Model Predictive Control Based Hydraulic Turbine Power Regulating System for Hydropower Plant

Case Study: Genale Dawa Hydropower plant

Alemayehu Tadesse Melkamu

A Thesis Submitted to the Department of Electrical Power and Control Engineering, School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master's of Science in Electrical Power and Control Engineering (Control Engineering)

Office of Graduate Studies

Adama Science and Technology University

June, 2024

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Adviser: - Dr. Endalew Ayenew (PhD)

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DECLARATION

I hereby declare that this Master Thesis entitled "**Model Predictive Control Based Hydraulic Turbine Governor Regulating System for Hydro Power Plant**" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Alemayehu Tadesse ________________ __________
Name of student Signature Date

RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "**Model Predictive Control Based Hydraulic Turbine Power Regulating System for Hydropower Plant**" prepared under my guidance by **Alemayehu Tadesse** submitted in partial fulfillment of the requirements for the degree of Master's of Science in Electrical Power and Control Engineering (Control Engineering). Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Dr. Endalew Ayenew	_______________	_________
Advisor	Signature	Date

APPROVAL SHEET

I, the advisor of the thesis entitled "**Model Predictive Control Based Hydraulic Turbine Power Regulating System for Hydropower Plant**" and developed by **Alemayehu Tadesse**, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Endalew Ayenew ______________ ______________
Advisor Signature Date

We, the undersigned, members of the Board of Examiners of the thesis by **Alemayehu Tadesse** have read and evaluated the thesis entitled "**Model Predictive Control Based Hydraulic Turbine Power Regulating System for Hydropower Plant**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Electrical Power and Control Engineering (Control Engineering).

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Final approval and acceptance of the thesis is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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ASTU	Adama Science and Technology University
AVR	Automatic Voltage Control
GD3	Genale Dawa Three
HT	Hydro Turbine
HTG	Hydro Turbine Governor
HPP	Hydro Power Plant
GA	Genetic Algorism
LFC	Load Frequency Control
LMPC	Linear Model Predictive Control
MPC	Model predictive controller
PhD	Doctor of Philosophy
PI	Proportional and Integral
PID	Proportional Integral and Derivative
PU	Per Unit
Min	Minimum
Max	Maximum

ABSTRACT

This study provides a comprehensive analysis of a hydraulic turbine governor regulating system that utilizes Model Predictive Control (MPC). The research focuses on the Genale Dawa Hydropower Plant in Ethiopia, which is currently in operation. The objective of the study is to enhance the performance and efficiency of the hydropower plant by implementing advanced control strategies. These controllers are often utilized in hydro turbine governor applications, but their effectiveness is limited by their reliance on linear plant models and fixed parameter sets. These control systems are optimized only for specific operating points, known as predetermined set points, and lack the adaptability and versatility necessary for use in hydropower plants with inherent non-linearity. To address this issue, this research the use defines of a model predictive control scheme to serve as a load governor in hydro turbines. The thesis's scientific contributions include a MPC algorithm developed for hydro turbine governor load control. The MPC algorithm is specifically designed to optimize the operation of the hydraulic turbine governor in real-time, taking into account system dynamics, constraints, and objectives. The simulation results demonstrate that the proposed system effectively improves the stability and efficiency of the plant by reducing oscillations in power output. Moreover, the system showcases its ability to adapt to changes in load and operating conditions, ensuring a stable and efficient operation of the plant. This proposed system has significant implications for the operation and maintenance of hydropower plants, particularly in areas where the power grid experiences frequent fluctuations in demand. By adapting to changing conditions and optimizing the governor's response, the system can help mitigate the risk of power outages and enhance the overall efficiency of the plant. In conclusion, this study highlights the potential of Model Predictive Control-based hydraulic turbine governor regulating systems in enhancing the stability and efficiency of hydropower plants.

Keywords: Model Predictive Control (MPC), Proportional Integral and Derivative (PID), Governor regulation system, Francis turbine, hydropower plant, proportional and integral (PI), Genetic algorithm(GA)

CHAPTER ONE

1 INTRODUCTION

1.1 Background of the Study

Global warming is a significant issue around the globe today. Utilizing hydroelectricity as a renewable energy source to produce power is crucial for protecting the environment. Water is the most dependable and least expensive source of renewable energy. A significant source of renewable energy in the world is hydroelectricity. Over the past few decades, the world's energy production has increased, especially in poorer countries where hydropower remains the primary source of electricity production (Lee et al., 2023). Hydraulic turbines are used in hydroelectric power to transform the energy in moving water into electricity. One method of producing electricity from potential renewable sources is through such a source. (Carine Adjassa et al., 2023).

