview

The thesis comprises of five chapters. Project background, problem statements, research objectives and limitation of the study are presented in chapter 1

In chapter 2 existing literature that is relevant to this control of PHP and its management is comprehensively discussed. Based on the discussion research gaps of the prevailing system with the efficient design of hydro turbine management are identified.

In chapter 3 the methodology adopted to approach the research objectives of this study are presented. The discussed methodology includes plant modelling, which consists of several sub-models that include the hydro turbine governor and load controller system. MATLAB Simulink version R2021a is used to model PHP and the management system. Furthermore, this chapter will represent the method analysis of the data achieved from the pico-hydro power plant modelling.

In chapter 4 the findings of this study are presented and discussed through comparisons of the results in tables and graphs to differentiate the performance of each control scheme. The results will enlighten how the control system works on turbine valves by using fuzzy logic controller and electronic load controller operation to determine the output performance using the membership rules (Mamdani's methods).

In chapter 5, the conclusion of this research study is presented and the implications along with recommendations for future research are also presented in this chapter.

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

Electricity has become an essential part of human lives in recent years and their dependence on electricity has also increased exponentially. Electricity is now integrated with every aspect of human livelihood such as health, work, and entertainment, etc. This increase in dependence on electricity and the increase of the world population has resulted in a significant increase in electricity demand. This excessive generation of electricity produces a considerable amount of greenhouse gas emissions, which makes it a substantial contributor to climate change. Therefore, the electrical power industry took the initiative to increase generation from renewable energy resources to alleviate these effects on climate change (Gielen *et al.*, 2019; Hidy *et al.*, 1994; Lehtola *et al.*, 2019). In light of the renewable energy initiative several developed countries have successfully integrated a sizeable amount of renewable energy into their national grids. Hydropower, wind, and solar are the major renewable energy resources being utilized to generate electricity by these countries (Hannan *et al.*, 2018; NREL, 2017; Sayed *et al.*, 2021). However, developing countries are still facing challenges in delivering uninterrupted power supply to consumers in both rural regions and metropolitan cities (Kubik, 2006).

Hydropower is a renewable energy resource which depends upon the global water cycle. Electrical power is generated using turbine generator set through hydropower. The hydropower turbine is moved by potential energy of flowing water, which is produced through difference in elevations of the water reservoir and the turbine inlet, also termed as head (Chala *et al.*, 2019; Jones, 2013; Margonis, 2017). Therefore, the amount of electricity generation from hydropower is solely dependent upon the availability of volume and flow of water resource. The flow of water is directly proportional to the head (difference in elevation). The turbine is mechanically couple to a synchronous generator. The turbine is moved by the water which in turn moves the generator rotor and electricity is generated. Higher head and heavy flow of water results in high electricity generator as it can govern a bigger turbine generator set. The energy generated by a hydropower plant containing large reservoir volume with small head and a plant containing small reservoir volume with large head is the same. However, the former requires lesser number of generating units than the latter (Quaranta *et al.*, 2020; Shiji *et al.*, 2021; Williamson *et al.*, 2014).

Hydropower is one of the oldest renewable resources used for electricity generation due to its stability and the capability of supplying base load demand. Hydropower has been used on large, medium and small scales (Egré *et al.*, 2002; Zhang *et al.*, 2021). Large hydropower plants can power thousands on household, they also impose some social and environmental issues. Whereas small hydropower plants cause no such issues as they are run off river plants constructed on streams and rivers. Small hydroelectric power plants have several advantages over conventional hydropower plants, including excellent water supply and irrigation, direct connection/disconnection to the network or autonomous operation, zero-emissions (during the operational phase), reliable uninterrupted stable supply, long service life, low-cost maintenance, little time amortisation of necessary investments, and others (Lu *et al.*, 2021; Rotilio *et al.*, 2017).

Standalone pico hydropower plant is even smaller than small hydropower plants and has low to none social and environmental impact, which makes it an optimal renewable energy solution for rural communities (Lu *et al.*, 2021; Margonis, 2017; Pascasio *et al.*, 2021). There are several limitations and challenges that exist pertaining to the efficient performance pico hydropower systems. Many researchers have worked on the pico hydro system with distinct preferences, such as modification of motor and turbine generation, usage of the piping system and others (Awang *et al.*, 2021; Basar *et al.*, 2011; Kadier *et al.*, 2018; Quaranta *et al.*, 2020). However, development of efficient controllers is with objective of maintaining a stable power output is one the prominent challenge for pico hydro systems. Conventionally control strategies such as PID control technique, zero-crossing technique, fuzzy control and neuro-fuzzy control technique are employed to achieve efficient control (Margonis, 2017). Efficient control of pico hydro system entails ensuring stable power output under varying water flow and load conditions. In this chapter, renewable energy technologies will be discussed and existing control techniques of pico hydro power plants will be extensively reviewed in this chapter.

2.2 Renewable Energy Resources

The exponential change in climate has pivoted the focus of electrical power industry towards generation from renewable energy resources. According to the US energy information administration, renewables contribute to 6% of the USA's electrical energy production, whereas the production of electricity from RES was increased by 73.4% in the European Union. Therefore, it is evident that the energy sector of the world is heading towards clean generation of electricity. Renewable energy is termed as green as it does not produce greenhouse gases, which are the root cause of climate change. Therefore, significant research is being conducted in addressing the limitations of RES. One of the most prominent challenges is the intermittent nature of RES which render them unsuitable to serve the base load demand. Therefore, current research is focused on developing a solution for both the long-term adequacy of the environmental consequences and the uninterrupted energy supply of specific sources. The long-term electrical power system models must recognize the distinctions between energy production methods and energy storage technologies that are capable of assuring energy preservation and mitigating the impact of climate change by reducing the production of greenhouse gas emissions. This is imperative to achieve efficient planning of clean, economical and reliable power system (Henninger *et al.*, 2020; Lai *et al.*, 2021). As a result, the electrical power systems are experiencing significant transformation. RES are classified into solar, wind biomass and hydropower as illustrated in Figure 2.1.

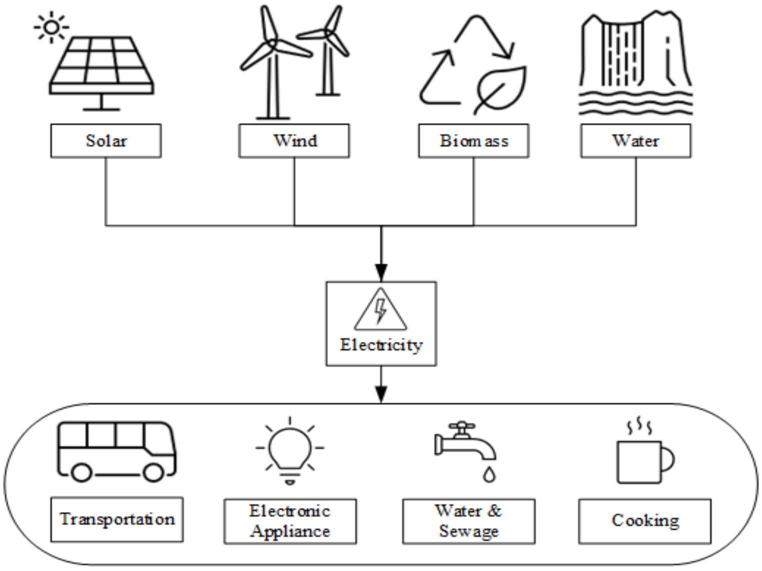


Figure 2.1: Renewable energy for electrification (Ammari *et al.*, 2021; Igogo *et al.*, 2021; Tan *et al.*, 2021)

2.2.1 Geothermal

The word geothermal is a composed of two Greek words, geo meaning earth and thermal meaning heat. Geothermal is renewable as heat is constantly being produced by the earth's core, which is harnessed in the form of geysers and volcanic eruptions (Arpasi, 2000; Benighaus *et al.*, 2019). Geothermal energy is utilized through hot water which is pumped naturally to the earth's surface and electricity is generated by driving a turbine through it. Geothermal energy is also widely used to heath households. Geothermal energy has great potential but its utilization is limited due to the geographic location of geothermal sources. Therefore, its percentage of contribution in producing electricity amongst other renewable resources is low (Clauser *et al.*, 2018; DiPippo, 2007; Soltani *et al.*, 2021). It has low environmental footprint because geothermal energy is regenerated spontaneously. However, geothermal energy also has drawbacks, such as the instalment cost of geothermal plants is high and they are also prone to earthquakes (Axelsson *et al.*, 2005; Bertani, 2009; Kubik, 2006; Sayed *et al.*, 2021; Yao *et al.*, 2021).

2.2.2 Biomass

Biomass is referred to as natural resources such as organic plants and animal materials. It has been the most ancient source of energy, ever since humans first burned wood to stay warm and cook food. Wood is still the most utilized biomass source to generate electricity (Azeta *et al.*, 2021; Korberg *et al.*, 2021; Lee, 2022; Ren *et al.*, 2020). Bioenergy is a type of sustainable energy obtained from biomass, which comes from the organic matter of natural living things and plants. Biomass energy can be produced in a variety of ways, for instance, through burning biomass or capturing methane gas produced by the natural degradation of organic matter in landfills. Wood, biofuels like ethanol, and methane recovered from landfills or burned municipal trash are all biomass sources. Burning of biomass sources releases carbon dioxide into the atmosphere which can be harmful, however the amount of carbon dioxide released is minimal and is absorbed by plants. Therefore, from an environmental point of view biomass sources are neutral (Miner, 2010; Springsteen *et al.*, 2011). Biomass can be utilised in everyday lives, not just for domestic use but industrial use as well. Biomass energy accounted for around 5% of total energy consumption in the United States in 2017 (NREL, 2017; Umar *et al.*, 2021; Wang *et al.*, 2021).

2.2.3 Wind

Wind are the most extensively used renewable energy resources due to the technological advances. Wind and solar are also abundantly available and are inexhaustible. Wind farms use wind turbines to harness the energy of the wind and generate electrical power. However, there are different design of wind turbines available each designed for specific wind patterns and each of them have their advantages and disadvantages (Do *et al.*, 2021; Schädler *et al.*, 2021; Shams *et al.*, 2021). The generation output of wind turbines ranges from kWs to MWs in a single unit. Wind speed is dependent upon weather which is directly linked to the solar radiation as it affects atmospheric temperature and geography of the system located (Ghaithan *et al.*, 2021; Pascasio *et al.*, 2021;Weschenfelder *et al.*, 2020). Wind energy is known as a clean energy source, which does not contaminate the environment with the residue of carbon dioxide (Ezhiljenekkha *et al.*, 2020; Neupane *et al.*, 2022).

2.2.4 Solar Energy

Solar energy is the most extensively used renewable energy resource in the world. In recent years, percentage of electricity generated from solar in the global world generation has been increasing. This rise is due to the technological advancements in photovoltaic (PV) technology and the advancements in grid connected inverters. Electricity is generated from solar is further divided into two technologies i.e., concentrated solar power and PV. Concentrated solar power plants are designed to focus sunlight on a specific receiver, using lenses or mirrors. The receiver is heated from the focused exposure of sunlight, which then drives a steam turbine coupled to an electric generator. The lenses or mirrors are designed to track the movement of the sun to maximize electricity generation. PV panels are semi-conductor devices that utilize the photonic nature of solar irradiance. The photon of light is absorbed by the PV panel, which is then converted into current.. This cost-free fuel makes solar the feasible solution to lower energy prices and supply energy to the remotest areas. Furthermore, increase in solar will decrease the dependence on fossil fuels which will improve the quality of the environment (Alkhayat *et al.*, 2021; Lehtola *et al.*, 2019; Tawn *et al.*, 2022).

2.2.5 Hydropower

Hydropower is an established technology with evidence of its utilization by ancient Greek civilization, China dynasty, roman and Islamic empires (Europe, Asia and Africa). In ancient times hydropower was employed to saw wood or pound metal, grind wheat, domestic lifts, dock cranes and in textile mills (Bartle, 2002; Egré *et al.*, 2002; German Ardul Munoz-Hernandez, 2013; Lewis *et al.*, 2014). Hydropower is the most established and widely utilized RES for electricity production as it is stable, reliable and is not intermittent in nature. It has been used to generate electricity since the start of 20th century. As discussed earlier, hydropower uses the potential energy of water created by the difference in elevation levels also termed as head to rotate turbine-generator set (Nedaei *et al.*, 2022; Shiji *et al.*, 2021; Zhang *et al.*, 2021). Furthermore, hydropower also acts as energy storage plants. Energy is stored in form of water in large reservoirs which can then be used to generate electricity when needed. The aforementioned features make hydropower a viable alternative to fossil fuels. However, it does have social, economic and environmental drawbacks, as it requires immense amount of land and relocation of the indigenous population.

Renewable energy power generation has great potential, and many countries have made significant investments in it. Transportation and Heating, ventilation, and air conditioning (HVAC) industries amount for 29% of global energy consumption making it the second largest sector energy sink (Hasanuzzaman *et al.*, 2019). RES has numerous advantages as discussed in pervious sections, however, there are still several challenges related to the integration of RES to the electrical power system. A study by (Pierri *et al.*, 2021) investigated the integration of RES into the process industry and concluded that RES alone cannot sustain uninterrupted power supply to the consumers which compromises the reliability and stability of the grid. Integration of RES to a coal-based energy system with the objective of using power to heat technology was studied by (Meha et al., 2020). Sinsel *et al* (Sinsel *et al.*, 2020) extensively reviewed the challenges of variable renewable energy to the electrical power system along with their solutions. The review identified photovoltaic and wind energy as essential renewable sources to enhance decarbonization. However, their intermittent nature it their biggest limitation. Hydropower systems on the other hand do not possess this issue of intermittency and therefore a stable and clean source of energy. Therefore, in this study pico hydropower system is taken into consideration due to its intermittency compare to other source of energy.

Nonlinear models are frequently illustrated using a block diagram when speed and power fluctuate in both small and large increments. The dynamic behaviour of governors is represented by mathematical formulations of ordinary differential equations. The regulator consists of two components: valve control parts and load control parts. It is important to analyse the power system response while modelling pico hydro components such as synchronous generators, turbines, and their governing control systems to create an efficient output system (Margonis, 2017). The dynamic features of the hydraulic turbine and the control mechanism of the regulating system in pico hydro impact power system stability during system disturbances like electrical failures, harmonic distortion, and overloaded circumstances. Figure 2.2 shows the basic concept of designing a pico hydro plant in this study using SIMULINK for analysis purposes.

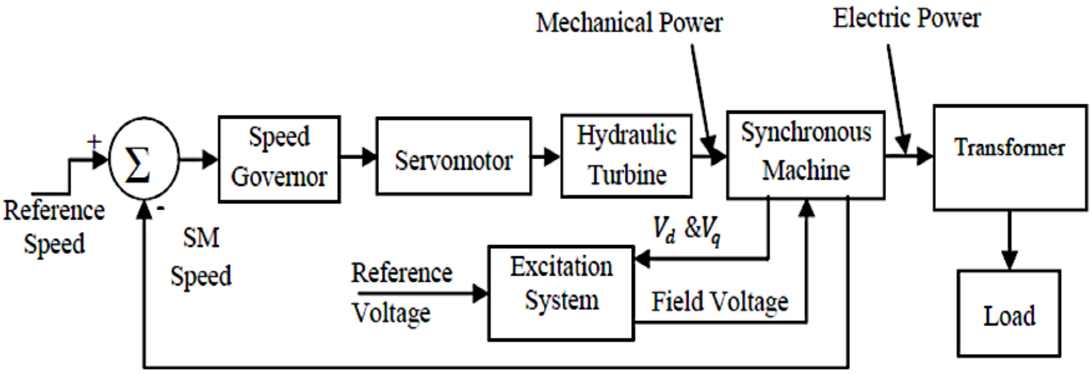


Figure 2.2 Basic Design Concept for Pico Hydro Plant in MATLAB Simulation software (Fortaleza *et al.*, 2018)

The PHP is modelled as a closed loop system and has governor speed control to ensure the system's stability. The generator speed is adjusted based on signals received from variations in system frequency and power along their preferred settings (Ellis, 2012; Lu *et al.*, 2021). This guarantees that generation at the generator is always at synchronous frequency. The mechanism of operation is based on the notion of a specific water flow rate from a specific height and the conversion of potential energy to kinetic energy. Hydropower then converts the potential energy into kinetic energy, which is then turned into mechanical energy as the turbine moves, and the moving turbine rotates the generator rotor attached to it which converts the mechanical energy into electrical energy. The suggested speed signal is created from the kinetic energy of the water flow via the penstock in this study. The signal is transmitted back to compare with the reference speed signal, this is known as the feedback loop. The PID controller acts as a speed governor by adjusting the speed deviation obtained by comparing the reference signal and synchronous generator speed as an input. PID is commonly installed and utilised as a turbine controller because of its high efficacy, stability, simplicity, and non-steady-state error. This PID controller generates the control signal, which controls the gate opening, which causes the turbine to generate torque, which is coupled to the generator, that generates electrical power. The speed controller reacts on the speed deviation from the generator caused by the turbine reaction (Kamble *et al.*, 2014; Safarzadeh *et al.*, 2011) (I. Salhi et al., 2010). The modelling governor, turbine and the AC generator is discussed in the subsequent subsections.

2.2.6 Hydro Turbine Governor (HTG)

In a hydropower plant, a turbine uses water flow as an input and contains a wheel or rotor that rotates as the water passes between its blades. The wheel's or rotor's speed increases as the water flow rate increases (Bošković *et al.*, 2020; Dhanalakshmi *et al.*, 2012). This rotation powers a shaft that is coupled with the generator, which produces electricity. Guide vanes or wicket gates normally govern the flow of water in the system, impacting the blades and, as a consequence, output power, which ultimately manages the turbine's performance. The kinetic energy of the following water is transferred to the buckets on the runner's periphery in the event of a high jet which, then rotate the shaft, converting it to mechanical energy (Gallego *et al.*, 2021; Kadier *et al.*, 2018; Okot, 2013). Subsequently, that rotation will produce electrical energy in the form of electricity. The power of a turbine is regulated by the location of the gates or nozzles, which govern the water flow into the turbine. The turbine governor, also known as the speed controlling system or turbine governing system, is responsible for this regulation. In general, there are two types of hydro turbines: reaction turbines and impulse turbines. Depending on the individual site characteristics, impulse and reaction turbines can be used to operate a hydroelectric system. Impulse turbines differ from reaction turbines such that they operate at greater heads and lower flow rates, whereas reaction turbines often require lower heads but higher flow rates to produce the same amount of energy (Chala *et al.*, 2019; Haidar *et al.*, 2012; Powell *et al.*, 2018).

Reaction turbine constructions are more suited to withstanding larger flow values, and as a result, they are more costly and complex to construct (Cobb *et al.*, 2013; Gallego *et al.*, 2021; Williamson *et al.*, 2014). There are two types of energy conversions in the response type turbine. The turbine is immersed in water, resulting in a pressure drop between the intake and outflow, which is transformed into axial power, also known as the reactive component. When water flows in between the turbine blades, it creates impulse forces owing to a difference in speed vectors. Francis, Bulb, and Kaplan turbines are the most often used response turbines, whereas Pelton turbines are the major impulse turbines employed nowadays. Classification of the three types of turbines is in use in industry is depicted by Table 2.1.

Table 2.1:Types of turbines (Breeze, 2018; Haidar *et al.*, 2012; Kadier *et al.*, 2018)

Types of turbines	Description
Kaplan	Low head, high flow plants
Pelton	High head, low to medium flow plants
Francis	Medium to high head, medium flow plants

2.2.7 Synchronous Generator

The alternating current (AC) system is primarily utilised for the generation, transmission, and distribution of electricity. A Synchronous Generator, often known as an Alternator, is a machine that transforms mechanical power into alternating current electrical power (Kamble *et al.*, 2014; Kougias *et al.*, 2019; Issam Salhi *et al.*, 2010). When the same machine is used as a motor, it is referred to as a synchronous motor. The mechanical power indicator determines the operation mode (positive for generator mode, negative for motor mode) (Geraldi Jr *et al.*, 2020; I Salhi *et al.*, 2010). The electrical part of the machine is a sixth-order state-space design and the mechanical part is the same as simultaneous machine block. Synchronous generators are prevalent in urban power generation because of their simple and robust construction, low maintenance, low cost, and ability to link to alternating current power sources. Aside from that, it is used in the pico hydro system since it can function at its operational voltage and maintain frequency in a remote location. Despite their output power level characteristics, both synchronous generators and induction motors are extensively employed for independent operation with a capacity of up to 10 MW.

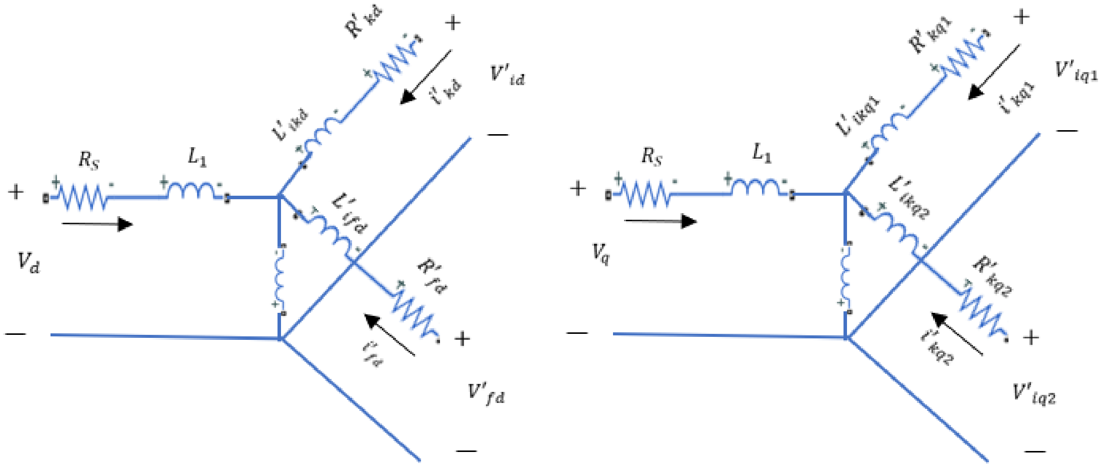
Rotational energy from the turbine is converted to electrical energy to produce electricity in the Pico hydro system, thus a generator is needed. A rotating magnetic field is generated by the generator rotor shaft coupled to the turbine inside the generator stator. Electromagnetic field induction converts the rotating magnetic field into current in the stator's coils. The selection of a synchronous generator for hydropower system is based on the expected power of a hydropower system, the kind of delivery system and electrical load, market available generating capacity, and cost-effectiveness (Kadier *et al.*, 2018). The most frequent sort of electric equipment utilised in a stand-alone power generation system is a synchronous generator. Due to the inherent complexities of excitation and voltage control, induction generators (asynchronous generators) have limited applicability. Permanent magnet synchronous generators (PMSG), self-excited generators, and auxiliary winding synchronous generators are all examples of this type of synchronous generator. Permanent magnet generators are used in some pico hydro systems because of their system's stability. Permanent magnet generators are among the most widely used equipment, some advantages of employing generators equipped with the PMSG excitation technique include the fact that the excitation field does not breakdown, enabling persistent short-circuit faults to clear, and that adjusting load has no effect on the excitation field (Onar *et al.*, 2015). The benefits and drawbacks of employing various types of generators are compared in Table 2.2.

Table 2.2: Different between induction generator and synchronous generator(Onar *et al.*, 2015)

Elements	Type of generator	
	Induction Generator	Synchronous Generator
Rotor construction	Uninsulated copper bars Relatively few conductors Firmly held in separate slots	Insulated wire or strap Many series turn Salient pole and round-type Many small connections

	Few connections Few basic parts	Many basic parts
Excitation	Requires separate excitation system No brush or collector rings	Attached DC exciter Brushed or brushless
Generated waveform	Tends to damp out harmonics Passive element	Tends to initiate harmonics in the system. Active elements
Costs	Lower first costs Low maintenance Lower efficiency Lagging power factor	Higher first costs Regular maintenance High efficiency Leading power factor possible

The dynamics of the stator, field, and damper windings were showed in this study. As demonstrated in Figure 2.2: A Synchronous Machine Electrical Model (Karnavas *et al.*, 2020) Axis quantity (*d* and *q*), Rotor and stator quantity (*R, s*), Leakage and magnetizing inductance (*l, m*), Field and damper winding quantity (*f, k*), the model's corresponding circuit is represented in the rotor reference frame (q/d frame). The stator includes all rotor characteristics and electrical values. All rotor characteristics and electrical quantities are identified by primary variables in the stator.



d axis q axis

Figure 2.3: A Synchronous Machine Electrical Model (Karnavas *et al.*, 2020) Axis quantity (*d* and *q*), Rotor and stator quantity (*R, s*), Leakage and magnetizing inductance (*l, m*), Field and damper winding quantity (*f, k*)

All the models in the SIMULINK block were derived using the equations and the parameters indicated in Figure 2.3: A Synchronous Machine Electrical Model (Karnavas *et al.*, 2020) Axis quantity (*d* and *q*), Rotor and stator quantity (*R, s*), Leakage and magnetizing inductance (*l, m*), Field and damper winding quantity (*f, k*). The squirrel cage induction generator will be represented using the Park method (Geraldi Jr *et al.*, 2020; Øyvang *et al.*, 2018) in a reference frame coupled to its stator, as shown in the equations.

$$V_{ds} = R_s I_s + \frac{\mathrm{d\varphi ds}}{dt} \tag{2.1}$$

$$V_{qs} = R_s I_{qs} + \frac{\mathrm{d\varphi qs}}{dt} \tag{2.2}$$

$$0 = R_r I_{dr}\ \mathrm{\omega r\varphi qr} + \frac{\mathrm{d\varphi qs}}{dt} \tag{2.3}$$

$$0 = R_r I_{qr} - \mathrm{\omega r\varphi qr} + \frac{\mathrm{d\varphi qr}}{dt} \tag{2.4}$$

Meanwhile,

$$\varphi ds = LsIds + Midr \tag{2.5}$$

$$\varphi qs = LsIqs + Miqr \tag{2.6}$$

$$\varphi dr = LrIdr + MIds \qquad (2.7)$$

$$\varphi dr = LrIds + MIqs \qquad (2.8)$$

The Rs and Rr are the single-phase winding resistance. Thus, Vds, Vqs is stator voltages, there are no rotor voltage components because the rotor is short-circuited. Meanwhile *Ids, Iqs, Idr and Iqr* are the current, while magnetic flux refer to $\varphi ds, \varphi qs, \varphi dr$ and φqr. Hence the total stator and rotor inductances was indicated with Ls and Lr, and M are the magnetized inductance respectively.

2.2.8 Fuzzy Logic Controller

Mamdani's System and the Takagi Sugeno technique are two significant techniques for regulating methods in fuzzy control (De Santis *et al.*, 2017; Sahoo *et al.*, 2018; Issam Salhi *et al.*, 2010; D. Wu *et al.*, 2005). Experts agree that Mamdani's system approach for obtaining knowledge and understanding of the system. It is used to describe skill in a more humanistic manner (Adhikary *et al.*, 2013; Shome *et al.*, 2012). A large amount of computing work is required for Mamdani's type of Fuzzy Inference System (FIS). Takagi-Sugeno is the other technique, which is computationally efficient and works well with optimization and adaptive methods, making it appealing in control concerns, particularly for non-linear behavioural systems. These adaptive techniques can be utilized to personalize the membership function so that the fuzzy system fit with the information. The distinction between Mamdani's and Sugeno's FIS methods is that Mamdani's technique uses crisp output derived from fuzzy inputs. Sugeno-type FIS uses a weighted average to determine the crisp output, whereas Mamdani's-type FIS uses a defuzzification approach. The Sugeno FIS loses the expressive power and interpretability of Mamdani's output because the guidelines' consequences are not fuzzy (Safarzadeh *et al.*, 2011). Sugeno, on the other hand, has a substantially faster processing time since the weighted average modifies the time-consuming defuzzification procedure. When compared to Sugeno FIS, Mamdani's FIS is less adaptable in terms of system style, since Mamdani's technique may be combined with the ANFIS tool for enhancing outcomes (Dhanalakshmi *et al.*, 2012). Mamdani's approach is used in this study to come up with membership rules for fuzzy logic control on the hydro turbine governor.

2.3 Pico Hydro Power Plant

Hydropower is the only RES which is feasible for constant and stable high capacity power generation, as discussed earlier (Awang *et al.*, 2021; Gallego *et al.*, 2021; Kadier *et al.*, 2018; Nfah *et al.*, 2009). Hydropower supplies 17 % of the world's electrical power demands (Killingtveit, 2020). Small-scale hydropower is cost-effective and most dependable energy system available for generating clean electricity. For numerous centuries, mini-hydro systems have been in use to run milling stones to grind cereals. The pico hydropower system utilizes the running water flow to rotate the wind turbine and drive the generator. Furthermore, mini hydropower systems are referred to as "run of the river" systems since they do not require huge dams or water storage reservoirs. The carbon footprint is decreased, as less than half of the river's water is required to drive the powerhouse. The carbon footprint is even smaller for PHP as its capacity is only up to 5 kW (Awang *et al.*, 2021; Rotilio *et al.*, 2017). The classification of hydropower plants is illustrated in Table 2.3.

Table 2.3: Hydroelectric Power Plant classification (Awang *et al.*, 2021; Breeze, 2018; Williams *et al.*, 2009)

Hydro Capacity	Power Output Capacity	Systems Classification
Large	> 100MW	Typically, they are connected to a big energy grid.
Medium	15 MW - 100 MW	Feeding into a power grid
Small	1 MW - 15 MW	Feeding into a power grid
Mini	100 kW - 1 MW	Stand-alone or, more frequently, grid-connected systems
Micro	5 kW - 100 kW	In distant places away from the grid, providing electricity for a small town or rural business
Pico	100 W - 5 kW	-

The compact size and capacity of PHP makes it an optimum solution to supply constant reliable electrical power to off-grid rural areas (Haidar *et al.*, 2012; Williams *et al.*, 2009). PHPs can also be configured as mini grids, to supply small towns and industries. PHPs can also be configured as grid connected distributed generators, especially when net metering is available. These diverse configurations are possible because PHPs can be built on minor canals, streams, and river branches, as it does not require water storage or a large reservoir. The efficiency of PHPs is directly proportional to the water flowing through it, the stable the water flow the greater the efficiency. The operation concept, power generations equipment, geometrical modelling, and system design are the same as in a hydroelectric plant (Gallego *et al.*, 2021; Valsan *et al.*, 2017). The power generated is proportional to the water pressure head and water volume flow rate of the turbine as depicted by equation 2.1.

$$P = n.\rho.g.Q.H \tag{2.1}$$

where, P is the power (W) produced by the system, n was a plant efficiency (%), ρ is a water density (Kg/m^3), g is the acceleration gravity (9.81 ms^{-2}), Q is water flow rate (m^3/s), and H is water head hight (m).

Maintaining the stand-alone pico power system in a stable state requires an efficient energy management scheme (Panda *et al.*, 2021; Tan *et al.*, 2021; Valsan *et al.*, 2017). Conventionally efficient energy management schemes consist of efficient energy storage systems as they are dependable and cost-effective, making them essential for maintaining consistency of output performance. An efficient energy management scheme also consists of a precise control system. The objective of a control system in a stand-alone pico power plant is to determine the active and inactive power resource and at the same time prevent voltage and frequency fluctuation during the intake process of the power supply from hydro turbine generation. This ensures uninterrupted power supply to consumers. Therefore, the quality of electrical power generated is affected if these requirements are not monitored. The control of PHP is primarily based on generator control. Adjusting the generator's excitation regulates the voltage while controlling the generator's speed will regulate the frequency. Therefore, the ideal solution is making use of an Automatic Voltage Regulator (AVR) to control and manage the terminal voltage of the generator by spontaneously regulating the field current or excitation current within its threshold value despite varying load conditions on the generator (Chapman, 2004). Therefore, this study is also focused on addressing the limitations of control of PHP.

2.4 Control Strategies for Pico Hydro System

Control systems are classified into open loop systems and close loop systems (Sonawat *et al.*, 2020). The difference between both systems is feedback, open looped systems do not have feedback whereas the closed loop systems have feedback. According to Ogata (Ogata, 2001), the controlled variables may relate to the conditions that must be specified and assessed in a system. The control signal also termed as the controlled variable is any factor that has been held steady by the system during the process that impacts the output whilst regulating other variables (Hidy *et al.*, 1994; Kougias *et al.*, 2019; Sultan *et al.*, 2018). According to control system theory consists of several elements which are plant, process, system, disruption and feedback control. The definitions of these elements are as follows

Plant : A plant might be a tool, possibly just referring to a set of device parts that operate together, to carry out a specific operation

Process : A process is defined as an artificial or voluntary, progressively ongoing operation that consists of a sequence of various regulated motions or movements that are methodically directed towards a given goal or result

Systems : A system is a combination of elements that work together to accomplish a determined research goal. Dynamic phenomena can be abstracted using the idea of a specific system

Disruptions : Disruption is a signal that has a detrimental influence on a system's output. In terms of disruption, it may be characterised as either internal or external.

Feedback Control : Feedback control is an operation that reduces the gap between a system's output and the reference input depending on the difference in the presence of disturbances.

System responses are classified into transient and steady state response. The steady state response refers to the response of control system under stable operating conditions, whereas transient response refers to the response of control system under unstable and transient operating conditions. Transients are short lived events which lasts for only seconds, whereas steady-state error is a response that is relatively long lived (Quaranta *et al.*, 2020; Sonawat *et al.*, 2020). If the system is not controlled, it may not be stable and may cause a steady-state error or oscillate indefinitely. A typical output response in terms of overshoot and steady-state error is depicted in Figure 2.2

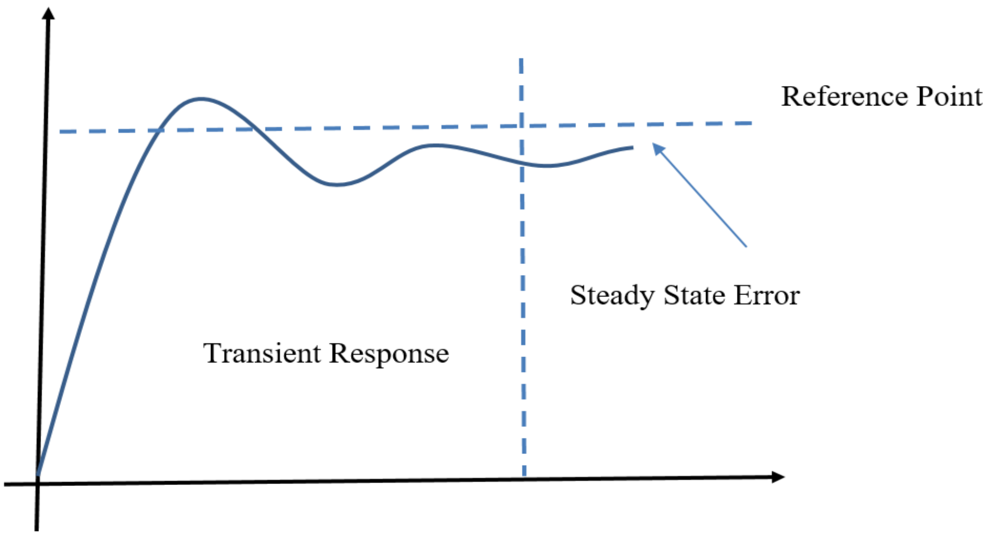


Figure 2.4: Fundamental of Step Response of a system (Boroujeni *et al.*, 2011)

The objective of control system application is to decrease the inaccuracy and discrepancy between a given signal and the actual system feedback response. The step response is used to evaluate the performance of the system. The step response is described using parameters like Maximum Overshoot (M_p), Peak Time (t_p), Settling Time (t_s), Rise Time (t_r), and Delay Time (t_d). These characteristics can be calculated theoretically or empirically via software simulation. Figure 2.4depicts the M_p, t_p, t_s, t_r, and td parameters for a particular step response. When compared to other system responses, these characteristics explain the behaviour of the system reaction and give measurable data. Each parameter has described in detail below

Maximum Overshoot (M_p)	:	Peak overshoot (M_p) is the highest divergence from the steady-state value of the output. M_p is often defined as the difference between the initial shot value and the overshoot value multiplied by 100 percent
Peak Time (t_p)	:	Peak time, is the amount of time necessary to attain the first, or maximum, peak
Settling time (t_s)	:	Settling time is necessary for the damped oscillations of the transient to reach and stay within 2% of the steady-state value

Rise Time (t_r) : Rise time is necessary for the waveform to progress from 0.1 to 0.9 of its steady-state values

Delay Time (t_d) : The time it takes for a response to reach 50% of its steady-state value is known as delay time

The controller, plant, and disturbances are all part of an open-loop control system. The controller directs the plant to a determined output called the controlled variable for a specified reference point or input (s). Each internal or external disturbance contributes to the controller and plant, which are added by the sum of their inputs. The open loop control system is unable to adjust contributory disruptions (Kayastha *et al.*, 2020; Kougias *et al.*, 2019; Quaranta *et al.*, 2020). On the other hand, closed-loop control is always consisting of feedback which enables the system to adjust to disruptions. Closed-loop control behaves similarly to an open-loop system when given a point of reference or an input. The sole difference between a closed-loop and an open-loop system is that a closed-loop may modify internal/external disturbances depending on the system's signal. The controlled variable(s) may cause a relative error, which is the difference between the reference and normal signals; hence, the controlled variable is significant to maintain stability. The controller uses a desired algorithmic programme to analyse the error and reduce the error to accomplish the control objective. In this study two different types closed loop controllers are taken into consideration. The controllers under consideration are PID controller and FUZZY controller with the objective of frequency control.

2.4.1 PID Controller

The load in the power system changes constantly and arbitrarily due to the various electrical power demands, resulting in an imbalance between the power generated and consumed. This action causes the frequency to fluctuate from time to time, requiring efficient frequency management controls (Khodabakhshian *et al.*, 2010; Mosaad *et al.*, 2019). These changes are transient events. Transient response and steady-state error are the elements that contribute to the discrepancy between the inputs and the outputs of a control system. It is imperative to control these two factors to have a stable system in terms of output responsiveness. There's a chance that steady-state error won't work in each scenario because the system is unstable or oscillates. PID controller efficiently controls the system under such scenarios (Khodabakhshian *et al.*, 2010; Mosaad *et al.*, 2019).

The PID controller consists of proportional, integral and derivate control options. The PID controllers are widely used in industries due to its simple design and efficient performance with low percentage of overshoot and low settling time for slow process plants. Approximately 95% of PID's are used by controllers in industrial process control applications such as motor drives, automotive, and flight control. An effective output response should have advanced control methods of a controller and be applied to the system between the process and the reference point to determine the required input level. Various methods for regulating the speed of a DC motor are now readily accessible in most industrial applications where the speed of a DC motor must vary within a specified range and limitations (Bošković *et al.*, 2020; Daou *et al.*, 2011; Khodabakhshian *et al.*, 2010; Margonis, 2017).

The characteristics of the different operating points of a non-linear plant would change over time. Tuning is a process for a particular operating point. The system works at various operating variables, it essential for the system to return to its stable state after disturbance which not possible without proper tunning of the controller. Tunning is also essential in scenarios when a process parameter changes with time or speed. Therefore, it is imperative to use an advanced control strategy, to keep the system stable (De Santis *et al.*, 2017; Ofosu *et al.*, 2019). The settings of the PID are carefully tuned using a variety of tuning methods The controller is capable of regulating factors in the process and keep refining it to reduce error or achieve zero error. The PID constant should be chosen so that the response has a rapid rising time, low overshoot, and a quick settling time. The process of settling these parameters is also called tuning.

Conventionally, PID settings adjustment was performed through experimentation, step response, and analytical methods. Tuning using the step response occasionally results in oscillatory feedback and improved output performance in terms of frequency responsiveness. Conventional PID controllers have been widely used in the industry, because of their simplicity, low cost and efficient performance for linear systems (Rajesh *et al.*, 2019; Sahoo *et al.*, 2018). Traditional PID controllers are not ideal for higher-order, time-delay, nonlinear, and complicated systems without precise mathematical models, as well as systems with uncertainties. Fuzzy logic PID controller performs better than conventional controllers for control strategies in hydro power systems as the element of intelligence is added to it. The Ziegler-Nichols approach is used to adjust PID controllers. In the Ziegler-Nichols tuning approach, the K_i and K_d benefits are primarily set to zero. The K_p gain is then increased from zero to a predetermined value at which persistent oscillations occur. In that instance, Ki is raised until any offset is fixed. The loop is sufficiently quick to return to its reference following a load disturbance, K_d is highly dominated (Ismail *et al.*, 2012) (Ismail et al., 2012). There are two techniques to determine gains in the Ziegler-Nichols method. The first technique involves an open-loop step response of a plant, whereas the second way employs the findings of trials carried out with the controller installed. The PID function is comprised of the following components:

$$G(s) = K_p + K_I + sK_D \qquad 2.9$$

PID control can also be of the form

$$G(s) = K_p.1 + \frac{1}{T_{Is}} + T_{Ds} \qquad 2.10$$

Where,

$K_I = \frac{K_p}{T_1}$ and $K_D = K_p T_D$

T_1 is the reset time, whereas T_D denotes the derivative time.

The Ziegler-Nichols approach demands that all control actions be disabled except for the proportional gain and that the proportional gain K_p, which is set to a low value. The value of K_p is then increased until the output exhibits persistent oscillations. This period of oscillations is known as the ultimate period, and is denoted by the symbol P_u. The proportional gain that produced the oscillation is denoted as $KP_{u,}$ also referred to as the greatest gain. According to Ellis *et al.* (Ellis, 2012) the period of oscillation utilised to calculate the modification of the rest rate T_I (which was discovered to be half of the ultimate period) has a direct impact on a wide range of control applications. At the final gain, the derivative time T_D should be around 1/8 of the period of a small-amplitude oscillation. The challenges of employing PID controllers include that they require regular tuning and are inefficient for highly nonlinear devices, producing a disruption to the loads and system.

PID controllers can regulate four different forms of electronic control for hydro turbines: P, PI, PD, and PID. Loucif *et al.* (Loucif, 2005) conducted simulation and hardware data for regulating voltage for a DC motor using a PID controller. The simulation demonstrated that hardware analysis for open loop and closed loop systems was carried out effectively. From the simulation, it was evident that the measured voltage was close to the reference voltage with a minimum error. Further investigation was carried out to check the controller under the comparison of voltage determined (output voltage) at the DC motor and the reference voltage (target voltage). The results show that closed loop systems performed better than open loop systems. However, it’s only suitable for linear systems, and once it's implemented on a non-linear system such as pico hydro, the uncertainty will affect the output response. Traditional PID controllers provide substantial implementation issues since they are not fit for nonlinear, complicated, time-delayed, unpredictable, and high-order systems. It also has delayed control performance and inefficient control, such as excessive overshoots and extended settling periods. Numerous new intelligent smart control techniques, including as fuzzy reasoning, artificial neural networks, Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Ant Colony Algorithm (ACA), and Bacteria Foraging Algorithm (BFA), have been suggested in the literature to modify PID specifications to address the shortcomings of ordinary PID controllers.

Zero Crossing Technique (Mažeika *et al.*, 2010) was demonstrated and proven to be an efficient approach for appropriately switching on and off fake loads in a digital load controller. One of the most important components of pico and micro hydropower systems is the digital load controller, which ensures that users receive reliable and high-quality energy. The amplitude and frequency of the output voltage are kept constant by maintaining the power load demand equal to the power generation; this is achieved by turning on and off many dummy loads with digital switches. These loads are switched on and off at random time intervals in the current condition, resulting in harmonics, noise, and transients in sinusoidal current and voltage. Rapid load variations result in significant energy loss and damage to electrical equipment connected to the system. Thus, the zero-crossing approach is used in this study to improve the quality of the power provided by MATLAB/Simulink and Proteus. The results show that zero-crossing switching produces a smooth sinusoidal waveform, whereas, random switching produces a distorted waveform. The zero-crossing approach, eliminates power losses during switching, avoids damage to electronic spikes, parts, transients, and harmonics. However, these control techniques cause a huge amount of energy wasted due to their dummy load’s installation.

(Mohamed Raged *et al*., 2020) presented an application of a PID controller scheme to regulate the frequency deviation in hybrid power system consists of wind turbine generator, PV, diesel engine generator, battery energy storage which are considered the most promising and sustainable configuration used in the kind of hybrid energy system.

Ozbay and Gencoglu *et al.* (Özbay *et al.*, 2010) proposed a novel technique for frequency management of a small hydro plant based on adaptive fuzzy control. They compared linear and nonlinear turbine designs while ignoring surge tank effects and the inelastic water column. In a small hydropower plant (SHPP), a fuzzy controller is employed as a governor to manage the wicket gate position through a servo motor based on the consumer load demand. The designs were created using the MATLAB/SIMULINK software tool, and the implementation employs a fuzzy inference method. The results of simulations reveal that it responds to load changes in the same way under both action and ramp input signals. However, due to the hydraulic hammer and water inertia effects on the servo motor, the stabilisation time was lengthened.

2.4.2 FUZZY Controller

Conventional control techniques are not the best approach to fix the complicated technical problems in nonlinear systems, especially those involving hydro turbine technology. Neural networks and fuzzy logic control have become one of the most active research areas. Zadeh (1965) introduced the idea of fuzzy logic, which is designed to behave the same way humans think. The introduced logic is a way of processing information and data in engineering that allows partial set membership rather than crisp set membership or non-membership by offering degrees of confidence to the solution to a logical query. fuzzy logic considers issues to be of varying degrees of "truth", in contrast to classical logic, which is built on binary sets of "true or false,". Fuzzy logic can be implemented securely and provides a simple way to acquire a certain result and can handle imprecise, noise-free data. Fuzzy logic's output is more consistent and smoother in terms of control across a wide range of input data

Considerable research has been conducted pertaining to utilization of neural networks and fuzzy logic to solve water level management problems. The fuzzy logic control approach is most suited and prominent in this application due of its simplexes. Fuzzy logic, often known as many-valued logic, is a sort of probabilistic reasoning that deals with complex thinking rather than just tuning. Unlike typical binary sets, where variables accept either 0 or 1, indicating true or false, fuzzy logic variables contain a range of values ranging from 1 to 0. Their value might range from totally true to totally false. Hence, fuzzy logic the optimum method for handling nonlinear behaviour of a system. Fuzzy logic could be considered an expert system or artificial intelligence system that analyses a human's actions. The computer can only analyse genuine or wrong values in application systems however a human reasoning can comprehend a range of true or false interpretations of human activities, which is why they are also known as intelligent control systems. Recent works pertaining to control of pico, small, and micro hydropower plants are described below and their comparison is illustrated in Table 2.2.

(Park et al., 1997) studied a self-organizing fuzzy logic controller for steam generator water level management. The proposed controller controlled the system efficiently without any initial control rules. Initial control rules are essential for conventional controllers, whereas the proposed controller creates its own rules and also tunes the membership function itself. The controllers use gradient descent method to update selected tuning parameters. The proposed controller was developed on an assumption that fuzzy relation can give the flow mismatch.

(Masters *et al.*, 2004) investigated servo motor position control with valves to achieve automated generation control. The suggested fuzzy controller chose the appropriate PI gain and settings for the plant's operation. In this system, the position of the gate control is the input to be measured. Based on the frequency and power requirement from the load demand, the controller regulates the position of the servomotor to shut or open gate openings. This is controller is generally used in standalone, small hydropower systems. However, this method is expensive and complex when applied on standalone pico hydro systems.

Wu *et al.* 2005 created a model of a water level control system using fuzzy logic and neural network control algorithms. They then implemented the twelve control algorithms into a standalone Digital Signal Processing (DSP) based microcontroller and evaluated their efficiency. Results show that both fuzzy logic and the neural network efficiently control the system and exhibit improved tracking performance and disturbance rejection. However, neural network performed better in regard to tracking and disturbance rejection.

Galzina *et al.* 2008 presented an application of fuzzy logic for boiler drum water level management and combustion quality assurance. A direct approach bypassing the conventional control system was adopted to design the fuzzy controller. Operator expertise and relative rule criteria for existing boiler space were used to create fuzzy control guidelines. By expanding the membership function to an interval type-2 membership function without increasing the system's complexity. The disadvantage of this approach is that it is application-specific and cannot be implemented on similar systems.

Mudi *et al.* 2008 investigated the possibility of improving PI-type fuzzy controllers by employing a distinct fuzzy type controller that uses the exact input as the main fuzzy to control the previous output set based on the current output. A simple mathematical formula was used to generate a new output that differed from the prior one, using input from the second controller and previous output. The control technique during the controller's output phase is a essential aspect of assessing the system's efficiency. However, owing to the intricacy of the fuzzy rule, it should be carefully developed because there is no systematic method for presenting the fuzzy rules.

Upadhayay *et al.* 2009 conducted research on the load control mode for micro hydro power plant (MHPP). In this study, a ballast load is added to ensure that the overall load connected to the synchronous generator remains constant, and the system's frequency is maintained. This method is simple, low-cost, and easy to implement. This method, however, causes harmonic distortion in the electrical system due to the presence of electronic switches. The presence of this harmonic distortion results in damage to the electrical equipment connected to the system. Significant energy is dissipated on the ballast load during the minimum demand of load by consumers, which could be utilised by other consumers during daytimes when there is peak demand.

Salhi *et al.* 2010 proposed an automated generation control (AGC) to manage the frequency of MHPP using traditional governors such as mechanical-hydraulic and electronic governors. Mechanical hydraulic governors are often employed as frequency regulators in mega hydropower plants. These sorts of installations are costly and require a significant amount of maintenance. Electro-hydraulic governors are considerably more difficult to execute because of its complexity and necessity for an exact and precise design. Flow control is conventionally not conducted using mechanical governors. A complex arrangement of guide flow control vanes, standard intake valves, and jet deflectors is required to efficiently operate mechanical governors. As a result of their complexity and cost, all the conventional governing systems described above are unsuitable for implementation. They are not preferred by industry due to high cost, and their incompatibility to control frequency of independent pico hydro systems. The authors developed a fuzzy logic-based controller and a fuzzy supervisor. The controller is designed to control frequency of the system and the supervisor controls the energy produced. Results show that the proposed controllers efficiently control the system frequency and manage the availability of water with changes in consumer demand.