In a hydroelectric power plant, water that has been stored is directed from a higher position to a hydro turbine, where the energy of gravity is converted into the energy of motion. The machine is then powered to produce electricity by shaft of the turbine, which receives ME (mechanical energy) from the conversion. The energy of a hydroelectric system refers to the amount of potential energy stored in the upper reservoir (Blakers et al., 2021).

The position of the wicket gates (nozzles) in a turbine is used to control the flow into the turbine, which in turn controls the power. Turbines commonly supply the mechanical power used to drive generators in power systems. To regulate its speed in order to produce the correct amount of power, each turbine is equipped with a mechanism called a turbine governor. The speed governing system, also known as the turbine governing system or the turbine governor, is what controls this((Altinoz et al., 2020).

When the system is subjected to disturbances, turbine governors serve as the primary frequency controllers of synchronous machines Power systems are transitioning rapidly from reliable conventional generation to intermittent renewable energy-based generation, which gives rise to numerous challenges in the regulation of frequency(Nour et al., 2023).

The Genale Dawa III hydropower plant unit in Ethiopia is one of the generation stations that exhibits a significant contribution to system frequency for this frequency regulation generation station. The system encompasses two distinct operational modes: frequency control and power control. This duality mitigates power grid frequency fluctuations by enabling generating units to autonomously adjust their power output in response to variations in grid frequency, thereby restoring equilibrium to the active power supply. By keeping the

voltage of a system, frequencies of a system, and other variables of a system within acceptable bounds, controllers help to ensure the power system operates safely. In contrast to voltage regulation, which is directly associated with reactive power management, frequency regulation is closely tied to active power control (Zepter et al., 2023).
When active power imbalances occur within the system, they lead to fluctuations in the system's frequency. These frequency changes are propagated throughout the entire system. A power system's frequency must stay within the permitted ranges to function satisfactorily(Y. Zhang et al., 2021).

1.1.1 Performance of Generating Units

In the context of power generation, it becomes paramount to equip the generating units with sophisticated speed governors. These governors play a pivotal role in regulating the rotational speed of the units. Here's how it all ties together:

1. Speed Control Operations: The speed governors facilitate precise control over the rotational speed of the generating units. By adjusting the load reference set-point within the speed controller, operators can influence the interplay between speed and load.
2. Interdependence of Speed and Load: The relationship between speed and load is intrinsically linked. When the load demand fluctuates, it directly impacts the rotational speed of the generator. This dynamic interdependence necessitates careful management.
3. Power Controller: Additionally, the system can manipulate this interdependence by employing a power controller. This controller modulates the power output of the generating units, ensuring that the grid remains stable and responsive.

Integrating effective speed governors and load control mechanisms is critical for maintaining the reliability and efficiency of power generation systems. Speed governors play a vital role in regulating the rotational speed of turbines or engines, ensuring they operate within safe and optimal parameters. This helps prevent damage to the machinery and fluctuations in electrical output. Similarly, load control mechanisms dynamically manage the amount of electrical load placed on the generators. This allows the system to respond to changes in demand, while maintaining a stable voltage and frequency (Kougias et al., 2019).

Figure 1.1 shows the operation of a hydropower plant involves several key components and processes. A dam is constructed across a river or a water source, creating a reservoir or a storage area for water. The dam regulates the flow of water and controls its release. Water from the reservoir is allowed to flow through an intake structure, which is typically equipped with gates or valves to control the inflow. In a penstock-based hydroelectric power plant, captured water is channeled through the pressurized conduit known as the penstock towards the turbine. The force of the directed water flow impinges upon the turbine blades, inducing their rotational motion(Kougias et al., 2019).

This conversion process harnesses the kinetic energy of the flowing water and transforms it into mechanical energy via the turbine's rotation. The rotating turbine shaft is then coupled to a generator, where the rotational energy is further converted into electrical energy. It rotates the generator's rotor, which produces electricity through electromagnetic induction. The electricity produced by the generator is sent to a transformer, which steps up the voltage for efficient transmission over long distances through power lines (Hoffstaedt et al., 2022).