A Mamdani and Takagi-Sugeno fuzzy inference system to implement a fuzzy logic controller with tuning on PI parameters for load frequency management of the MHPP (Issam Salhi *et al.*, 2010). Two fuzzy sets are carried out in this research to achieve better performance. The first control focused on minimising the waste of water by controlling the gate position through a servomotor. In this case, water flow was governed by a fuzzy controller. Another set of fuzzy control regulated electrical load by dumping excess power into the damper load. The results proved that the proposed method was feasible to control load and frequency. It was also evident from the results that the controller performs better than the existing controllers. The method ensured that the system's closed-loop stability is maintained under all operational situations.

Boroujeni *et al.* 2011 found that using a genetically scaled fuzzy logic controller can increase the effectiveness of a load frequency regulation in a multi-area electrical power system. The upper and lower limits of the fuzzy membership functions are obtained via GA in this novel control technique. To demonstrate the effectiveness of the suggested technology, a standard PI type controller was created and compared to the recommended genetic scaled fuzzy logic controller. The simulation resulted in programmes that indicate that the genetic fuzzy control methodology significantly improved the standard PI controller method in terms of settling time, percentage overshoot and rising time.

Zhao *et al.* 2012 created a unique period type-2 fuzzy control system. The control system can effectively decrease the uncertain disruptions from a real-site environment. The proposed controller overcomes the limitation of the conventional fuzzy controller such as high static error which exists because of low immunity. Traditional membership functions were extended to type-2 membership functions, to deal with the stochastic disturbance incurred by the physical parameters of the system. This extension of the membership function decreases complexity that exists in the traditional system. The proposed controller was tested on twin-tank water level system. The results exhibited that the proposed controller improved the static and dynamic control of test system compared to the traditional fuzzy control method.

Shome *et al.* 2012 proposed an intelligent controller with fuzzy logic control to deal with the non-linearities of boiler steam temperature and water level for accurate control. The proposed controller was implemented with fuzzy inference system. Two separate controllers each based on fuzzy inference system are implemented. One controller is implemented to control the temperature of the boiler and the second to control the water level of the boiler. Each inference system fuzzifiers the inputs after which the concerning rules are applied to them and then calculates the defuzzified value. The proposed controller efficiently controls the temperature and water of the boiler.

Adhikary *et al.* (Adhikary *et al.*, 2013) proposed a novel, user-friendly controller-based fuzzy reasoning method for Pico Hydro Power Plant (PHPP) using a synchronous generator. Despite varying load demands throughout the day, the controller maintained a steady and consistent frequency, output power, and system voltage. The controller also controlled water flow by opening and shutting gates controlled by servomotors. The study demonstrated the efficacy of fuzzy logic in terms of time adjustment and overshoot parameters. Both variables decreased considerably. However, the proposed methodology can be expanded to build a more efficient control by using different language factors.

Kamble *et al. (Kamble et al., 2014)* proposed a novel control strategy based on the combination of a fuzzy controller and a fuzzy supervisor to assure a efficient output response in terms of effectiveness in the frequency management of the MHPP. The proposed controller was designed to provide an overall control of the MHPP. It has three specific controllers; first controller maintains system frequency under load variations. Second controller reduces water waste through flow rate control by reducing the power dump on the damper load. Third controller manages the power distribution among several mini distribution networks. Results, illustrate that the proposed control scheme efficiently controls the frequency, waste water and load distribution of the system in different test scenarios.

Goyal *et al.* (Goyal *et al.*, 2014) developed a flow control approach for hydro turbine speed control. The spear valve was used to regulate the rotating motion by altering the power. A flow control-based architecture was proposed for the automated operation of small hydropower plants. In this research, a servo motor was used to control the spear valve and trigger a "constant" control of the water flow rate. The implementation and suitability of servomotors for the control of small hydro power plants are discussed, and conventional PI controllers are utilised to improve their governing ability. The suggested design is mathematically designed using state area representation. Additional simulations are run to examine the various behaviours of the proposed design. Criterion optimization is carried out by utilising artificial neural networks.

A technique to optimize the fuzzy aided controller design employing improved grey wolf (IGWO) optimization algorithm was proposed in (Sahoo *et al.*, 2018). The proposed technique was designed to control the frequency of power system. IGWO is used to optimize the PID controller gains. IGWO also optimizes the hybrid fuzzy PD and PID parameters related to fuzzy. The proposed frequency controller algorithm is tested on two area six-unit test system, each of which has different primary energy source and a three-area non-linear system. Results are compared with existing artificial intelligence techniques such as grey wolf optimization (GWO), gravitation al search algorithm (GSA) and particle swarm optimization (PSO) etc. and illustrate the superiority of the proposed technique over them. Furthermore, the proposed technique is efficiently controlling the frequency of the aforementioned test systems under load disturbances with uncertainties.

Hammid *et al.* (Hammid *et al.*, 2018) proposed a fuzzy control method for water intake of a small hydropower plant. ANN is used to decompose the input variables of net head and flow rate. Right angle triangle membership functions were used in this study to decrease the complexity of tuning membership functions. Mamdani type model was used in the fuzzy inference system. The proposed controller was tested by various random input variables to simulate the uncertainty of the water intake. Results show that the proposed controller efficiently maintains water flow under varying conditions.

A fuzzy PI controller based electronic load controller (ELC) is proposed (Ofosu *et al.*, 2019). Membership functions of the fuzzy logic controller are optimized using Bacterial Foraging Algorithm (BFA). The controller was designed to maintain the frequency of the system under the specified ranges. The proposed controlled sheds the excess load to the damper load when system load variations affect the system frequency. The proposed controller is also cost effective as it is microcontroller based. The performance of the proposed ELC was tested under various test conditions and results indicate that it was able to efficiently maintain the system's frequency.

Hamdaouy *et al.* (El Hamdaouy *et al.*, 2020) proposed a novel controller, management and security system (CMSS) to manage the overall operation of PHPP. The CMSS was designed with objective of developing a cost-effective comprehensive control system for standalone PHPPs. The proposed comprehensive system can be implemented to achieve various control requirements for example frequency and load control, system start up and emergency stop. The CMSS is built using microcontrollers sensors and PI control scheme. The proposed CMSS was tested under diverse set of scenarios with varying conditions to prove its robustness. Results show that the CMSS efficiently controls the frequency of the system under load variations of the system and protects the PHPP against electrical and mechanical faults making it more reliable.

A fuzzy inference system (FIS) integrated with traditional PID was implemented to control the water level intake of run of river hydro power plants was presented in (Saeed *et al.*, 2020). A novel three-pond model was proposed for storage of water. The proposed control scheme was tested with sinusoidal and flash flood disturbance scenarios. Results prove the robustness of the proposed control scheme as the water level in all three ponds was maintained during every disturbance compared to single pond model.

A fuzzy logic control based controller designed based on Mamdani's method is proposed in (Kang *et al.*, 2021). The authors implemented fuzzy logic controller to control the charging process of battery energy storage system (BESS) integrated with Pico hydro system. The traditional electronic load controllers waste energy and dump extra load to maintain frequency when load demand increases. Therefore, in this study the authors integrated a BESS with the pico hydro system and its charging was controlled with fuzz logic controller designed on

Mamdani method containing twenty five membership functions. The objective of the controller was to efficiently use the excess energy available during low load demand hours and charge the BESS and then utilize the storage energy in high load demand hours. The model was implemented on SIMULINK and results depicted that the proposed scheme efficiently manages the operation of Pico hydro system.

Butchers *et al.* (Butchers *et al.*, 2021) has developed a simple, less expensive, and quick-response fuzzy logic-based frequency control system. The frequency controller maintained the water flow rate by manipulating electrical valves and kept the micro hydropower system's frequency practically constant. However, in this study, no execution was carried out. According to the simulation findings, the output response of overshoot for a 35% load shift is roughly 0.9 %, and the settling time is 26.85 seconds. Meanwhile, at 75% load change, overshoot is around 3.04%, and the settling time is 27.65 seconds. With steady-state conditions, it was also revealed that the energy dissipated on the valve is always near zero. It is also evident that the total cost is inexpensive, about 10–20 USD per kilowatt, compared to ELC, which costs 70–120 USD per kilowatt. A fuzzy controller, which functions successfully under all operating situations, has often been used to improve short-term and steady-state efficiency. The controller plays an essential role in low-cost micro-hydropower plant development in rural areas.

Asoh *et al.* (Asoh *et al.*, 2022) presented an artificial intelligence based frequency and load control scheme of small hydropower plants (SHPs). The controller utilizes fuzzy logic and is capable of handling the non-linear nature of SHPs. Furthermore, with objective of reducing cost of the controller, a novel one-input fuzzy logic control was proposed. The linear and non-linear plant models were simulated in SIMULINK. The proposed controller was tested under various scenarios and the results were compared with a conventional PI/PID controller. Results illustrate that both overshoot and settling time decreases significantly. Moreover, it was also evident from the results that the efficient load frequency control also increases the dynamic stability of SHPs.

There are numerous models which have been used to describe various components of the power system. Differential mathematical equations efficiently model the dynamic behaviour & non-linearities of the pico hydro system (Valsan *et al.*, 2017). A transfer function is used to model and simulate each component, and they are all connected to represent the system under study. The state-space model is utilised for system investigations in a large system and is described using linear differential equations. Meanwhile, nonlinear differential formulae are used in a short-term stability research investigation. Nonlinear models are more useful for wide domain signal time simulations of turbines, but linear models are better customary for small system performance of turbines (Safarzadeh *et al.*, 2011). Furthermore, non-linear mathematical modelling is chosen for the construction of the SIMULINK block due to the load varying from time to time, system repair and breakdown, and so on.

Table 2.4: Comparison of recent works pertaining to control of pico, micro and small hydropower plant

Ref	Controller scheme	Parameters and system to be controlled	Advantages	Limitations
(Park *et al.*, 1997)	Self-organizing fuzzy controller	Water level control Nuclear steam generator level control	Does not require initial control rules Updates selected parameter itself	Developed on an assumption that fuzzy relation can give the flow mismatch
(D. Wu *et al.*, 2005)	Sugeno fuzzy & reference adaptive neural network control	Water level control system	Improved control of water flow Neural network does not require training	Membership functions are determined heuristically or by trial and error
(Galzina *et al.*, 2008)	Fuzzy logic control	Boiler drum water management	Operator expertise used to create fuzzy control guidelines Boiler drum water is efficiently managed	The designed control is application specific as fuzzy control rules are specific
(Mudi *et al.*, 2008)	Ziegler–Nichols tuned PI controllers	High order linear and non-linear dead-time processes	Fuzzy logic based controller which is capable of auto-tuning its parameters	Empirical values of k1 and k2 parameters were used, which should have been attained through appropriate algorithm The algorithm was not tested on power system models
(Upadhayay, 2009)	Ballast load control	Micro hydro power plant	Efficient load control of micro hydro power plant	Ballast technique introduces harmonics in the system
(Issam Salhi *et al.*, 2010)	Mamdani and Takagi-Sugeno fuzzy inference system implemented with fuzzy logic controller	Frequency and load management of laboratory prototype of micro hydro system	The controllers guarantee quality of the electrical power system whilst making it cost-effective	The controllers do not manage the waste water in form of dissipated power

Ref	Controller scheme	Parameters and system to be controlled	Advantages	Limitations
(I Salhi *et al.*, 2010)	Fuzzy logic controller	Frequency and load control of Micro hydro power plant	Efficient control of system frequency under load variations Minimization of waste water through limitation of dissipated power	The system's performance was compared with conventional controller. It should have been compared with other intelligent methods
(Özbay *et al.*, 2010)	Self tuning fuzzy PI controller	Load frequency control of small hydro power plant	The controller updates its tuning parameters itself with the integration of fuzzy logic	The linear turbine model was taken into consideration and the inelastic column was assumed
(Boroujeni *et al.*, 2011)	Scaled fuzzy controller Genetic Algorithm	Load frequency control of multi area power system	The genetic fuzzy control methodology efficiently controls the system's load and frequency under disturbances	The system's performance was compared with conventional PI controller, rather it should have been compared with other intelligent methods
(Zhao *et al.*, 2012)	Type 2 fuzzy controller	Twin-tank water level system	Robust control of water level of tank	Real time control was not implemented Closed loop stability was not studied
(Shome *et al.*, 2012)	Fuzzy inference system (FIS) logic controller	Temperature and water level control of boiler	Efficiently controlled the temperature and water level of the boiler under-consideration	The controllers were tested on a laboratory based boiler. The industrial boilers are more complex and non-linear
(Dhanalakshmi *et al.*, 2012)	Adaptive Neuro-Fuzzy inference System (ANFIS)	Load frequency regulation of an isolated wind-micro hydro diesel hybrid power system	The ANFIS inference system optimized the settings of the fuzzy logic and improved the system efficiency to manage the frequency deviation and power difference	The system's performance was compared with conventional PI controller, rather it should have been compared with other intelligent methods
(Adhikary *et al.*, 2013)	User friendly fuzzy based reasoning method	Frequency, voltage and power of Pico Hydropower plant Control of water intake of hydro turbine	Efficient control of pico hydropower plant was achieved with low values of time adjustment and overshoot parameters	Inclusion of different language factors can improve the system's efficiency

Ref	Controller scheme	Parameters and system to be controlled	Advantages	Limitations
(Kamble *et al.*, 2014)	Fuzzy logic controller	Frequency regulation, water waste limitation and power distribution management of micro hydro power plant	Efficient control of system's frequency, waste water and load distribution under different test scenarios	The system's performance was not compared existing fuzzy controllers
(Goyal *et al.*, 2014)	Artificial neural network (ANN) with PID controller	flow control of turbine of hydro power plant	ANN auto tunes the parameters of the PID controller and efficiently controls the water flow of the turbine	The system's performance was not compared existing fuzzy controllers
(Sahoo *et al.*, 2018)	Improved Grey wolf optimization technique Fuzzy logic	Frequency control of power system Three area nonlinear system Two are six unit system	Efficient control of system frequency for both test system Capable of controlling the system under uncertain stochastic load variations	The computational time of the proposed hybrid IGWO fuzzy PID control is high
(Hammid *et al.*, 2018)	Fuzzy Artificial Neural Network based controller	Water level control of small hydropower plant	Efficient control of water level under varying conditions	The performance of the proposed scheme was not compared with existing control techniques
(Ofosu *et al.*, 2019)	Bacterial foraging algorithm (BFA) integrated with fuzzy logic based electronic load controller	Frequency control of micro hydropower plant	The proposed control was cost-effective and efficiently controls the system frequency as the BFA algorithm selects optimal values of membership functions of fuzzy controller	The performance of the proposed scheme was not compared with existing control techniques
(Saeed *et al.*, 2020)	FIS logic controller	Water level control of run of river hydro power plant	Efficient control of water level of three pond model	
(El Hamdaouy *et al.*, 2020)	Fuzzy logic based PI controller	Controller, management and security system (CMSS) to manage the overall operation of Pico Hydropower plant	The proposed system is cost-effective and can be implemented to achieve various types of control models such as load frequency control, system start-up and emergency stop etc.	The performance of the proposed scheme was not compared with existing control techniques

Ref	Controller scheme	Parameters and system to be controlled	Advantages	Limitations
(Kang *et al.*, 2021)	Fuzzy logic controller	Battery energy storage system integrated with pico hydro system	Efficient control of standalone pico hydro system during peak load demand hours	The performance of the proposed scheme was not compared with existing control techniques Membership should have been incorporated using various fuzzy-logic-linguistic variables to make the controller more efficient
(Asoh *et al.*, 2022)	Fuzzy logic controller	Load frequency control of small hydro power plants	One-input fuzzy logic controller Efficient control and enhanced stability of non-linear small hydro power plants	The system's performance was compared with conventional PI/PID controller, rather it should have been compared with other intelligent methods

2.5 Discussion

Global warming is now evident from the unprecedented changes is weather. The intensity and frequency of extreme weather-related events has been increasing in recent years. The extreme unprecedented events have shifted the paradigm electrical power generation from fossil fuel resources to environment friendly renewable energy resources to reduce the amount of greenhouse gasses in the atmosphere.

Hydropower is the only renewable energy resource which has been utilized to generate power since the start of twentieth century. Moreover, hydropower plants are not intermittent in nature like solar and wind etc. and generate stable power which is used to supply the base load of the national grid. Conventionally, hydropower plants are mega-structures as large amount of water is stored in reservoirs which is then used to drive the hydropower turbines around the clock. These installations have high installation costs, but low to none operational costs.

In recent years, installations of small, micro and pico run-off river hydropower plants are increasing. This is because they do not require large reservoirs or dams which incur high installation costs. One salient feature of these small, micro and pico hydropower plants is that they can securely supply power to numerous consumers and can operate in standalone and grid connected modes. Furthermore, these power plants are also used for irrigation purposes.

Numerous advantages of small, micro and pico hydropower plants have been identified in this literature review, however, it is also apparent that limitations still exist pertaining to efficient control and management of pico hydro power systems. Pico hydropower plants are hydropower plants rated at capacities below 5kW as discussed in this chapter. One of the most significant challenges in achieving efficient operation of pico hydropower plants is variations in flow of water intake. Pico hydropower plants requires a low amount of water flow to generate power, which makes their installation feasible on rivers and canals. However, the rate of flow of water in those rivers and canals is not constant due to which the generated power supply is also not constant. Several water level management and control techniques have been proposed by researchers for different types of electrical power generating sources. Conventionally flow control valve is used to control the water flow into the turbine but it is not efficient. An efficient control system for water flow of turbine intake for a pico hydropower plant still needs to be developed.

2.5.1 Research Gaps

Based on the discussion the following research gaps have been identified. An intelligent flow control technique to control the water flow (speed) of pico hydro turbine needs to be developed in order to improve and maintain the output performance. On the other side, a load frequency control technique needs to be developed too due to the consumer load variations. The system's performance under consumer load variations needs to monitor and analysed from time to time.

2.5.2 Summary

Pico hydro power plants usually operated is standalone off grid mode and supply electricity to small number of consumers in rural areas. The degree of variation in load demand of these rural areas is very high. These variations render the system unstable as they are directly related to frequency of the synchronous machine. The system frequency drops significantly when load demand increases beyond the capacity of the generator, and if the load is decreased suddenly the frequency overshoots from the normal operating value. This causes swinging phenomenon in the electrical system. Therefore, efficient load management system is of the utmost importance. Several efficient load frequency management techniques based on fuzzy logic and neural networks have been proposed by researchers as discussed in section 2.4 of this chapter. However, majority of the load frequency management techniques are design for small or micro hydropower plant and utilize ELCs. Pico hydropower plants are more sensitive to changes in consumer load compared to small or micro hydropower plants due to their small generator size and irregular water flows. Therefore, an efficient load frequency management scheme designed specifically for pico hydropower plants is yet to be investigated.

CHAPTER 3 : RESEARCH METHODOLOGY

3.1 Introduction

The methodology adopted to model a pico hydropower plant and its fuzzy logic-based controller is discussed in this chapter. In this study, SIMULINK MATLAB is used to model the PHP and its controllers. PHP is modelled as a closed loop system. This chapter explain on the design of the proposed controller for pico hydro-power plant. A full design circuit on PHP with control system has been design, modelling and run in MATLAB simulation. In order to improved and maintained the output performance, the proposed fuzzy logic controller is discussed to maintain system frequency due to various load disruptions. The development of a PID controller is relatively simple however, the addition of fuzzy rules increases design complexity, there are couple of basic standards for setting the specifications of a fuzzy controller. Pico hydro powerplant is a non-linear system, therefore the designed PID controllers should be adaptive and are required to constantly update depending on the consumer load to ensure system stability.

Fuzzy logic controller is implemented in this research because it is capable of processing information similar to human thinking and possesses nonlinear intelligent control characteristics. Self-tuning controller is used to readjust the parameters of the PID gains in order to improve the output response. The self-tuning controller is utilized as the PID control has nonlinear characteristics and intellectual faculties, and at the same time enhances fuzzy control with a PID-control configuration. Fuzzy control design has no standardized procedure such as root-locus design, frequency response design, pole placement design, or stability margins, because the rules are often non-linear. Therefore, describing the basic components and functions of fuzzy controllers is solved, in order to recognize and understand the various options in commercial software packages for fuzzy controller design.

3.2 HYDRO POWER PLANT

The study is based on accurately modelling a pico hydropower plant, which is characterized as a hydropower plant with a capacity of 5kW or less. Therefore, to simulate / model a PHP all elementary components of a hydropower plant need to be precisely modelled. These elementary components are reaction turbines using a penstock, wicket gates, a turbine, and a generator. The generator and turbine are connected primarily by a vertical shaft. High water flow rates are produced by the existence of a high head, which flows through the penstock and arrives at the turbine. The valve and gates govern the quantity of water that flows into the turbine by altering the opening of the pivot around the turbine's circumference. Servo-actuator, is used to regulate the position of gates. The head through penstock converts the potential energy of water to kinetic energy as it flows. The turbine-generator set is powered by water flow (Bošković *et al.*, 2020; Fortaleza *et al.*, 2018; Goyal *et al.*, 2014; Margonis, 2017). (Bošković et al., 2020). All the components are modelling in this research.

Simulation and modelled of power system elements is conducted using SIMULINK. Power systems elements are modelling efficiently in the form of blocks in SIMULINK. All elements are modelled with steady state and transient response capabilities.

The accuracy of modelling design is dependent upon the details of specifications of power system elements and parameter tuning in the control system, such as governor control, is one of the important parts of this research. Similarly, the controllers also require to be setup with detailed specifications to achieve optimal performance diverse situations. Therefore, in this chapter, an examination of the mathematical system modelling of the fundamental elements of a hydroelectric power plant is conducted to achieve an exact simulation in MATLAB software.

3.3 Overall Flow Chart of Research

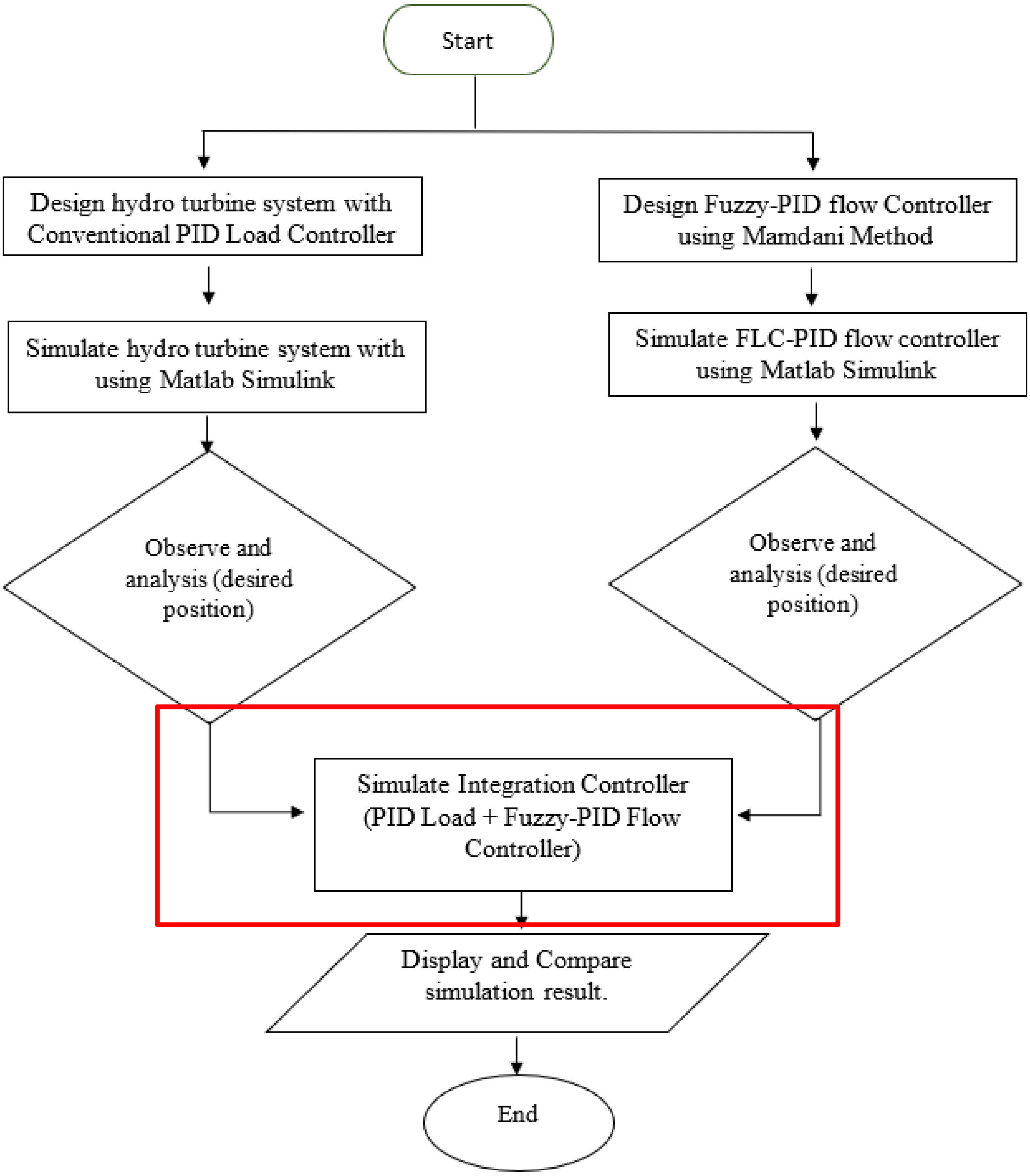


Figure 3.1: Overall research design process for simulation.

The overall research flow of simulation design is depicted in Figure 3.3. It is design and simulate into two different controllers at the initial stage. Integration controller was added to compare and for result analysis purpose.

3.4 Flow Chart for Designing of Fuzzy controller

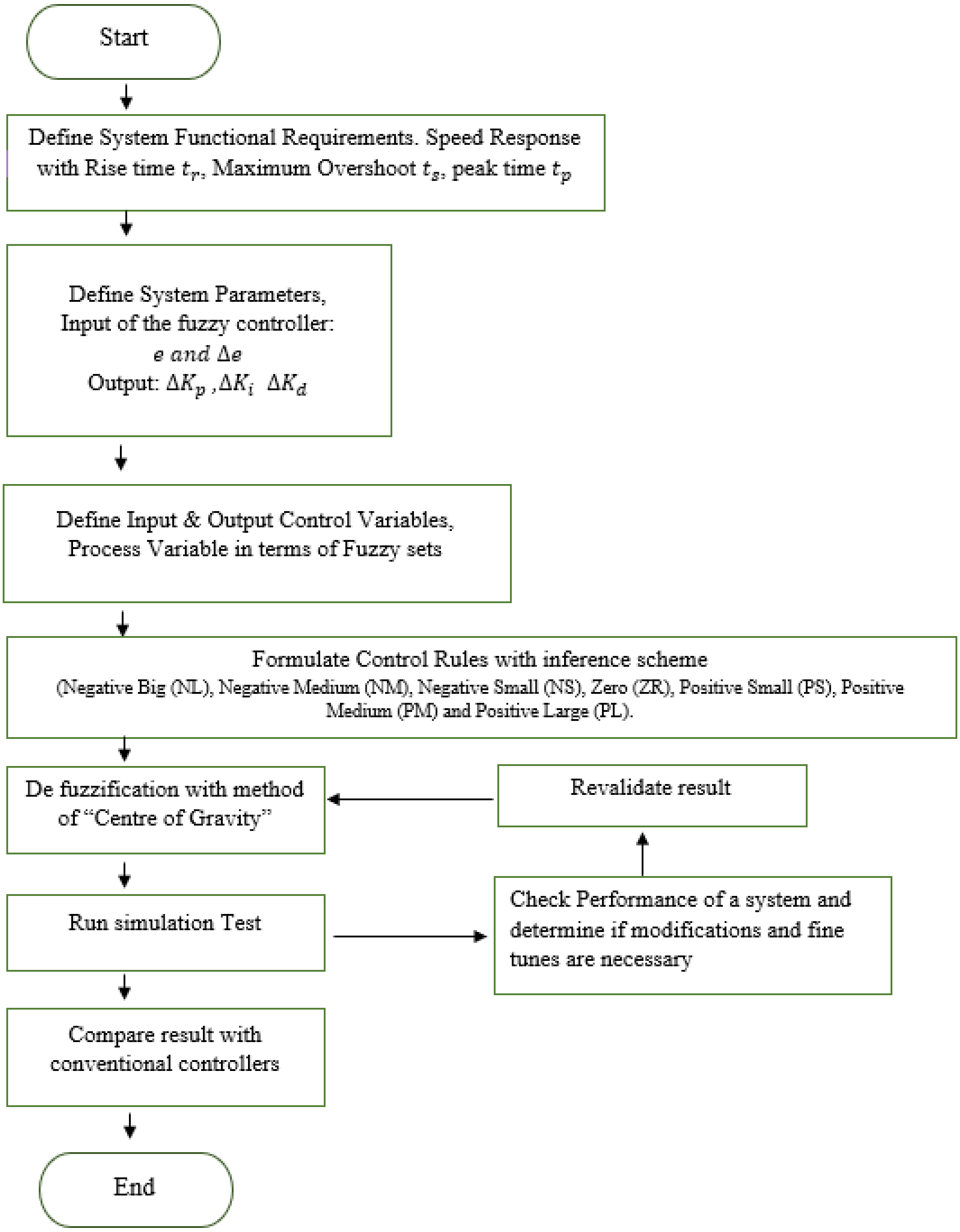


Figure 3.2: Fuzzy Logic Controller Design Steps.

Theoretically, a fuzzy controller can be designed based on few steps which was fuzzification, inference scheme and defuzzification method as shown in Figure 3.4.

3.5 Design of The Control System for Pico Hydro Powerplant

The design of the proposed controller for pico hydro-power plant is explained in this subsection. To proposed fuzzy logic controller is designed to observe the variations in system frequency caused by various load disruptions. The objective of the controller's design is to improve and maintain a stable output. The proposed controller is a hybrid of PID and Fuzzy controller. The PID controller must constantly update itself in accordance to the load demand of consumers to ensure stable power output of the generator. Therefore, a self-tuning controller tunes the PID controllers gain parameter. The design of a PID controller is relatively easy however, the addition of a fuzzy controller adds complexity to it. The design of fuzzy controller has been discussed in detail in literature and setting specifications of fuzzy control are also standardized. Fuzzy logic controller is implemented in this research due to its human like thinking capability and non-linear control characteristics, as the Pico hydro system is non-linear. Therefore, hybrid PI and fuzzy control of the system is capable of performing self-tuning due PID controller's non-linear characteristics and fuzzy controller's adaptive characteristics and human like thinking. As the design of a fuzzy controller is different from any control system theory control because in fuzzy control concepts such as root-locus, frequency response, pole placement or stability margins are not available. Design of Fuzzy logic entails initialization of parameters, variables to be optimized, constraints and objective functions.

3.5.1 Hydro Power System Modelling

A standalone pico hydro system is developed and design through MATLAB Software version R2020a 64 bit. An overall SIMULINK model for pico hydro system with integrated controller is shows in Figure 3.5. The model is tested through integration controller and compared to standalone controller of pico hydro system. Output response of hydro turbine flow control and load control is investigated and the results focus on rise time, peak time and overshoot percentage. All the simulink sub-systems such as hydro turbine governor, synchronous motor, excitation system, is described in detail in this section.

Hydroelectric plants work on the principle of converting the potential energy between two water levels, first into mechanical power and later into electrical power. Below in the figure the main components of a plant are shown. The basic principle is that water flows from a reservoir or river through a penstock and powers a turbine which creates a mechanical torque and rotational speed which generates electrical power from a generator.

Equation (1) showing output of gross power:

$$P(gross) = pqghn \tag{3.1}$$

Where:

P is the density of water.
g is the gravity constant (9.81 Newton).
n is the turbine efficiency. n
h The gross head in a plant is defined as the height between the water level of the reservoir and water level of the outlet destination.

The penstock is modeled by assuming that the flow is incompressible when the rate of change of flow in the penstock is obtained by equating the rate of change of momentum of the water in the penstock to the net force on the water in the penstock when:

$$pL\frac{dQ}{dT} = F_{net} \tag{3.2}$$

Where:

q is the volumetric flow rate.

L the penstock length.

p the mass density of water.

The net force on the water can be obtained by considering the pressure head at the conduit. On entry to the penstock the force on the water is simply proportional to the static head, while at the wicket gate it is proportional to the head across the turbine. Due to friction effects in the conduit, there is also a friction force on the water represented by the head loss so that the net force on the water in the penstock is:

$$F_{net} = H_S - H - H)Apg \tag{3.3}$$

Where:

A is the penstock cross-sectional area. A
g is the acceleration due to gravity.

Substituting the net force into Equation (4) gives

$$pL\frac{dQ}{dT} = (H_S - H - H)Apg \tag{3.4}$$

It is usual to normalize this equation to a convenient base. Although this base system is arbitrary, the base head $h\ base$ is taken as the static head above the turbine, in this case, while the flowrate $q\ base$ is taken as the flowrate through the turbine with the gates fully open and the head at the turbine equal to (IEEE Committee Report, 1992).

$$\frac{dQ}{dT} = (1 - H - H)\frac{1}{T_w} \tag{3.5}$$

Where:

q are the normalized flow rates and pressure heads respectively h.

$$T_w = \frac{Lq_{base}}{Agh_{base}} \tag{3.6}$$

Where:

T_w is the water starting time, which is theoretically defined as the time taken for the flowrate in the penstock to change by a value equal to q_{base} when the head term in brackets changes by a value equal to h_{base}

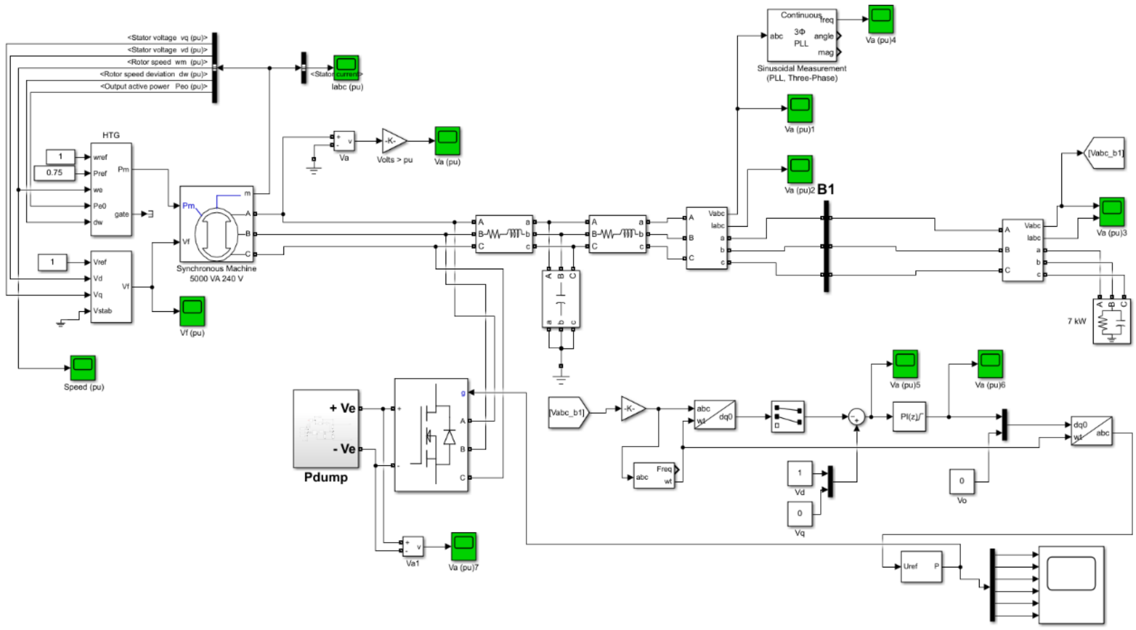


Figure 3.3: Overall Simulink Model for Pico Hydro System with Integrated Controller

To create and simulate pico hydro system, of the hydraulic turbine and governor need to be designed according to Matlab Simulink block. An efficient hydro turbine management unit consisting of two controllers which are; intelligent valve control with fuzzy logic at the primary input of turbine and electronic load controller to adjust and balance load on consumer end through dump load control system. Standalone PID controller block was added in order to act as an integrated controller. Hybrid PID fuzzy controller and standalone PID both are simulated in a pico hydro modelling circuit. PID controller also known as electronic load controller with the purpose of generator output control in the system will ensure a stability of the system in terms of frequency and voltage regulation. Moreover, a valve controller was also added at the hydro turbine side to control the primary energy that flows into the turbine. Intelligent approach fuzzy-PID controller was designed and added to ensure flow control into the turbine to maintain mechanical output while ELC remains as a load controller for generator output. The research concept of the complete design is depicted in Figure 3.6.

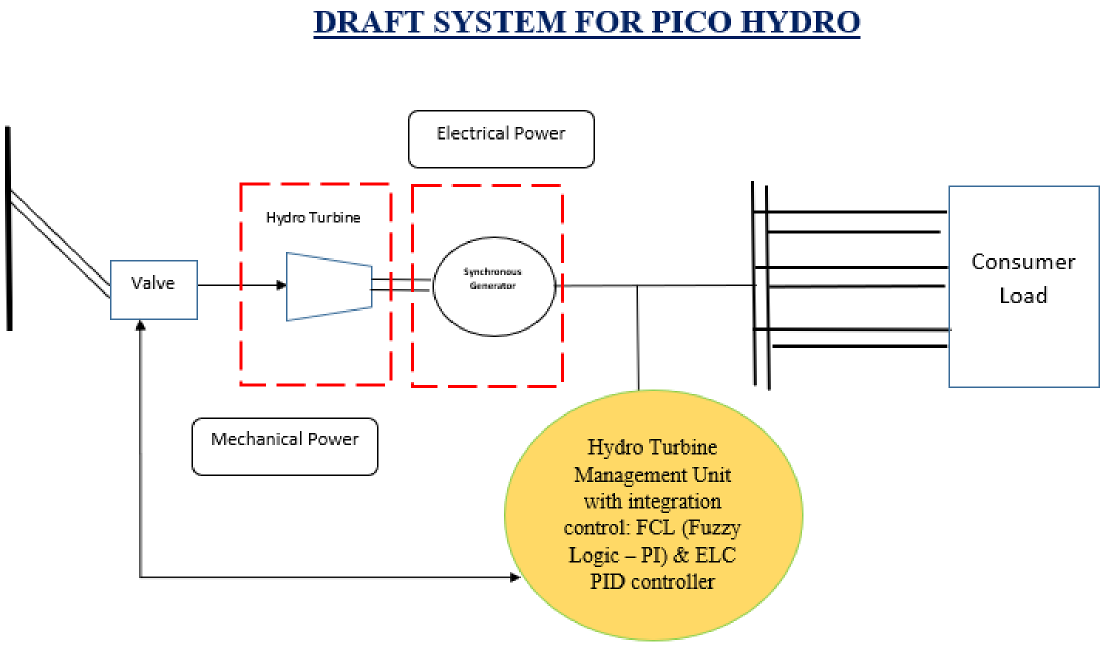


Figure 3.4: Overall Concept of Pico Hydro system with Integrated Controller

Simulation parameters such as flow rate and head measurement are identified based on default data in the simulink block. A circuit with standalone PID controller was simulated initially to observe the output response of mechanical power, P(mech). Fuzzy logic was integrated to the system on the valve control side. This will show a hybrid control system with fuzzy valve control and PID control on load side. Analysis is conducted on the output response of the generator to determine whether integrated controllers can stabilize the system in terms of rising time and overshoot percentage.

3.5.2 Hydro Power Plant with Synchronous Machine

The hydro power plant model developed in this study is illustrated in Figure 3.5. The model consists of hydro turbine governor, synchronous machine with 5000VA and 240V rating, 3 phase active and reactive power measurement block. An excitation system combined with exciter act as the voltage regulator.

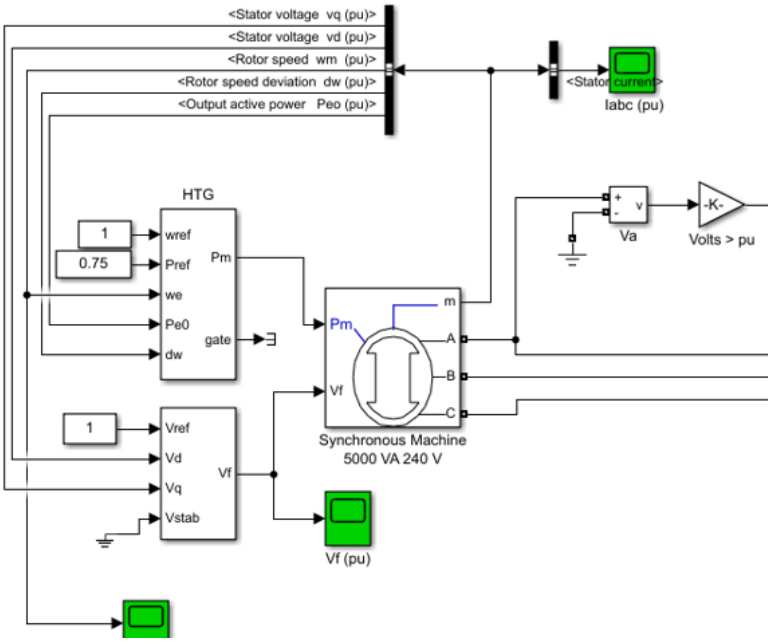


Figure 3.6: Hydro Power Plant Model with Synchronous Machine. (Matlab R2021)

The Synchronous Machine model can operate in both, generator or motor mode. The operating mode is dictated by the sign of the mechanical power (positive for generator mode, negative for motor mode). The synchronous machine is fed by the output power of Hydro turbine governor which is represented P(mech).

In modelling the turbine, itself both its hydraulic characteristics and mechanical power output must be modelled. Firstly, the pressure head across the turbine is related to the flowrate by assuming that the turbine can be represented by the valve characteristic:

$$Q = kG\sqrt{H} \tag{3.7}$$

Where:

G is the gate position between 0 and 1.
k is a constant.

With the gate fully open =1 and this equation can be normalized by dividing both sides by:

$$q = G\sqrt{H} \tag{3.8}$$

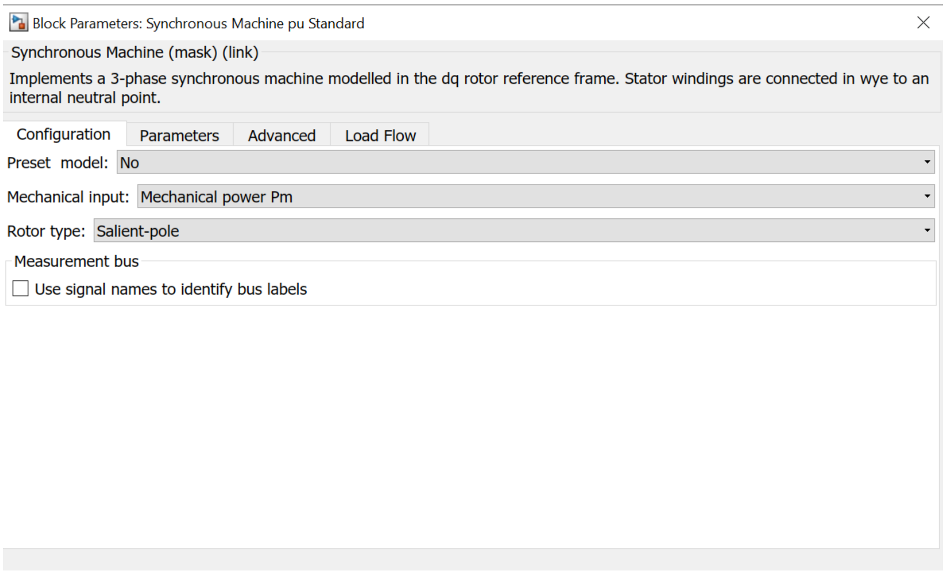
Secondly, the power developed by the turbine is proportional to the product of the flowrate and the head and depends on the efficiency. To account for the turbine not being 100% efficient the no-load flow is subtracted from the actual flow to give, in normalized parameters

$$P_m = h(q - q_{nl}) \tag{3.9}$$

Where:

P_m is the mechanical output power.

The configuration details of the synchronous machine are presented in Figure 3.9.



Block Parameters: Synchronous Machine pu Standard

Synchronous Machine (mask) (link)

Implements a 3-phase synchronous machine modelled in the dq rotor reference frame. Stator windings are connected in wye to an internal neutral point.

Preset model: No

Mechanical input: Mechanical power Pm

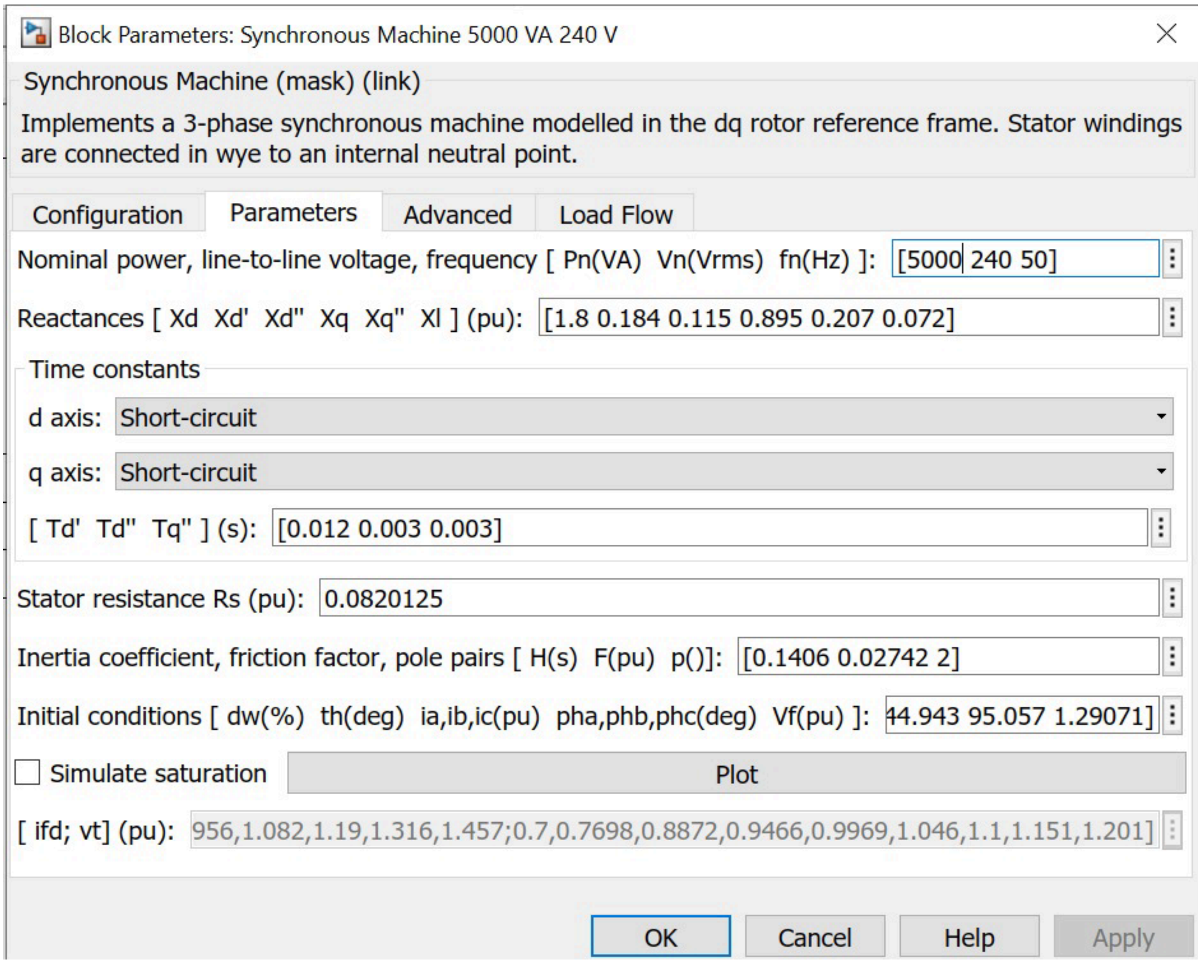
Rotor type: Salient-pole

Measurement bus

☐ Use signal names to identify bus labels

Figure 3.7: Configuration Tab of the synchronous generator in SIMULINK.

Preset model is not used in these cases. Output is connected to an oscillator for analysis of the speed and voltage performance. The electrical part of the machine is represented by a sixth-order state-space model and the mechanical part is the same as in the Simplified Synchronous Machine block. The model takes into account the dynamics of the stator, field, and damper windings discussed in section 3.3. The cross-sectional shape of the rotor can be salient or cylindrical. Salient pole construction is mostly used in low-speed applications where the diameter to length ratio of the rotor can be large to accommodate the high pole number. In this SIMULINK model, salient pole synchronous machines are simulated as they are installed in hydro generators to match the low operating speed of the hydraulic turbines. Salient here, refers to the protruding poles, the alternating arrangement of pole iron and interpolar gap results in preferred directions of magnetic flux paths or magnetic conductivity. The parameter setting of the synchronous machine are presented in Figure 3.10.



Synchronous Machine (mask) (link)

Implements a 3-phase synchronous machine modelled in the dq rotor reference frame. Stator windings are connected in wye to an internal neutral point.

Nominal power, line-to-line voltage, frequency [Pn(VA) Vn(Vrms) fn(Hz)]: [5000 240 50]

Reactances [Xd Xd' Xd" Xq Xq" Xl] (pu): [1.8 0.184 0.115 0.895 0.207 0.072]

Time constants

d axis: Short-circuit

q axis: Short-circuit

[Td' Td" Tq"] (s): [0.012 0.003 0.003]

Stator resistance Rs (pu): 0.0820125

Inertia coefficient, friction factor, pole pairs [H(s) F(pu) p()]: [0.1406 0.02742 2]

Initial conditions [dw(%) th(deg) ia,ib,ic(pu) pha,phb,phc(deg) Vf(pu)]: 44.943 95.057 1.29071]

☐ Simulate saturation

[ifd; vt] (pu): 956,1.082,1.19,1.316,1.457;0.7,0.7698,0.8872,0.9466,0.9969,1.046,1.1,1.151,1.201]

Figure 3.8: Parameters Tab of the synchronous generator in SIMULINK

3.5.2.1 Nominal power, line-to-line voltage, and frequency

Total three-phase apparent power (VA), RMS line-to-line voltage (V), frequency (Hz), and field current (A). This line is identical to the first line of the fundamental parameters in SI dialog box, except that you do not specify a nominal field current. This value is not required here because we do not need the transformation ratio. Since rotor quantities are viewed from the stator, they are converted to pu using the stator base quantities derived from the preceding three nominal parameters.

3.5.2.2 Reactance

The d-axis synchronous reactance Xd, transient reactance Xd', and subtransient reactance Xd'', the q-axis synchronous reactance Xq, transient reactance Xq' (only if round rotor), and sub-transient reactance Xq'', and the leakage reactance Xl (all in pu).

3.5.2.3 Time constants (d-axis time constants, q-axis time constant(s)

The d-axis and q-axis time constants (all in s). These values must be consistent with choices made on the two previous lines: d-axis transient open-circuit ($T_{do'}$) or short-circuit ($T_{d''}$) time constant, d-axis subtransient open-circuit ($T_{do''}$) or short-circuit (Td'') time constant, q-axis transient open-circuit ($T_{qo''}$) or short-circuit ($T_{q'}$) time constant (only if round rotor), q-axis subtransient open-circuit ($T_{qo''}$) or short-circuit ($T_{q''}$) time constant.

3.5.2.4 Inertia coefficient, friction factor, pole pairs, Initial conditions, Simulate saturation

Saturation parameters is the same initial conditions and saturation parameters as in the SI units' dialog box, but all values are expressed in pu instead of SI units. For saturation, the nominal field current and nominal RMS line-to-line voltage are the base values for the field current and terminal voltage, respectively.

3.5.3 Excitation System Modelling

DC excitation system is taken into consideration in this study, which utilizes a direct current generator with a commutator as the source of excitation for power system. The function of an excitation system model is to generate the excitation voltage that is necessary for the synchronous generator to work effectively. Feedback systems are used through Fuzzy-PID controllers to regulate both the generated excitation voltage as well as mechanical power produced by the turbine. The model of excitation system is presented in Figure 3.10. The principal input to this model is the output, from the terminal voltage transducer and load compensator model. At the summing junction, terminal voltage transducer output, is subtracted from the set point reference. The stabilizing feedback is subtracted, and the power system stabilizing signal is added to produce an error voltage. In the steady-state, these last two signals are zero, leaving only the terminal voltage error signal. The resulting signal is amplified in the regulator. The time constant and gain associated with the voltage regulator, utilize power sources that are essentially unaffected by brief transients on the synchronous machine or auxiliaries' buses. The time constants may be used to model equivalent time constants inherent in the voltage regulator, however these time constants are usually small enough to be neglected, and a provision should be made for zero input data. The exciter is represented by the following transfer function between the exciter voltage V_R and the regulator output E_{FD}. A signal derived from field voltage is normally used to provide excitation system stabilization V_F via the rate feedback with gain $K_F$and time constant T_F.

$$\frac{V_R}{E_{FD}} = \frac{1}{K_{E+sTe}} \tag{3.10}$$

Where:

K_F is the feedback gain.

V_F is the excitation system stabilization.

V_R is the exciter voltage.

E_{FD} is the regulator output.

The exciter is represented by the transfer function block between the exciter voltage and the regulator output in Figure 3.11. A signal derived from field voltage is conventionally used to provide excitation system stabilization via the rate feedback with gain and time constant.

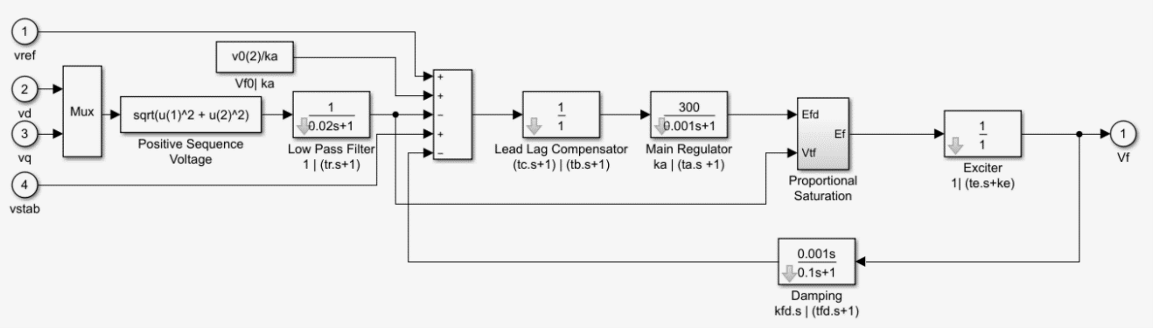


Figure 3.9: SIMULINK Block Model for Excitation System. (Matlab R2021)

3.6 Fuzzy Logic Controller Design

Fuzzy logic controller can be design based on Mamdani's fuzzy inference method or Sugeno's fuzzy inference method discussed in chapter 2. Mamdani's system technique is commonly implemented for capturing expert knowledge and understanding. One significant advantage of implementing the Mamdani's system technique is that the algorithm is designed to behave in a human-like manner. Mamdani's-type FIS requires a considerable computational time. Whereas, Takagi- Sugeno method is computationally effective and works efficiently with optimization and adaptive algorithms, which makes it really attractive in control system applications especially for non-linear systems. Takagi- Sugeno can be utilized to personalize the membership function so that fuzzy system fits the information. The difference between Mamdani's-type FIS and Sugeno-type FIS is the crisp generated output from the fuzzy inputs. While Mamdani's-type FIS utilizes the strategy of defuzzification of a fuzzy output, Sugeno-type FIS utilizes the weighted average to calculate the crisp output. The expressive power and interpretability of Mamdani's output is lost in the Sugeno FIS since the consequents of the guidelines are not fuzzy. However, Sugeno has much better processing time as the consideration of weighted average decreases the processing time of the defuzzification process. Mamdani's FIS is less versatile in system style compared to Sugeno FIS as it can be integrated with ANFIS tool to enhance the outputs. In this research, fuzzy logic control on hydro turbine governor using Mamdani's method is implemented to acquire the membership rules. The block diagram of Fuzzy logic model is presented in Figure 3.12.

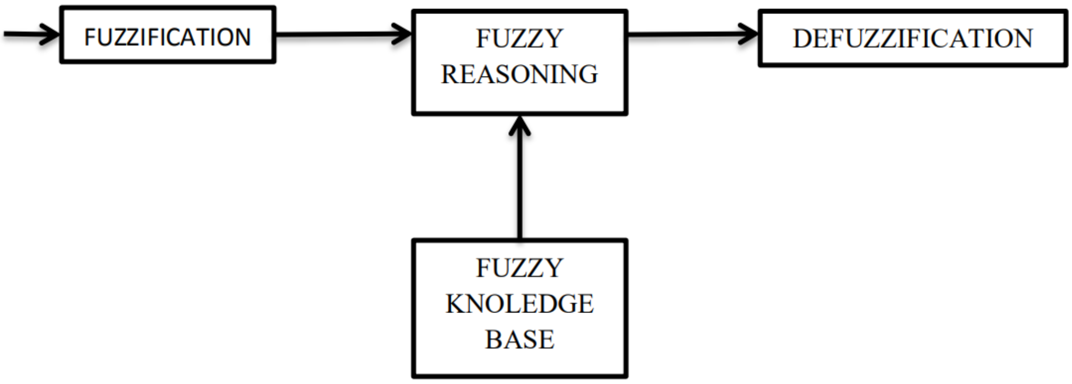


Figure 3.10: Block Diagram of Fuzzy Logic Model

Fuzzification, membership rule, fuzzy inference and defuzzification is designed based on the previous research guidance, expert experience and engineering knowledge. Based on the control actions, Fuzzy if-then guidelines can be deduced from observations of an operator's control actions or a log book. These guidelines define an input-output relationships and suggest adjustment, if they are needed. Based on a fuzzy model of procedure, linguistic rules base may be considered as an inverted design of the controlled process. Therefore, the fuzzy control guidelines may be obtained through fuzzy model and process. This method is limited to low order systems; however, it supplies a specific solution for the fuzzy designs of the open and closed loop systems. Fuzzy identification or fuzzy model-based control is another approach for controller design. Based on previous research, self-tuning controller can tune parameters based on the rules. This approach of control is implemented at neural networks fuzzy controller.

3.6.1 Fuzzifier Design

Fuzzification is the first process in fuzzy controller design. Fuzzification determines the precise control strategies by referring the inputs and outputs of the controller. Fuzzy self tuning PID as an integration flow controller. In hydro turbine governor SIMULINK block, a fuzzy logic controller is added to provide an improved output performance in terms of step response. Frequency error e and change in frequency error Δe are selected as inputs for fuzzy logic, while the outputs of the fuzzy controller are proportional gain (K_p), integral gain (K_i) and derivative gain (K_d). All the three outputs control the gate of servo motor that varies the water flow when the disturbance exceeds a certain limit compared to the nominal turbine power. The controller gains are also acquired to stabilize the frequency of the generator when it deviates from the nominal value. Non-linear hydro turbine governor model with fuzzy controller is presented in Figure 3.13 and with fuzzy-PID control system is presented in Figure 3.14. The governor system with fuzzy logic controls the gate opening of the servo motor during load variation and in the presence of disturbance in order to maintain turbine speed.

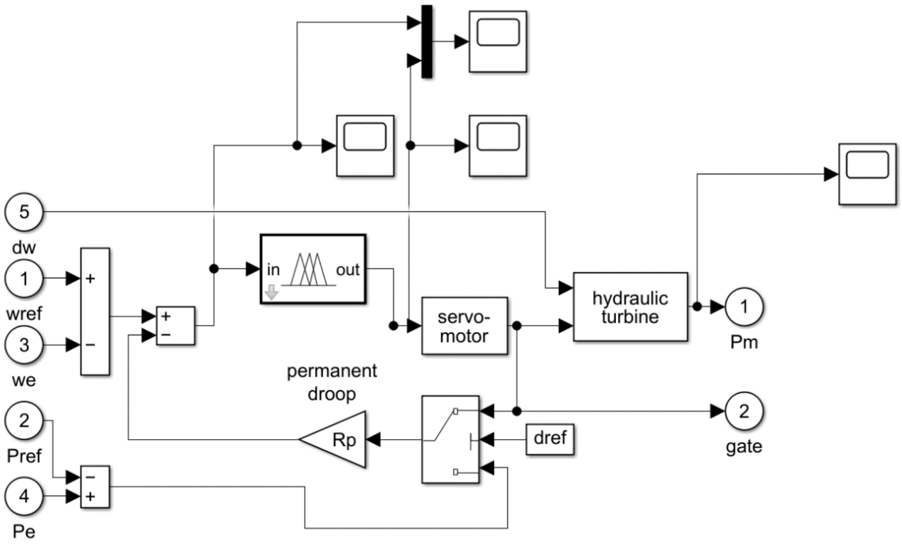


Figure 3.11: Hydro Turbine Governor Model with only Fuzzy Logic Control system (Matlab R2021)

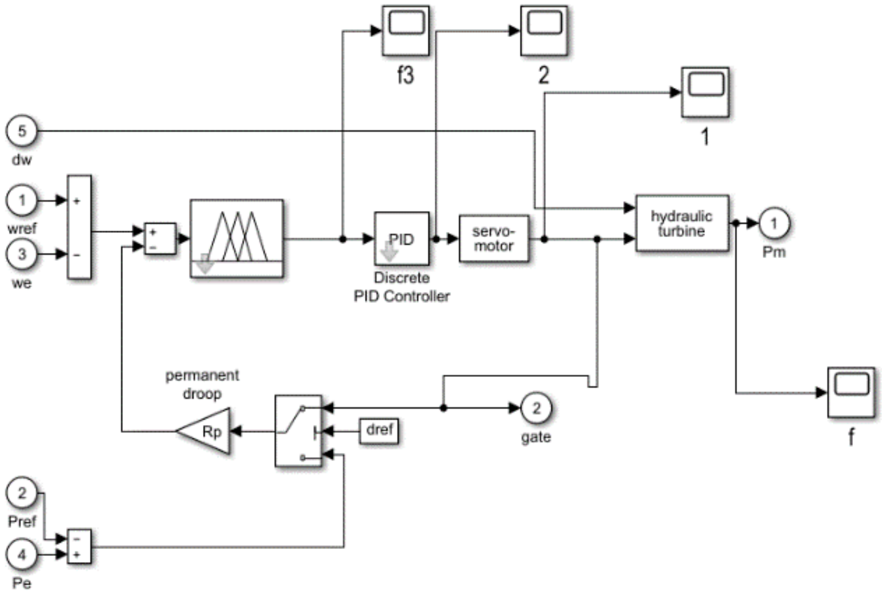


Figure 3.12: Hydro Turbine Governor Model with added Fuzzy -PID Control system (Matlab R2021)

The turbine speed is fed into controller of fuzzy-PID based on the reference speed with permanent droop. The controller calculates signal error, and fuzzy PID controller will send the appropriate signal to the servo motor to control the gates maintaining the required water flow. The servomotor limits the opening speed of the gate. The maximum and minimum speed of the gate are represented by V_{gmax}(pu/s) and V_{gmin}(pu/s) respectively. The block parameters for the hydro turbine governor are presented in Figure 3.15. Parameters of the block was explained as below:

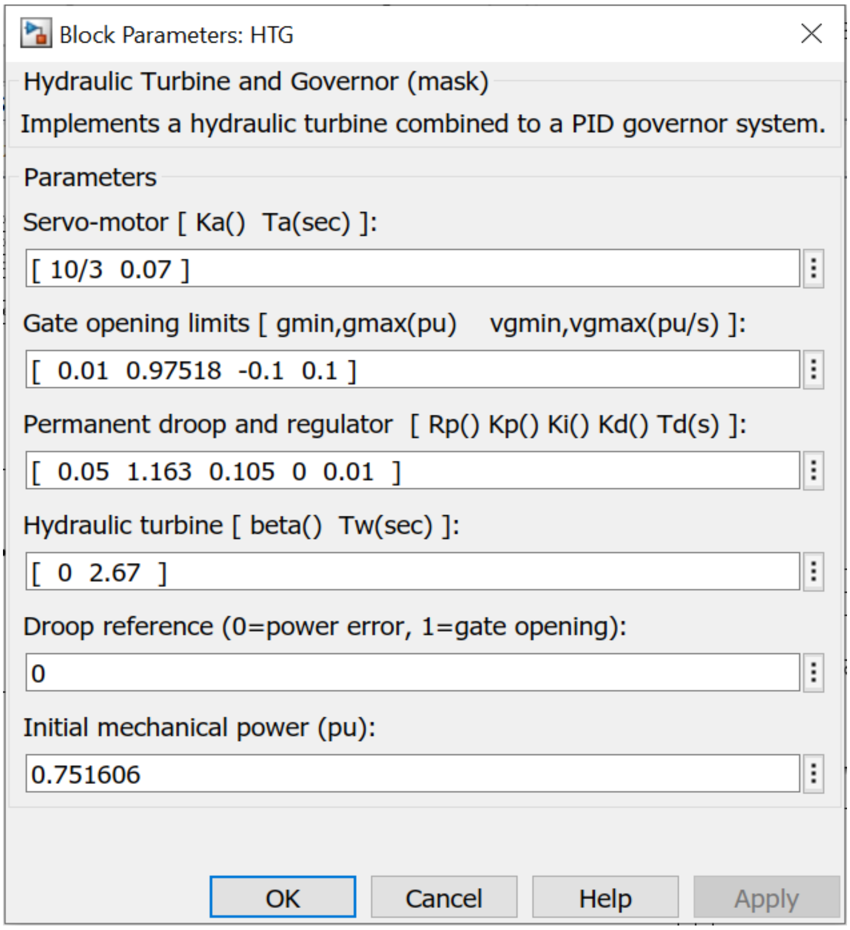
Servo-motor: The gain Ka and time constant Ta, in seconds (s), of the first-order system representing the servomotor.

Gate opening limits: The limits $gmin$ (pu) and $gmax$ (pu) imposed on the gate opening, and V_{gmax} and V_{gmin} (pu/s) imposed on gate speed.

Permanent droop and regulator:

The static gain of the governor is equal to the inverse of the permanent droop Rp in the feedback loop. The PID regulator has a proportional gain K_p, an integral gain K_i and a derivative gain K_d. The high-frequency gain of the PID is limited by a first-order low-pass filter with time constant T_d (s).

Hydraulic turbine: The speed deviation damping coefficient β and water starting time T_w (s).



Hydraulic Turbine and Governor (mask)

Implements a hydraulic turbine combined to a PID governor system.

Parameters

Servo-motor [Ka() Ta(sec)]: [10/3 0.07]

Gate opening limits [gmin,gmax(pu) vgmin,vgmax(pu/s)]: [0.01 0.97518 -0.1 0.1]

Permanent droop and regulator [Rp() Kp() Ki() Kd() Td(s)]: [0.05 1.163 0.105 0 0.01]

Hydraulic turbine [beta() Tw(sec)]: [0 2.67]

Droop reference (0=power error, 1=gate opening): 0

Initial mechanical power (pu): 0.751606

Figure 3.13: Block parameters of Hydro Turbine Governor

An appropriate membership function is required for inputs and outputs. Every element in the universe of discourse is a member of a fuzzy set to some grade, maybe even zero. The grade of membership for all its members describes a fuzzy set, such as Negative (N), and Positive (P). In fuzzy sets, elements are assigned a grade of membership, such that the transition from membership to non-membership is gradual rather than abrupt. The set of elements that have a non-zero membership is called the support of the fuzzy set. The function that ties a number to each element of the universe is called the membership function. According to fuzzy set theory the choice of the shape and width is subjective, but a few rules of thumb apply. In this study triangular and trapezoidal shapes have been adopted for the membership functions for all inputs and outputs variables. The shape of the membership function and the universe of discourse for each function is found by trial and error after conducting several simulations. Input membership function for speed error is illustrated in Figure 3.16 and Input membership function for the difference change in speed error is illustrated in Figure 3.17.

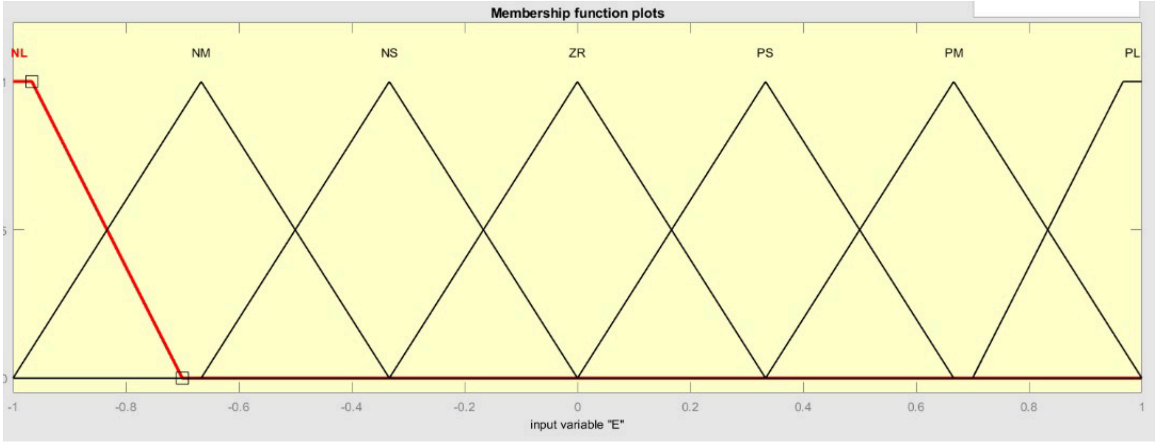


Figure 3.14: Input membership function for speed error.

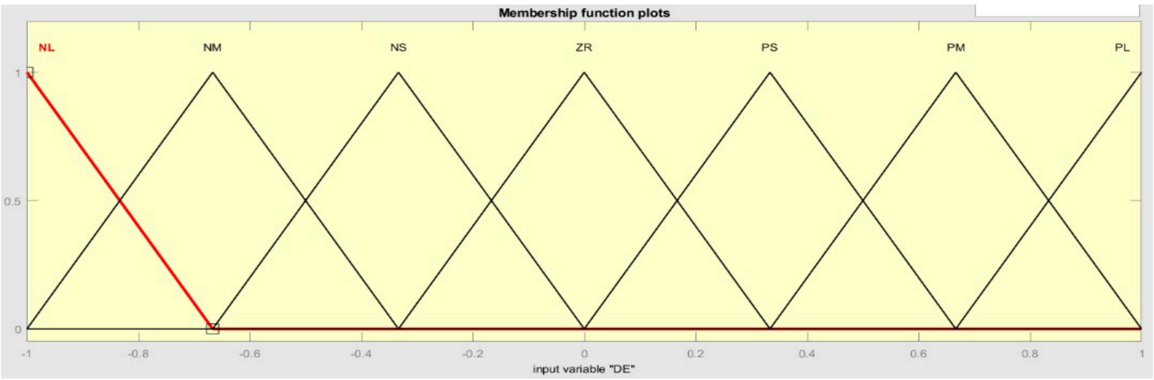


Figure 3.15: Input membership function for the difference change in speed error

The inputs speed error e and the change in speed error Δe are used as numerical variables from the real system. For error and change in error, the input is found by trial-and-error method in order to determine the range of speed error and change in speed error. The range for speed error and change in speed error in terms of membership function are kept greater in number in order to open the required actuator valve. The inputs are most often hard or crisp measurements from some measuring equipment, rather than linguistic. To convert numerical values of the inputs to linguistic variables several fuzzy sets are presented. The error can be both negative and positive as the actual speed can either be high or lower than the desired value. Values of error with a Negative sign indicate that the current output speed w_rr(t) has a value above the reference-point i.e., Speed ref since e = speed ref – output speed, w_rr(t)> 0. Whereas, the values of error e with a positive sign indicate that the current value of w_r is below the reference-point value. The change of speed error Δe with a negative sign indicates that the current output speed w_r (t) has increased compared with its previous value w_r (t-1), since e = -w_r(t) + w_r(t-1) < 0. Values of Δe with a positive sign indicate that w_r(t) has decreased its value compared to w_r(t-1).

For input e seven fuzzy sets are chosen in the simulation which are: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Big (PB); and seven fuzzy sets are chosen for Δe too: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (Z), Positive Small (PS), Positive Medium (PM), and Positive Big (PB).

The speed error and change in speed error are stated as [-1, 1]and the input scaling factor for error and change in error are found by trial and error to make the range of speed error and change in speed error normalized. The membership functions for speed error and change in speed error are kept greater in number in order to activate only the required actuator valve and to minimize error. The membership functions of NL and PL are trapezoidal type as depicted in Figure 3.16 and all the remaining membership functions are of triangular type as depicted in Figure 3.17. The fuzzification uses centre of gravity method to convert a system input into one or more fuzzy sets.

3.6.1.1 Knowledge Base to Controller

Fuzzy base rule is a collection of if-then rule that contains all pertinent information for the controlling parameters. It is set according to professional experience and the operation of the device control. The most significant part of a fuzzy system is its knowledge base that consists of If-Then rules. A fuzzy If-Then statement characterizes words by continuous membership functions. Rules must be defined to describe the action to be taken for each combination of control variables based on the requirements set by definition of the fuzzy sets and also confirm their membership functions. These rules will relate the input variables to the output variable using If-Then statements which allow decisions to be made.

The fuzzy rule algorithm includes some of the following fuzzy control rules listed below in

Table 3.3: Membership Function Universe of Discourse of Error. A classic interpretation of Mamdani method was used to define the rule bases. Under rule base, rules are constructed for outputs. The rules are in “If Then” format and formally the If side is called the conditions and the Then side is normally called the conclusion. A rule base controller is easy to understand and easy to maintain for a non- specialist end user. An equivalent controller can be implemented using conventional techniques.

Table 3.1: Membership Function Universe of Discourse of Error

e/de	NL	NM	NS	ZR	PS	PM	PL
NL	NL	NL	NL	NM	NS	NS	ZR
NM	NL	NL	NM	NS	ZR	ZR	PS
NS	NL	NM	NS	NS	PS	PS	PM
ZR	NM	NM	NS	ZR	PM	PM	PM
PS	NM	NS	ZR	PS	PM	PM	PL
PM	NS	ZR	PS	PS	PL	PL	PL
PL	ZR	PS	PS	PM	PL	PL	PL

All the membership functions are symmetrical for positive and negative values of the variables. The linguistic labels are divided into seven group which are: Negative Big (NL), Negative Medium (NM), Negative Small (NS), Zero (ZR), Positive Small (PS), Positive Medium (PM) and Positive Large (PL). The shape of membership function and the universe of discourse are found by trial and error through several simulations. Control theory for fuzzy PID as shown below:

Equation (1) showing output of PID Controller

$$\boldsymbol{C(p) = P_{out} + I_{out} + D_{out}} \tag{3.21}$$

By theory output of the proportional (P_{out}) as (2),

$$\boldsymbol{P_{out} = Kp.et} \tag{3.12}$$

Equation (3) showing output of the integral (I_{out})

$$\boldsymbol{I_{out} = ki \int_0^t e(t)dt} \tag{3.13}$$

Equation (4) showing output of the derivative,

$$\boldsymbol{D_{out} = Kd\frac{de}{dt}} \tag{3.14}$$

Subsequently substitute (2) & (3) & (4) into (1),

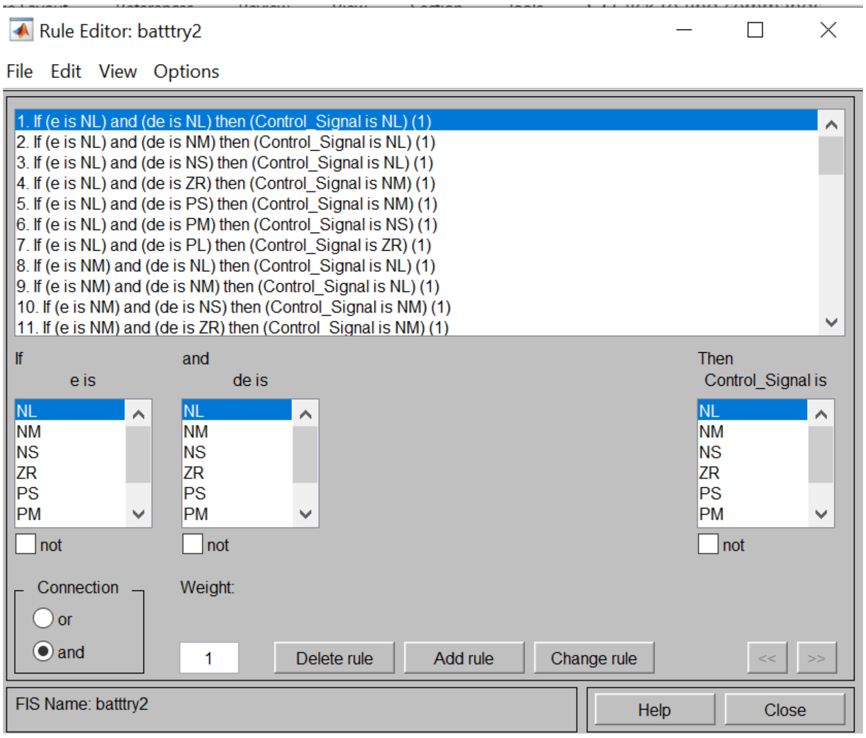
$$\boldsymbol{C(p) = Kp.e + Kd\frac{de}{dt} + ki\int_0^t e(t)dt} \tag{3.15}$$

Output of a conventional PID is showing in (5).

By adding fuzzy logic control, a modified control equation is as below:

$$\boldsymbol{C(p) = (\Delta Kp + Kp).e + (\Delta Kd + Kd)\frac{de}{dt} + (\Delta ki + ki)\int_0^t e(t)dt} \tag{3.16}$$

The output of hydro turbine after adding fuzzy logic controller into the system is illustrated in Equation 6. Fuzzy PID controller given a new value of proportional, derivative and integral. Thus, a detail on the input and output by using if then rules was summarized as Figure 3.18. The proposed fuzzy PID controller has been designed to adjust on-line the parameters of proportional gain Kp and integral gain Ki of a PID controller based on the frequency error e and the change in frequency Δe. Kp is the sum of the reference value Kp * and Δ Kp. Ki is the sum of the reference value Ki * and Δ Ki. Kp * and Ki * are the reference values of the controller.



1. If (e is NL) and (de is NL) then (Control_Signal is NL) (1)
2. If (e is NL) and (de is NM) then (Control_Signal is NL) (1)
3. If (e is NL) and (de is NS) then (Control_Signal is NL) (1)
4. If (e is NL) and (de is ZR) then (Control_Signal is NM) (1)
5. If (e is NL) and (de is PS) then (Control_Signal is NM) (1)
6. If (e is NL) and (de is PM) then (Control_Signal is NS) (1)
7. If (e is NL) and (de is PL) then (Control_Signal is ZR) (1)
8. If (e is NM) and (de is NL) then (Control_Signal is NL) (1)
9. If (e is NM) and (de is NM) then (Control_Signal is NL) (1)
10. If (e is NM) and (de is NS) then (Control_Signal is NM) (1)
11. If (e is NM) and (de is ZR) then (Control_Signal is NM) (1)

If e is NL and de is NL Then Control_Signal is NL

Connection: ○ or ● and

Weight: 1

FIS Name: batttry2

Figure 3.16: If THEN rules for Fuzzy Controller

Total 49 rules are created to give a better control to a servomotor. Fuzzy inference process is a process in which membership function is combined with the control rules to derive the output. In this research if then rules involving fuzzy sets, fuzzy logic and inference is mapped and given as output. An example is as below;

If e is NL and de is NL, then control signal is NL

If e is NL and de is NM, then control signal is NL

Fuzzy linguistic variable can be easily performed and characterized by some common terms such as “Negative Large (NL), Negative Small (NS), Negative Medium (NM), Negative Small (NS), Zero, Positive Small (PS), Positive Medium (PM), and Positive Large (PL)”

3.6.1.2 Defuzzification Process

Defuzzification of the engine inference evaluates the based rule on controlling activities for sent sources of fuzzy inputs. This operation transforms the inferred fuzzy type controlling activity into a numerical value at the output side by forming a group of the output side obtained from every rule. The centre of that area algorithm is utilized for defuzzification. The output defuzzification membership function for K_p, K_i and K_d after being through the membership rule editor is shown in Figure 3.19 and Figure 3.20.

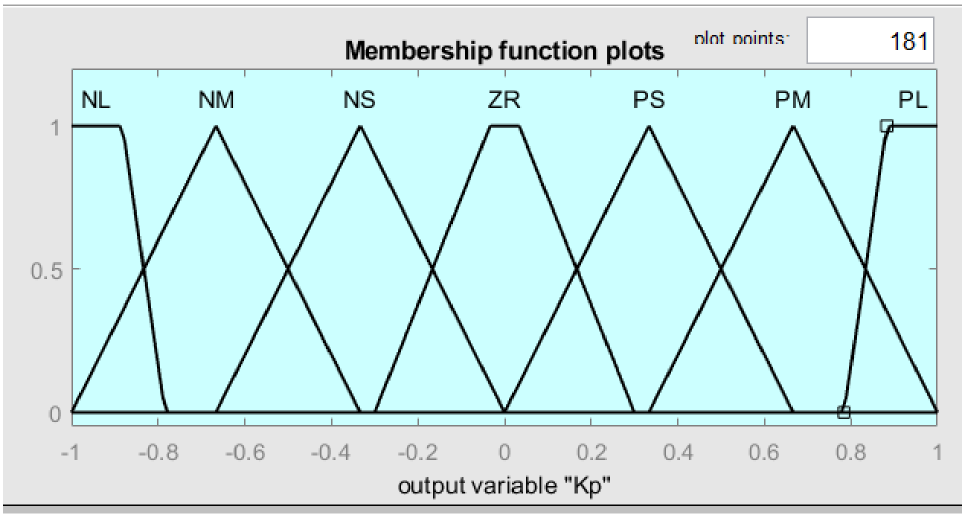


Figure 3.17: Output membership function for K_p

For proportional gain, K_p, seven fuzzy subsets are chosen as an output which are Negative Large (NL), Negative Small (NS), Negative Medium (NM), Negative Small (NS), Zero, Positive Small (PS), Positive Medium (PM), and Positive Large (PL)

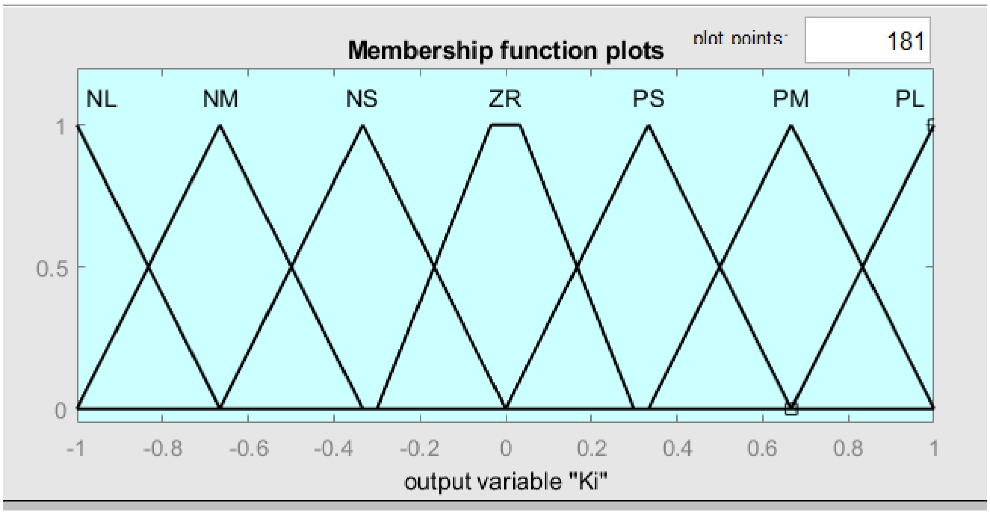


Figure 3.18: Output membership function for K_i

For integral and derivative gain presented in Figure 3.20 and Figure 3.21, also seven fuzzy subsets are chosen as an output which are Negative Large (NL), Negative Small (NS), Negative Medium (NM), Negative Small (NS), Zero, Positive Small (PS), Positive Medium (PM), and Positive Large (PL).

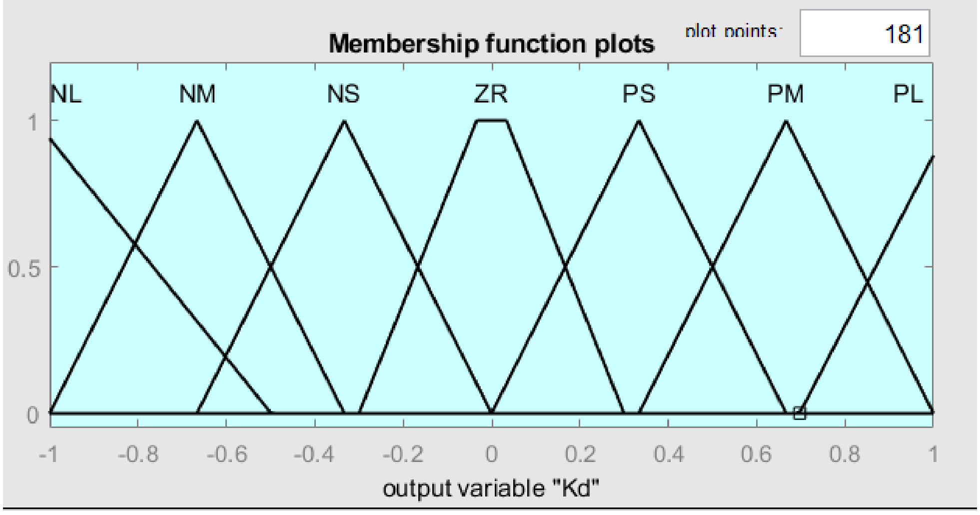


Figure 3.19: Output membership function for K_d

By using method Centre of Gravity, the degree of membership function is determined within the range [-1 to 1]. The design process of fuzzy control rules involves defining the rules that relate the input variables to the output model properties. After the rules are evaluated, each output membership function will contain a corresponding membership. From these memberships, a numerical (crisp) value was produced. The imprecise fuzzy control action generated from the inference must be transformed into a precise control action in the application.

CHAPTER 4 RESULTS

4.1 Introduction

Implementation of methodologies adopted to develop flow and load controllers is illustrated in this chapter. Several different cases are developed to obtain results that advocate the efficacy of the proposed controllers. The simulations are carried out in MATLAB SIMULINK. In this simulation, the voltage is primarily controlled through the excitation of the generator and the system's frequency is maintained by eliminating the mismatch between generation and load demand through load shedding. Moreover, these two parameters are also interlinked, such that when the load is reduced the frequency of the system increases which also increases the system's voltage. Therefore, both parameters have to be controlled simultaneously. Two scenarios are considered, in scenario one response of controllers to changes in system load is considered and in scenario two response of controllers to changes in water intake flow is considered. Each scenario further consists of several test cases. The cases under study corroborate the premise that the proposed controller is able to efficiently control the water flow and output of the Pico hydropower plant under load changes. The chapter is further divided into three subsections. In the first subsection cases and results of load reductions are illustrated. In the second subsection cases and results of changes in water flow are illustrated and in the third subsection results of both controllers are discussed.

4.2 Results of changes in load

Results of changes in the load and the controller's capability of maintaining system frequency under different cases are presented in this section. The proposed controller is termed as integration control which consists of a Fuzzy PID controller to control the water flow and a PID controller load controller. The performance of the proposed controller is compared with a standalone PID load controller and the standalone Fuzzy PID flow controller. Results of changes in load for each controller are obtained for the following test cases.

1) Steady-state system operation
2) System operation with 20% load reduction
3) System operation with sudden 50% load reduction and return to normal load

4) System response during a three phase fault

4.2.1 Steady-state system operation

The first case taken under consideration investigates the performance of the proposed integration controller, standalone PID controller and Fuzzy PID flow controller under the steady-state operating condition of the system. This case will also serve as a benchmark for future cases, as the performance of the controller under steady operation will be compared with the performance of the controller under load changes. The result of the standalone PID load controller under steady-state operation is presented in Figure 4.1. It can be observed that the orange line depicting the operation of the system is wide which indicates there is still small variation in the system's performance and the system is oscillating even in stable condition. It can also be observed that the rise time is 1.29s and peak time is 3.61s and the response settles at 11.65s. The system response also has an overshoot value of approximately 1.5 %.

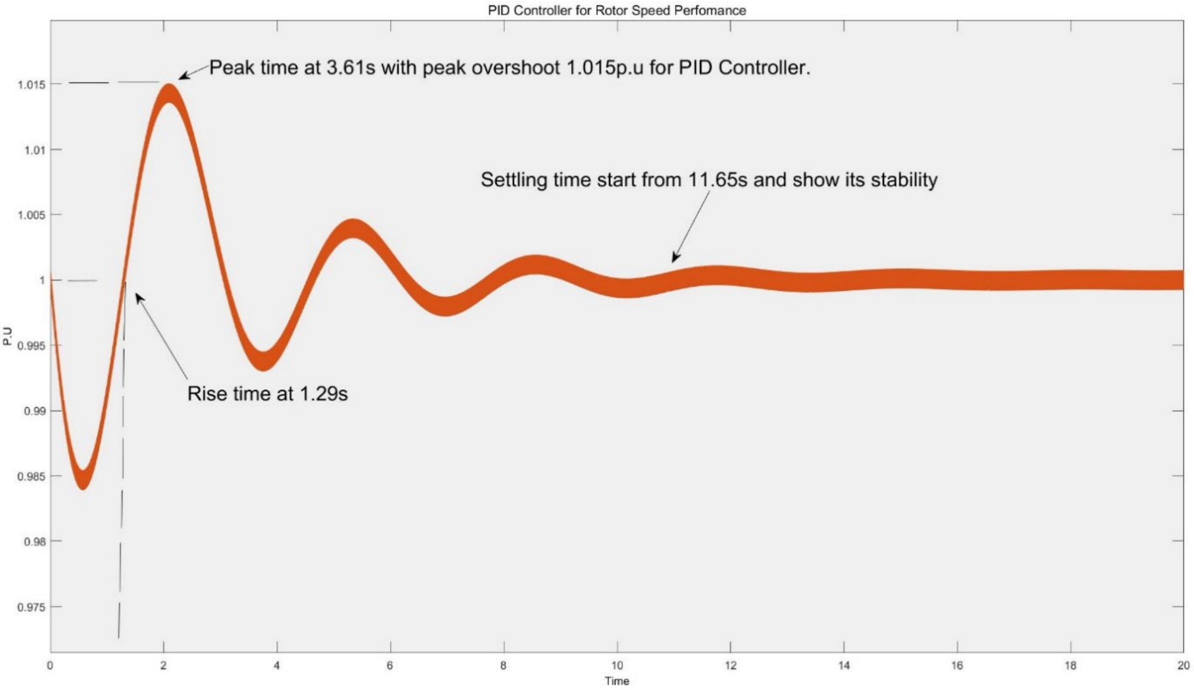


Figure 4.1: Performance of PID controller under steady-state

The performance of the proposed Fuzzy PID flow controller under steady-state operation is illustrated in Figure 4.2. It can be observed that the system's response is depicted by a solid blue line which is also narrow similar to the response of the integration load controller, indicating that the system is stable. It can also be observed that the response starts approximately 2.5% below the desired value. This happens due to the nature of the load, generally, when the load is inductive the system exhibits a low value in the start of the response. The system then transitions to an overshoot response, before settling at 9.6 seconds. The rise time of the response is 3.35 seconds, and the response peaks at 4.12 seconds. The overshoot is almost negligible at 0.2 %.

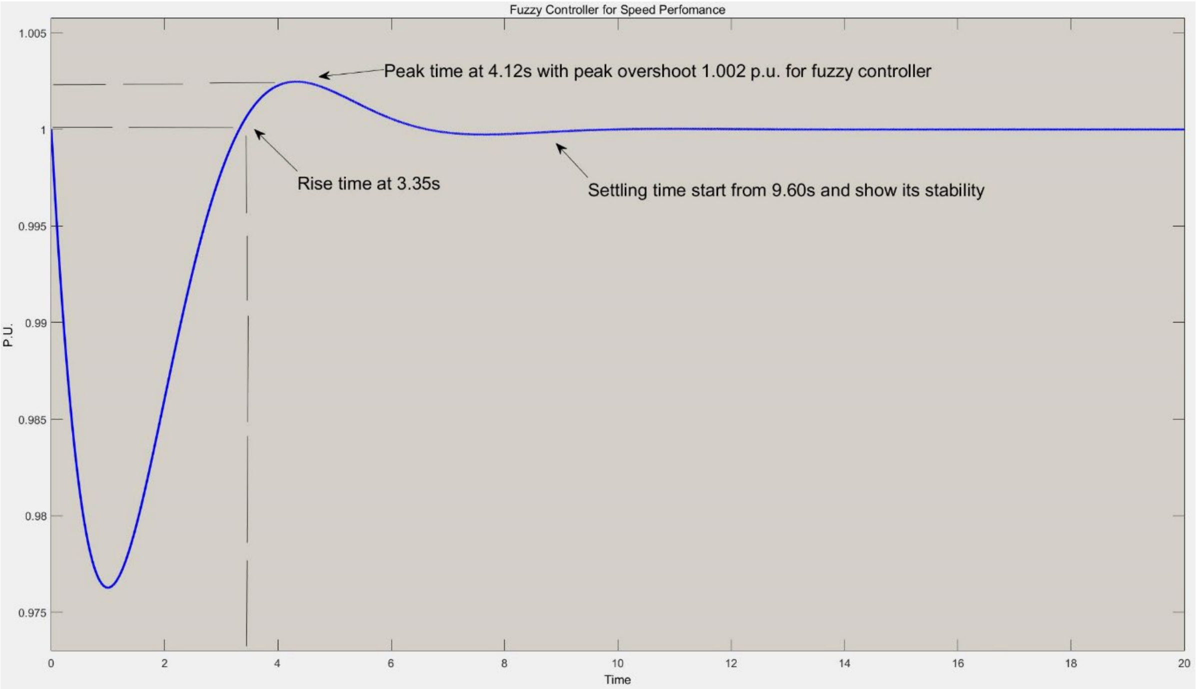


Figure 4.2: Performance of Fuzzy PID flow controller

The result of the integration controller for under steady-state operation is presented in Figure 4.3. It can be observed that the system's response is depicted by a dashed magenta line. Moreover, the system's response is a narrow line unlike the wide line of the PID controller, which indicates the is entirely stable when it settles. The rise time of the response is 2.24s which is greater than the PID controller, whereas the peak time is 3.61s which is the same as the PID controller. The system settles at 14.49 seconds. The percentage overshoot is 10%. It can be observed that the percentage overshoot is 5% less than the PID controller and this system's oscillations have decreased significantly. However, the settling time has increased by 2.84 s.

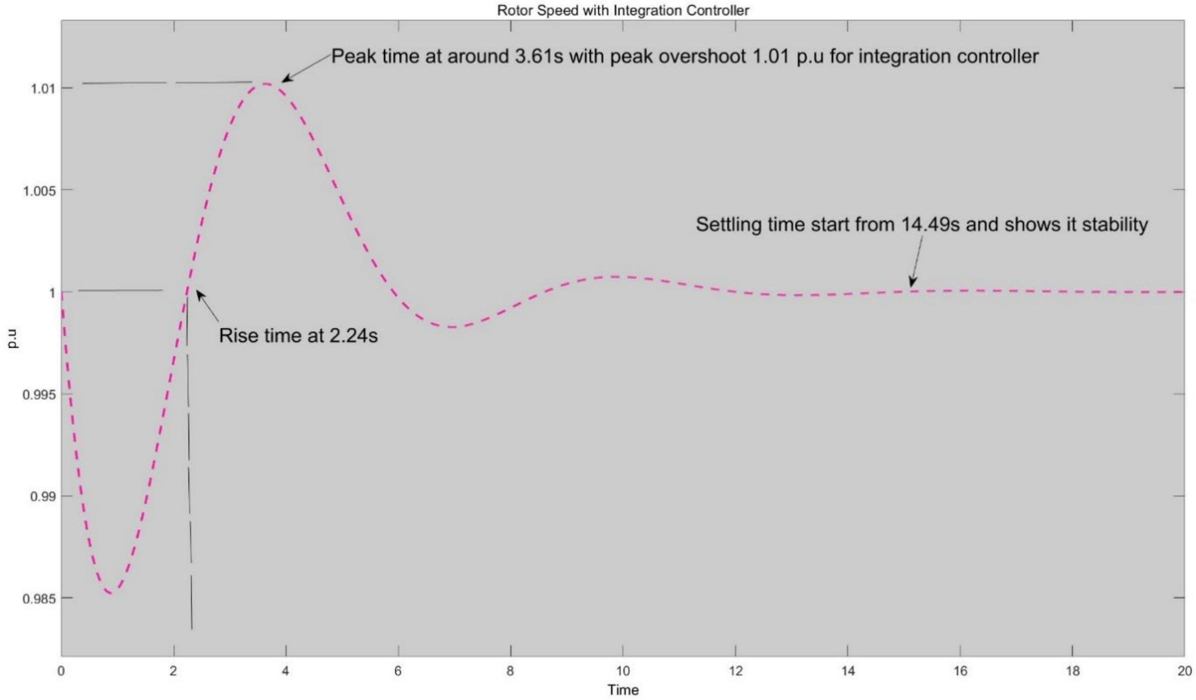
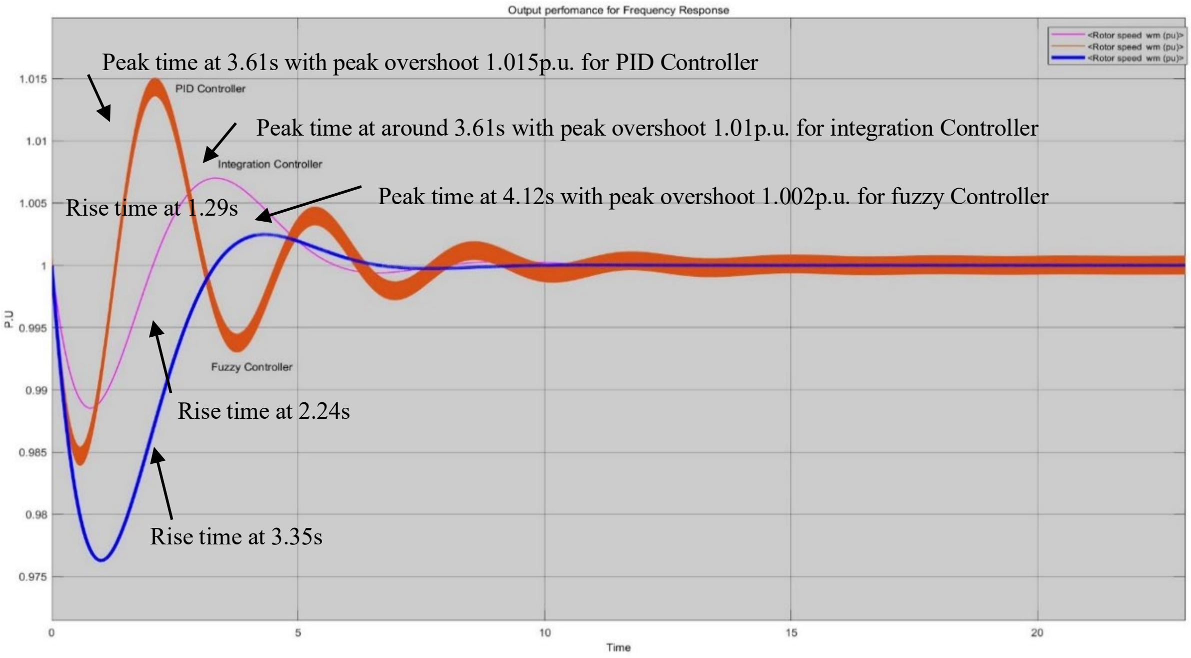


Figure 4.3: Performance of Integration controller under steady-state

The comparison of the steady-state responses discussed above is presented in Figure 4.4. The response of the standalone load controller under steady-state operation is depicted by the orange line. The response of the integration load controller under steady-state operation is depicted by a pink solid line. The response of the PID flow controller is depicted by a solid blue line. Figure 4.4 is the superposition of these three responses. It can be observed that the response of the standalone controller has the greatest number of oscillations and the response is very wide, indicating that the system is highly underdamped. The Fuzzy PID flow controller starts 2.5 % below the desired reference value. The response of the integration controller is an improvement over the standalone controller's response as the percentage of overshoot has decreased. Furthermore, it can also be observed that the number of oscillations in the system has also decreased significantly. The rise and peak time of the response is higher than that of the standalone controller which indicates that the system's damping has increased.



Peak time at 3.61s with peak overshoot 1.015p.u. for PID Controller

Peak time at around 3.61s with peak overshoot 1.01p.u. for integration Controller

Peak time at 4.12s with peak overshoot 1.002p.u. for fuzzy Controller

Rise time at 1.29s

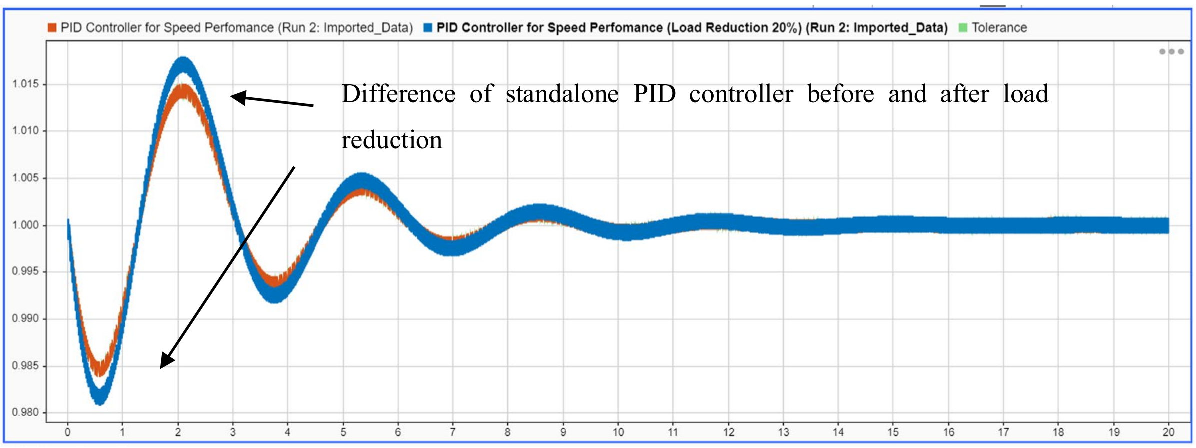
Rise time at 2.24s

Rise time at 3.35s

Figure 4.4: Comparison of steady-state responses.

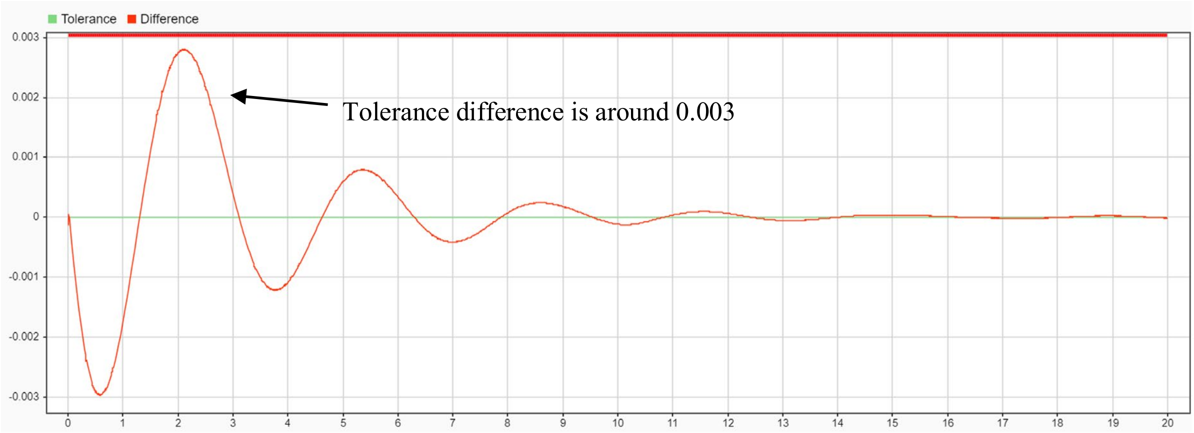
4.2.2 System operation with 20% load reduction

The second case taken into consideration is the system's response after a 20% reduction in the system's load. This specific case is taken into consideration to prove that the proposed controller performs efficiently in a scenario of load reduction. The performance of the standalone PID controller's response before and after a 20% load reduction is shown in Figure 4.5. The response before the reduction is depicted in orange colour and the response after a 20% reduction is depicted in blue colour. It can be observed that the number of oscillations is the same for both responses, however, after a reduction in load the percentage overshoot has increased and the percentage of starting value representing the initial dip has also increased. The difference between both responses in shown in Figure 4.6. It can be observed that the difference in both responses is very small.



Difference of standalone PID controller before and after load reduction

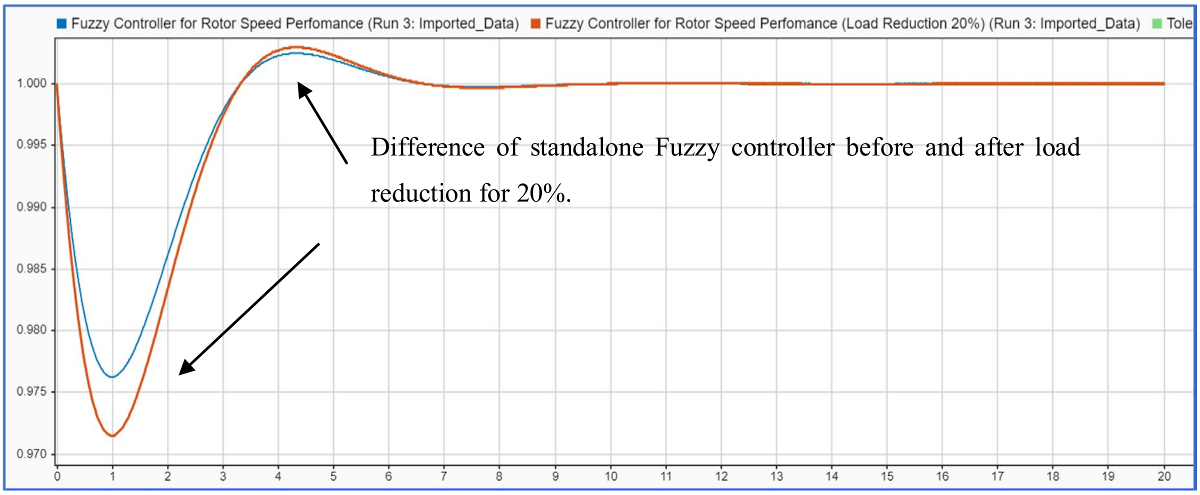
Figure 4.5: Response of system with standalone PID controller under steady-state operation and after 20% load reduction



Tolerance difference is around 0.003

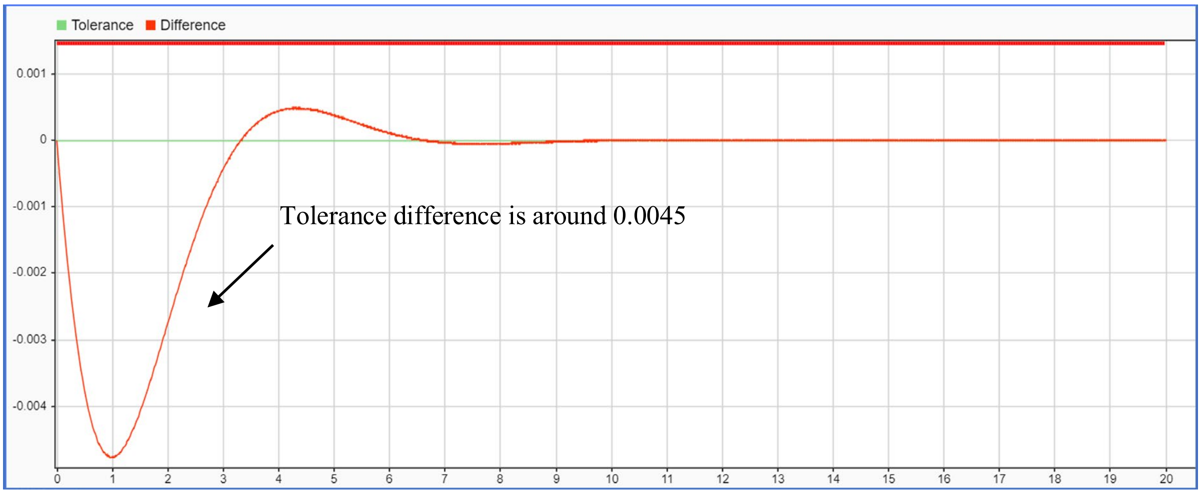
Figure 4.6: Difference in responses before and after 20% load reduction

The results of the Fuzzy PID flow controller to 20 % reduction in load are presented in Figure 4.7. Furthermore, the response after 20% load reduction (depicted by a solid orange line) is compared with the performance of the Fuzzy PID flow controller under steady-state operation (depicted by a solid blue line). As discussed in section 4.2.1 the response resembles that of an overdamped system as it rises slowly, but the system is not entirely overdamped as there is an overshoot also present. The same pattern is observed for the response of the controller after a 20 % reduction in the system's load. It can be observed that the percentage of overshoot is increased. This increase in overshoot represents the instability introduced in the system due to load reduction. The instability is caused due to the increase in frequency and voltage due to a reduction in load. The difference in responses of the Fuzzy PID flow controller before and after the 20 % load reduction is presented in Figure 4.8. It can be observed that the difference in initial value is 0.005 pu which is minute, whereas the difference in overshoot is 0.0005 pu which is almost negligible. Moreover, it can also be observed that the settling time and final value of both responses is the same, which indicates that the controller has efficiently controlled the system in its transient state and has returned the system's response to steady-state before the settling time.



Difference of standalone Fuzzy controller before and after load reduction for 20%.

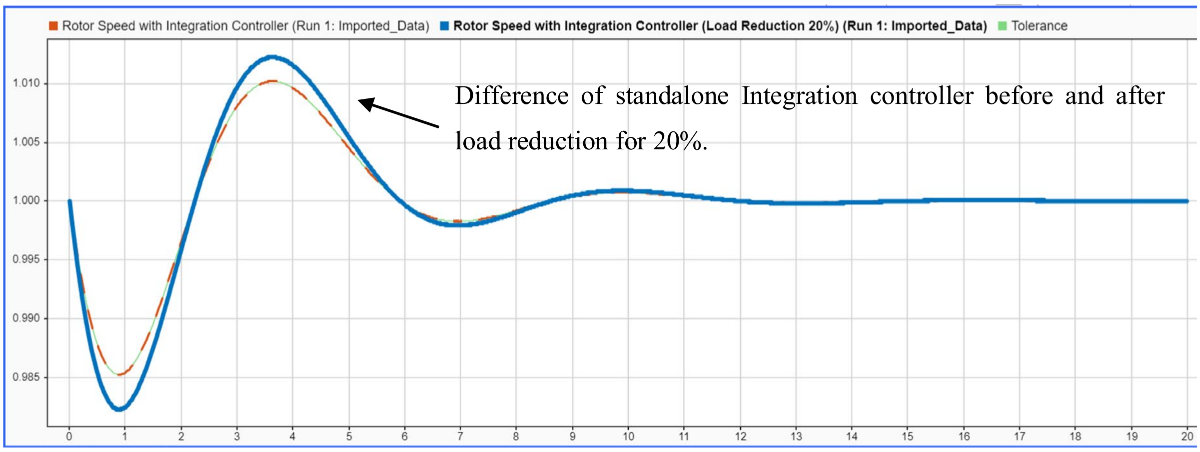
Figure 4.7: Response of system with Fuzzy PID flow controller under steady-state operation and after 20% load reduction



Tolerance difference is around 0.0045

Figure 4.8: Difference in responses before and after 20% load reduction

The results of the integration load controller obtained after a reduction of 20 % are presented in Figure 4.9. Furthermore, the response after 20% load reduction (depicted by a solid blue line) is compared with the performance of the integration load controller under steady-state operation (depicted by a solid orange line). The integration controller comprises of both the flow and load controllers. This means that whenever there is a disturbance in the system both the power mismatch and the flow of water are controlled to stabilize the system. Therefore, it can be observed that the response shown in Figure 4.9 is also the combination of the PID load controller response and the Fuzzy PID flow controller response. The response has an initial value characteristic similar to that of the Fuzzy PID controller and the number of oscillations and overshoot are similar to that of the PID load controller. It can be observed that the pattern of the response after a reduction of 20 % in load is similar to that of the system's operation under steady-state. However, the percentage of overshoot and initial value has increased. It can also be noted that the settling time of both the responses is the same which indicated that the controller swiftly and efficiently returned the system to steady-state. The difference between both responses before and after a reduction of 20 % in load is presented in Figure 4.10. It is evident that the initial value has decreased by 0.003 pu and the overshoot has increased by 0.002 pu, which are both minute increments.



Difference of standalone Integration controller before and after load reduction for 20%.

Figure 4.9: Response of system with integration controller under steady-state operation and after 20% load reduction

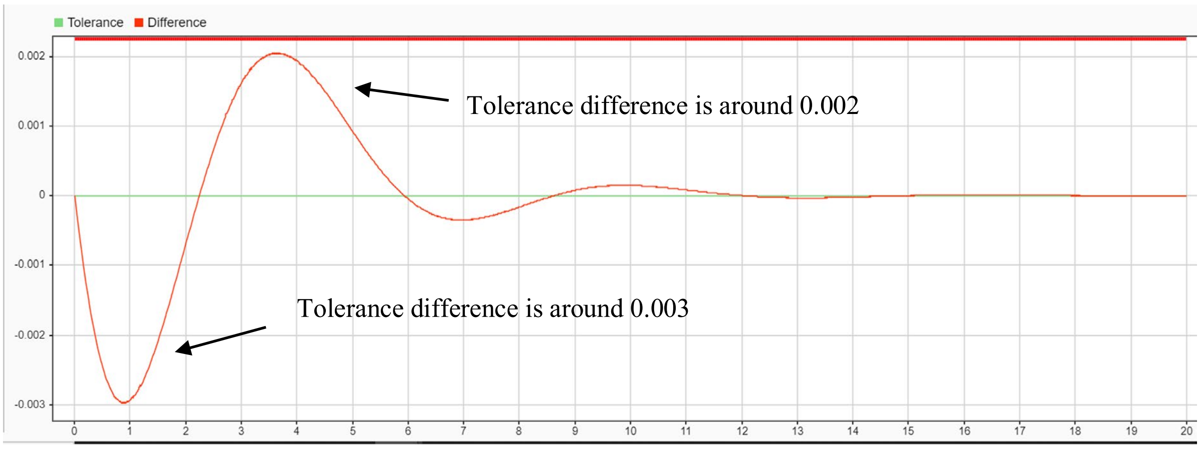


Figure 4.10: Difference in responses before and after 20% load reduction

A plot of variation in the system's frequency is presented in Figure 4.11. It can be observed that the system was operating between 50.1 Hz and 49.99 Hz under steady-state conditions. The reduction in the load increased the magnitude oscillations of the system's frequency between 50.02 Hz and 49.98 Hz. This increase was detected and controlled by the integration controller which returned the system's frequency to steady-state in 0.2 seconds.

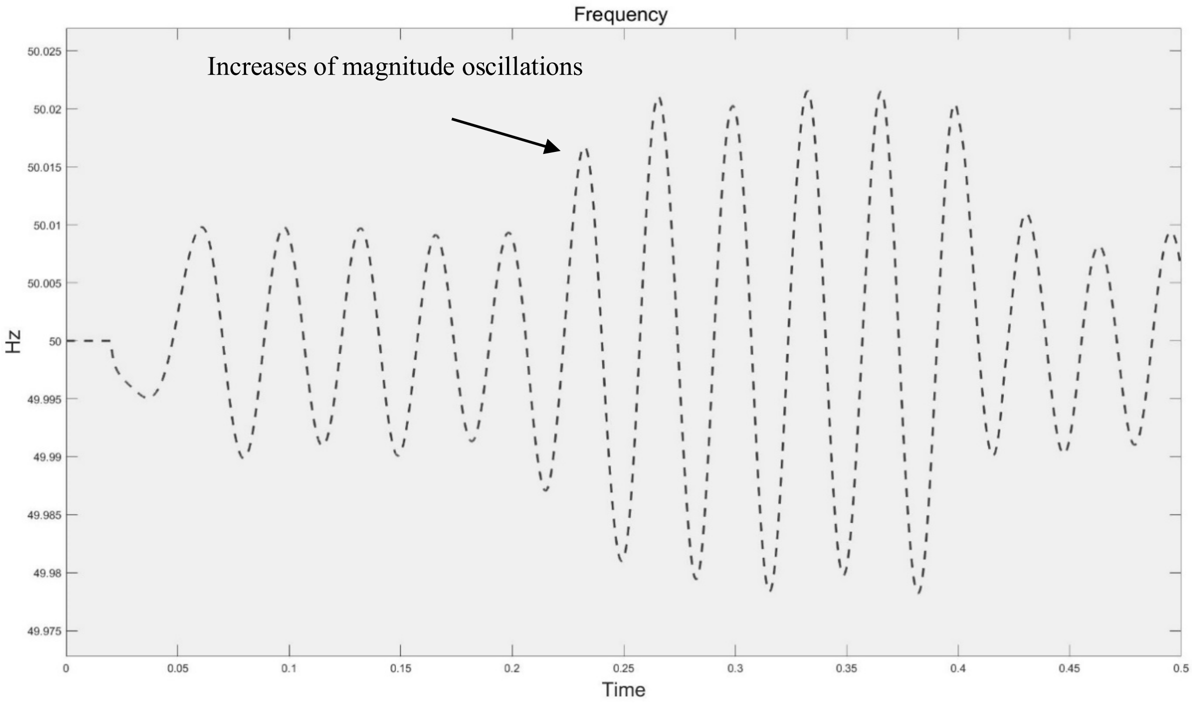


Figure 4.11: Frequency variation after a 20 % reduction in load

4.2.3 System operation with sudden 50% load reduction and return to normal load

The third case taken into consideration is a sudden reduction in the system's load by 50 %. In this case, the system is initially running at steady-state with rated load capacity and the system's load is suddenly decreased by 50 % at a specific time of 12 secs and then returned back to normal load at 14 seconds. The time of change in load is kept constant during the acquisition of responses of all three controllers to maintain uniformity. This specific case is taken into consideration to show the performance of the proposed controller under sudden changes of high magnitude. In this case, the system's load is suddenly reduced to 50 %.

The response of the PID load controller to a sudden 50 % reduction in the system's load is presented in Figure 4.12. It can be observed that the number of oscillations in the overall response of the system is high. It can be observed that there are three overshoots present in this response. The first overshoot is due to the initialization of the system after which it maintains a steady-state. The second overshoot is due to the sudden change of high magnitude in the load, which inserts transient into the system. The third overshoot is due to the controller's efforts of stabilizing the system after the load is increased back to normal value at 14 seconds. The value of the first overshoot is approximately 1.02 pu, the value of the second overshoot is 1.009 pu and the value of the third overshoot is 1.01 pu. The rise time of all three responses varies as well. The systems settle after experiencing this transient event at 27.31 seconds.

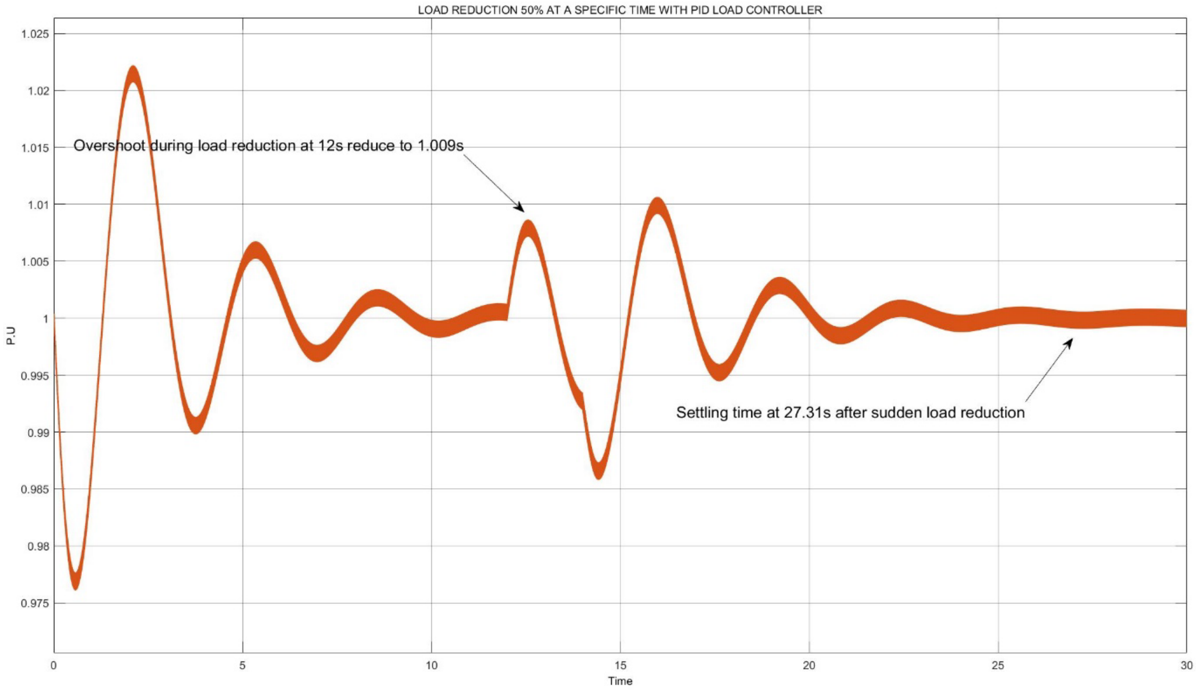


Figure 4.12: Response of PID load controller to a load reduction of 50% at 12 sec and return to normal load at 14 sec

The response of the Fuzzy PID flow controller to the transient event is shown in Figure 4.13. It can be observed that there are also three overshoot values in the system similar to that of the PID load controller. Each overshoot value represents a different state of the system. The value of the first overshoot is approximately 1.003 pu, the value of the second overshoot is 1.02 pu which is 1.7 % higher and the value of the third overshoot is almost equal to the reference value. It is evident from the results that the response of the Fuzzy PID flow controller is a significant improvement over the response of the PID load controller, as the percentage overshoot has decreased, and the number of oscillations has also decreased. The settling time of the response is 23 seconds which is also an improvement over the PID load controller. However, it can be observed the rise time of all three responses has increase compared to the PID load controller.

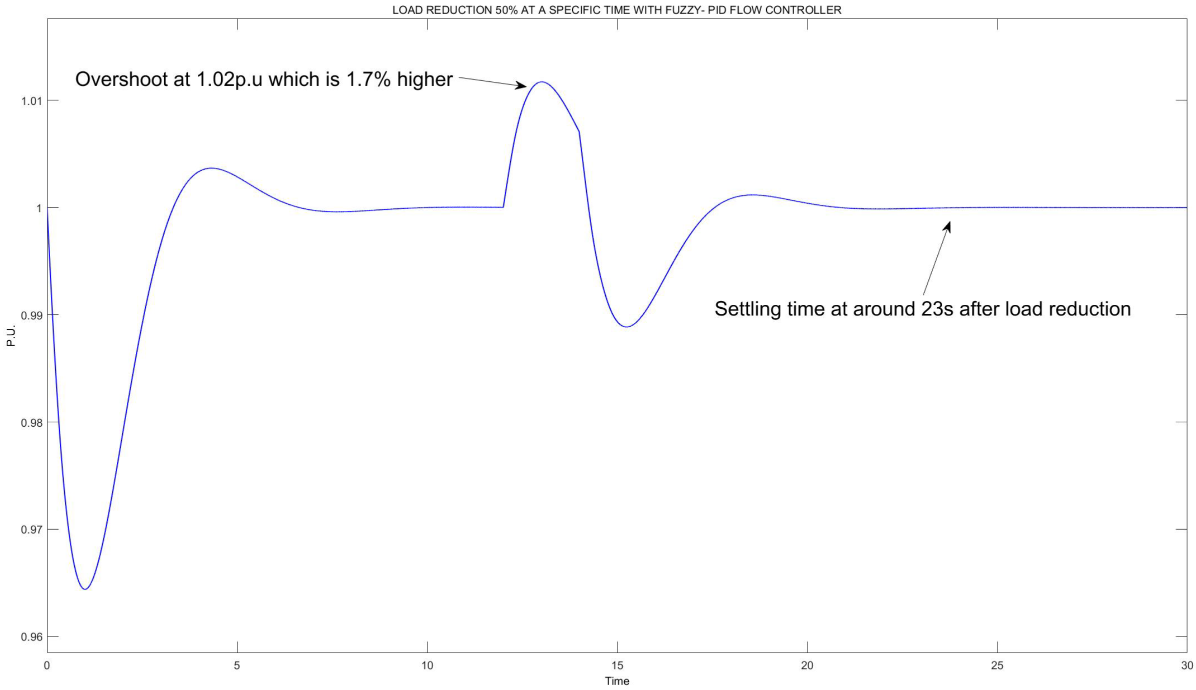


Figure 4.13: Response of Fuzzy PID flow controller to a load reduction of 50% at 12 sec and return to normal load at 14 sec

The response of the integration controller to the transient event is presented in Figure 4.14. It can be observed that similar to the previous controller's responses three overshoots also exist in this response as well. The value of overshoot at the instance of sudden load reduction is 1.007 pu, which is less compared to the Fuzzy PID flow and PID load controllers. Furthermore, the system's overshoot value after sudden load gain at 14 seconds is 1.005 pu which is also an improvement. It can also be noted that the rise time for all three responses of the integration controller is higher compared to the Fuzzy PID flow and PID load controllers. However, the settling time is slower compared to Fuzzy -PID flow control with the reduction of 50% load reduction which is at around 25.7s. This proves that the integration controller in the hydro turbine management unit performs better than either standalone fuzzy -PID flow control or standalone PID load control. Even with a sudden load reduction, the integration controller is able to maintain speed oscillation and reaches its steady-state in a short time after 14s.

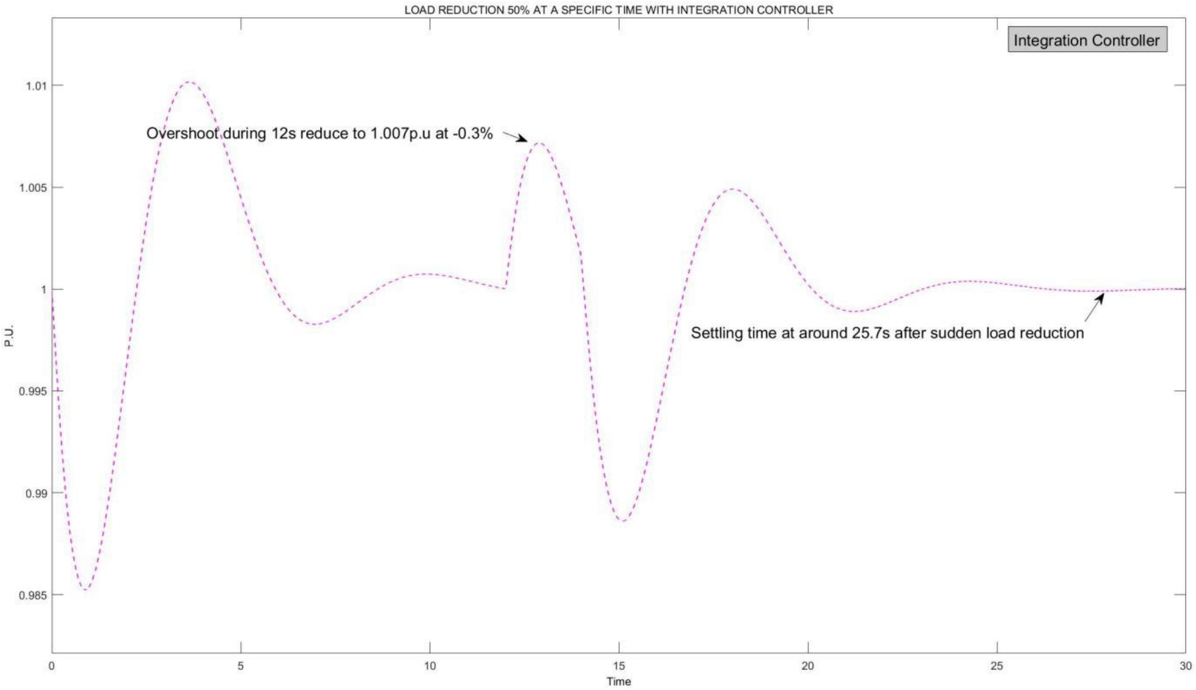


Figure 4.14: Response of Integration controller to a load reduction of 50% at 12 sec and return to normal load at 14 sec

4.2.4 System response during a three-phase fault

The fourth case taken into consideration is the occurrence of a three-phase fault in the system. The system experiences a three-phase fault occurring at 10 seconds and is cleared at 12 seconds. After the fault is cleared the system then returns to its normal operating conditions. The frequency of the system drops significantly during fault. This specific case is taken into consideration to prove the efficacy of the proposed controller under system fault conditions. A comparison of the performance of standalone PID load controller, Fuzzy PID flow controller and integration controller is presented in Figure 4.15. The response of the standalone PID load controller is depicted by a solid orange line, the response of the Fuzzy PID flow controller is depicted by a solid blue line and the response of the integration controller is depicted by a solid magenta line.

The rotor speed decreases as the load current increases when the fault is incurred in the system. It is evident from Figure 4.15, that the integration controller outperforms both the PID load and Fuzzy PID flow controllers, as it has the lowest value of overshoot when the fault is incurred on the system at 10 seconds. This advocates the ability of the integration controller to swiftly and efficiently control the system during fault. It can be also be noted that the slope or fall time of the response immediately after the overshoot is lowest for the integration controller as well. This indicated that the integration controller can maintain system stability through the minimization of oscillations.

The fault is cleared at time of 12 seconds, after which the system transitions towards its steady-state. It can be observed that the integration controller has the lowest initial value which indicates that it has the lowest percentage of deviation from the reference value. Subsequent to this the system overshoots again while transitioning to steady state. The percentage overshoot of the integration controller is slightly higher as compared to the Fuzzy PID flow controller; this is due to the fact that the Fuzzy PID flow controller tries to keep the system's response overdamped. The settling time of the integration controller is also slightly higher as compared to the Fuzzy PID flow controller, this is also due to the fact the response of the integration controller is more underdamped as compared to the Fuzzy PID controller. However, the rise time of the integration controller is high due to its underdamped nature. Overall, it is evident that the integration controller performance is better compared to the other controllers.

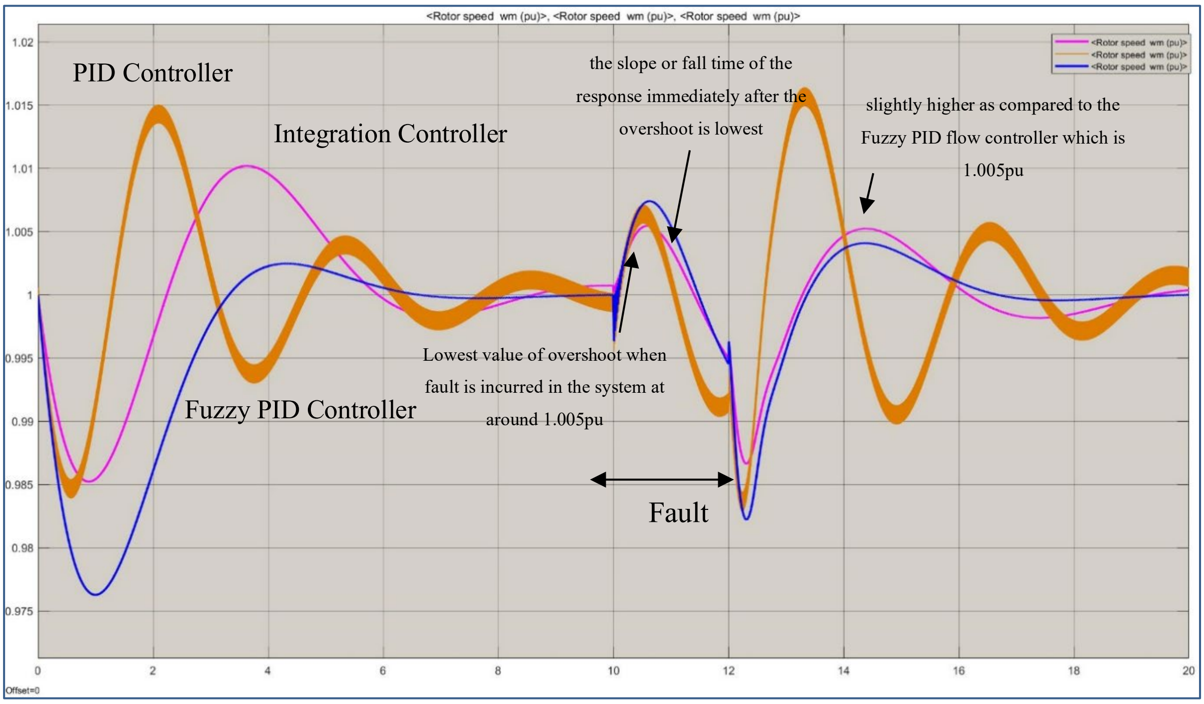


Figure 4.15: Performance comparison of standalone PID load, Fuzzy PID flow and Integration Controllers

4.3 Discussion

The results presented in section 4.2 are discussed in this subsection. An integrated controller comprising of Fuzzy PID flow controller and PID load controller was proposed in this study. The analysis of its performance under several different cases is discussed in this subsection. The proposed integration controller was designed with the objective of simultaneously controlling the water intake flow (speed) of the Pico hydro turbine and the load frequency controller of the generator. The performance of the proposed integration controller is tested on below scenarios: in which the load of the system is changed and each of that consists of several cases.

The results of each of the case is presented in section 4.2. The first case which is taken into consideration is steady-state operation of the system. This case also served as a reference for subsequent cases as well. The comparison of performance parameters of PID load controller, Fuzzy PID flow controller and integration controller under case 1 is presented in Table 4.1. The parameters under consideration are rise time (t_r), overshoot percentage and settling time (t_s), It can be observed the standalone PID controller has the quickest rise time (1.29 sec), this is the reason that the number of oscillations is high in it. Whereas the Fuzzy PID flow controller has the slowest rise time (3.35 sec), this is also undesirable as the system takes a long time to reach the reference value. The integration controller has an intermediate value of rise time (2.24 sec), due to which the number of oscillations is less compared to the PID controller, and it reaches the reference value quicker than the Fuzzy PID flow controller.

The percentage of overshoot is the second performance parameter under consideration. It can be observed that the percentage overshoot of the PID controller is the highest (1.5%) and as a result the number of oscillations in the system is also increased. The percentage overshoot of the Fuzzy PID flow controller is the lowest (0.2 %) this is due to the high-rise time. The percentage overshoot of the integration controller is intermediate (0.7 %), which indicates that the system rises quickly and also has a minimal percentage of overshoot.

Settling time is the third performance parameter under consideration. The settling times of the PID controller, Fuzzy PID flow controller and integration controller are 11.65 sec, 9.6 sec and 14.49 sec respectively. It can be observed that the integration controller has the highest settling time, which is not ideal, however, the controller has better rise time and percentage overshoot.

Moreover, the response of the PID controller was broad line has shown in Figure 4.5 which indicated the system is oscillating even under after settling, and the Fuzzy PID controller is has a very high rise time. Therefore, it is evident from the collective analysis of all three parameters and the response shapes integration controller performs better than the other controllers under steady-state operation.

Table 4.1: Comparison of performance parameters of controllers under case 1

Performance parameters	Standalone PID controller	Fuzzy-PID flow controller	Integrated controller
Rise time, t_r	1.29	3.35	2.24
Overshoot percentage	1.5	0.2	0.7
Settling time (t_s)	11.65	9.60	14.49

The second case taken into consideration is the reduction of system load by 20 %. The comparison of performance parameters of PID load controller, Fuzzy PID flow controller and integration controller under case 2 is presented in Table 4.2. The performance parameters presented are in reference to case 1, to allow a better understanding of the controller's performance. It can be observed that the reduction in load by 20 % did not have any effect on the rise times of any controller compared to case 1. The percentage overshoot has increased for all three controllers with the highest increment (0.35 %) seen in the standalone PID controller. The percentage overshoot increased by 0.1 % for Fuzzy PID controller and by 0.2 % for integration controller. The PID controller's settling time increases by 2 secs due the increase in number of oscillations and percentage overshoot. The Fuzzy PID controller's settling time remain the same. The settling time of the integration controller is decreased by 0.2 seconds. It is evident from analysis of all three performance parameters that the integration controller efficiently controller the system under a load reduction of 20 %. It maintains the rise time, has minute increase in percentage overshoot and settles quickly after load reduction.

Table 4.2: Comparison of performance parameters of controllers under case 2

Performance parameters	Standalone PID controller	Fuzzy- PID controller	Integrated controller
Rise time, t_r	Almost same	Almost same	Almost same
Overshoot percentage, %	0.35% higher than case 1	0.10% higher than case 1	0.20% higher than case 1
Settling time, (t_s)	2s Slower than case 1	Almost same	0.2s faster than case 1

The third case taken into consideration is a sudden reduction in system's load by 50 % at time 12 secs and then the return of the system load back to 100 % at time 14 secs. This creates a transient event of 2 seconds. The comparison of performance parameters of PID load controller, Fuzzy PID flow controller and integration controller under case 3 is presented in Table 4.3. In can be observed that the overshoot percentage of the Fuzzy PID flow controller is the highest (1.7 %) during this transient event. The PID controller's percentage is 1.1 % lower to that of case 1. The percentage overshoot of the integration controller is also 0.3 % lower than that of case 1. However, the percentage overshoot value of PID controller is significantly higher than that of the integration controller, meaning that even after a decrease of 1.1 % the value of percentage overshoot of PID controller is higher compared to the 0.3 % decrease in percentage overshoot value of the integration controller. It is evident that in this case also the integration controller performed better than both controllers.

Table 4.3: Comparison of performance parameters of controllers under case 3

Performance parameters	Standalone PID controller	Fuzzy -PID Flow controller	Integrated controller
Overshoot percentage, %	1.1% lower compared to case 1	1.70% higher than case 1	0.30% lower than case 1
Settling time, (t_s)	Took longer than fuzzy & Integrated controller	Faster at 23s	Neutral at 25s

The fourth case taken into consideration is the occurrence of a three-phase fault in the system at time 10 secs, which is cleared at time 12 secs. This case illustrates the response of the controllers during a fault event. The responses of all three controllers are presented in Figure 4.15. It was observed that when the fault occurs the integration controller has the lowest percentage overshoot during the fault event. The rise time of both the Fuzzy PID and the integration controller is the same during the fault event. Moreover, the slop of the system's response is also low for the integration controller which indicated that it is trying to keep the system close to the reference value even under fault. Once the fault is cleared the at 12 secs the integration controller still performs efficiently and transitions the system from fault to steady-state.

4.4 Summary:

In this chapter the results obtained after the implementation of the methodology discussed in chapter 3 are presented and discussed. The performance of the proposed controller was compared with a standalone PID controller and a Fuzzy PID flow controller. The responses of the controllers to changes in system load were obtained. The scenario further consisted of several test cases to obtain pertinent results. From the analysis, it is evident the proposed integration controller provides an enhanced control of the Pico hydro system during normal operating conditions and well as transient and fault conditions.

CHAPTER 5 CONCLUSION AND FUTURE WORKS

5.1 Conclusion

One of the limitation of PHPs identified by researchers is the inadequate control of the water inflow and output frequency of the turbine, following their installation. PHPs are usually installed in rural areas as standalone units, and after their installation the indigenous population is responsible for their maintenance. However, the indigenous population lack the resources and the technical knowledge to run and maintain PHPs, particularly when it comes to frequency regulation. The lack of expertise in distant villages about maintaining a mechanical flow governor has been a severe problem for many years. Standalone controllers cause unbalance between power supply and load demand and thus affect the power quality, which is extremely inconvenient for the consumers. Therefore, it is necessary to conduct research into developing an effective integrated controller with the objective of providing stable electricity through frequency and voltage management.

Conventionally, the PID controller has been employed for the purpose of PHP management. A PID controller responds to errors and changes in errors. It has been one of the most sophisticated and extensively used controller in industrial process control applications due to its simplicity and adaptability. Tuning is a process for a particular operating point. A system works at various operating variables, and retuning is essential for the system to maintain system stability. The settings of the PID are carefully tuned using a variety of tuning methods. The PID constant should be chosen so that the response has a rapid rising time, low overshoot, and a quick settling time. Efficient energy management in a system cannot also be neglected while trying to improve system stability. An integrated system with an intelligent approach of Fuzzy-proportional-integral control and proportional-integral-differential control for flow control valve is proposed in this study to improve performance of Pico hydropower plant.

It was evident from the discussed literature that non-linear controller is essential for a Pico PHP to maintain stable supply to the consumers. Several researchers have proposed AI and AI integrated with PID controllers as a feasible solution to this control problem. It can be observed from the literature, that to ensure efficient control of PHP dedicated controllers are needed at the water flow of the turbine, at the load supply side of the generator along with a battery management system. A hydro turbine management unit with separate integrated controllers has not been designed to prevent unwanted equipment downtime and maintenance expenses in this study

In this study a fuzzy logic based integration controller was proposed to achieve efficient water flow and load control of a Pico hydro power plant. The proposed technique is an integrated system with an intelligent approach of Fuzzy-proportional-integral control and proportional-integral-differential control for flow control valve to improve performance of PHP. The proposed controller comprises of Fuzzy PID flow controller and a PID load controller, which work simultaneously to achieve efficient control of the Pico hydro power plant. The proposed technique is also capable of efficiently handling the non-linearities of the PHP. The Pico Hydro power plant and the proposed controller was designed in MATLAB SIMULINK.

The study accurately modelled a PHP, which is characterized as a hydropower plant with a capacity of 5kW or less. Therefore, to simulate / model a PHP all elementary components of a hydropower plant were precisely modelled. These elementary components were reaction turbines using a penstock, wicket gates, a turbine, and a generator. The generator and turbine are connected primarily by a vertical shaft. High water flow rates are produced by the existence of a high head, which flows through the penstock and arrives at the turbine. The valve and gates govern the quantity of water that flows into the turbine by altering the opening of the pivot around the turbine's circumference. Servo-actuator, is used to regulate the position of gates. The head through penstock converts the potential energy of water to kinetic energy as it flows. The turbine-generator set is powered by water flow.

A standalone Pico hydro system was developed and design through MATLAB Software in this study. An overall SIMULINK model for Pico hydro system with integrated controller was modelled. The model was tested through integration controller and compared to standalone controller of Pico hydro system. Output response of hydro turbine flow control and load control is investigated and the results focus on rise time, peak time and overshoot percentage. All the simulink sub-systems such as hydro turbine governor, synchronous motor, excitation system, were modelled precisely. The hydro power plant model developed consisted of hydro turbine governor, synchronous machine with 5000VA and 240V rating, 3 phase active and reactive power measurement block. An excitation system combined with exciter act as the voltage regulator. Output of the generator was connected to an oscillator for analysis of the speed and voltage performance. The electrical part of the machine was represented by a sixth-order state-space model and the mechanical part by the Simplified Synchronous Machine block. The model by default takes into account the dynamics of the stator, field, and damper windings. The cross-sectional shape of the rotor was selected to be salient. Salient pole construction is mostly used in low-speed applications where the diameter to length ratio of the rotor can be large to accommodate the high pole numbers. In the SIMULINK model, salient pole synchronous machines were simulated as it is installed in hydro generators to match the low operating speed of the hydraulic turbines.

Fuzzy logic controller is implemented in this research because it is capable of processing information similar to human thinking and possesses nonlinear intelligent control characteristics. Self-tuning controller is used to readjust the parameters of the PI gains in order to improve the output response. The self-tuning controller is utilized as the PI control has nonlinear characteristics and intellectual faculties, and at the same time enhances fuzzy control with a PI-control configuration.

Fuzzification is the first process in fuzzy controller design. Fuzzification determines the precise control strategies by referring the inputs and outputs of the controller. In hydro turbine governor SIMULINK block, a fuzzy logic controller was added to provide an improved output performance in terms of step response. Speed error and change in speed error were selected as inputs for fuzzy logic, while the outputs of the fuzzy controller were proportional gain, integral gain and derivative gain. All the three outputs control the gate of servo motor through PID parameters that varies the water flow when the disturbance exceeds a certain limit compared to the nominal turbine power. The controller gains were also acquired to stabilize the frequency of the generator when it deviates from the nominal value. The governor system with fuzzy logic controlled the gate opening of the servo motor during load variation and in the presence of disturbance in order to maintain turbine speed.

An appropriate membership function was required for inputs and outputs. Every element in the universe of discourse is a member of a fuzzy set to some grade, maybe even zero. The grade of membership for all its members describes a fuzzy set, such as Negative, and Positive. In fuzzy sets, elements were assigned a grade of membership, such that the transition from membership to non-membership is gradual rather than abrupt. The function that tied a number to each element of the universe was termed as the membership function. In this study triangular and trapezoidal shapes were adopted for the membership functions for all inputs and outputs variables. The shape of the membership function and the universe of discourse for each function was found by trial and error after conducting several simulations.

The efficacy of the proposed controller was tested against a standalone PID load controller and Fuzzy PID flow controller under one scenario. The performance of the proposed controller was test against changes in load through four test cases. In case one, the performance of the system under steady-state operation simulating stable running conditions was taken into consideration. Responses of all three controllers were compared. The proposed controller performed better than standalone PID load and Fuzzy PID flow controller

In case two, the performance of the system under load reduction of 20 % was taken into consideration. The specific case was taken into consideration to show that the proposed controller is capable of efficiently stabilizing the system under low load running conditions. The responses of all three controllers were compared. It was observed that the all three controllers were able to stabilize the system, however, the proposed integration controller has better rise time, less percentage overshoot and good settling time.

In case three, the performance of the system running in steady-state being subjected to a sudden reduction of load by 50 % and then increase to normal load was considered. This specific case simulated a transient event which lasted for two seconds. It was observed from results that the performance of the proposed integration controller was superior to the standalone PID load and Fuzzy PID flow controller. When the load was decreased suddenly the proposed integration controller has lowest decrease in percentage overshoot and stabilized the system to its reference value quickly.

In case four the performance of the system under fault was taken into consideration. A three-phase fault is incurred on the system for two seconds and then it is cleared after which the system returns to its steady-state operation. This specific case was taken under consideration to prove that the proposed controller is capable of maintaining system stability under fault conditions. It was observed from the results that the proposed integration provided improved control of the system during and after fault. During the occurrence of the fault, it prevented the system from overshooting and oscillating. After the fault was cleared it had the lowest initial variation from the reference value and low percentage overshoot.

It is evident from the results that the proposed integration controller performs better than PID load controller and Fuzzy PID controller. The proposed controller's response had low rise times and low percentage of overshoots compared to the PID load controller and Fuzzy PID flow controller. Results prove that the proposed technique can efficiently control the system's frequency and intake water flow during load and flow variations.

5.2 Future Work

An analytical model to predict the performance and effectiveness of Pico hydropower system especially in rural area is investigated in this study. Integration controller comprising of Fuzzy PID flow controller and PID load controller to achieve efficient control of Pico hydro power plant was proposed in this study. Simulation results exhibit the efficacy of the proposed fuzzy control system, even for random substantial load system. Possible future works include:

1) The proposed controller can be integrated with battery energy storage system to provide support during sudden increase in demand of load.
2) There are plenty of renewable energy sources which maybe relevant for rural electrification such as wind energy and solar. Therefore, performance of fuzzy logic controller can be investigated by implemented it in those type of generation.
3) The proposed controller should be implemented on hardware to conduct in depth analysis of its benefit to the rural communities. Integration controller can be installed and compared to the output result with the simulation. Based on a survey of Sarawak there has been no hardware implementation of integration controller so far.
4) Most of the rural areas have budgetary constraints, therefore construction/implementation of a cost-effective hardware controller should be researched in order to have affordable and reliable controller. Innovated product in terms of cost effectiveness will surely benefit rural communities.
5) Other intelligent control technologies such as artificial intelligence control and neuron control are potentially more feasible compared to conventional controller. Such a complex hydropower system normally will require an intelligent controller capable of adapting which changing conditions in order to provide improved performance. This is because Pico hydro system normally consists of integrated water, motor, machine and electricity. Therefore, an advance controller is suggested to be included in the future works.

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