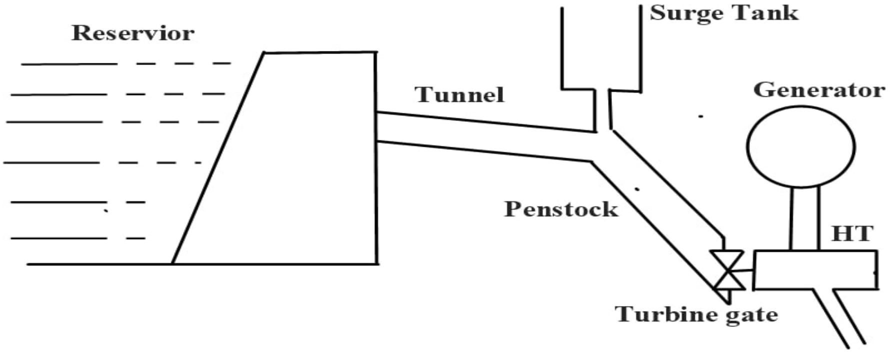


Figure 1.1: General representation of a hydropower station with a single generating unit (Weldcherkos et al., 2021).

1.2 Motivation

Maintaining consistent frequency is crucial for the proper operation of a power system. Fluctuations in frequency can have adverse effects on the efficiency, reliability, and overall functioning of the system. Retaining power system frequency within specified tolerance ranges is essential to a robust and stable grid; it goes beyond simple operational ease. Whether temporary or persistent, deviations from the normal frequency have a domino effect that puts at risk system stability, equipment integrity, and efficiency.

For example, lower frequency affects motor-driven auxiliaries' performance, which in turn affects generator output. Moreover, it causes harmful magnetizing currents in transformers and motors, increasing the need for reactive power. These effects also extend to domestic products, such as air conditioners and televisions, where variances result in increased reactive power usage and efficiency prosses.

1.3 Statement of Problem

Hydroelectric power stations are known for their complex and non-linear dynamics. The traditional application of PID-based governors for hydro turbines presents a considerable challenge since these governors are limited to fixed parameters. As a result, optimal performance is only achieved when operating near a preselected design point. This study seeks to develop and present a Model Predictive Control algorithm as a more effective option than traditional PID regulators. The MPC algorithm is tailored for the load control of hydropower plants and actively updates its internal prediction model parameters to align with the current operating conditions. This thesis will provide detailed information on the development of the MPC algorithm for hydropower plants. Improper management of control structures and configurations in hydro units may result in frequency control challenges. Implementing model predictive control controller can be a valuable technique for managing the active power of a unit to contribute to grid frequency stabilization. Enhancing frequency regulation within hydro units is critical for ensuring stable grid frequency. It is imperative to establish appropriate control structures and settings to achieve efficient frequency control in these units.

1.4 Objectives

1.4.1 General Objective

The main objective of this thesis is to create a detailed model for the Genale Dawa III hydro power plant unit, taking into account its operational efficiency and environmental impact, in order to achieve the optimal active power output using an MPC controller.

1.4.2 Specific Objectives

- To Simulate the model of Genale Dawa III hydro power unit involves identifying the necessary parameters of the generation system.
- To construct a simulation of Hydro governor regulation with MPC controller
- To compare the combination of the MPC controller and existing PID controller.

1.5 Scope of the Study

The scope of a thesis, which is focused on hydropower plants in Ethiopia. The study only considers Francis-turbine powered power plants located in Genale Dawa III, which is The power station lies across the Ganale Doria River, along the border of Kobadi Woreda and Meda Welabu Woreda, in the Bale Zone of the Oromia Region of Ethiopia.

1.6 Significance of the Study

This thesis provides important study result for cost effective, reliable, and faster frequency controller. Thus, the result will have the significances for frequency controller in Genale Dawa III hydropower plant such as initiate for easy maintenance used by frequency controll er, serve the automatic generation control of hydropower systems by frequency controller and this research experiences for our country.

1.7 Thesis Contribution

For any electrical power production system to operate steadily, the operating frequency must be kept within a certain range. Variations in the system's load level frequently cause the frequency to deviate from the intended level. For this reason, efficient load frequency control (LFC) systems are essential to keeping power quality and grid stability. The creation and modelling of an advanced LFC strategy for the Genale Dawa III hydropower plant unit is the main objective of this thesis. This work's main contribution is the development of a MPC that uses to accomplish the best possible frequency regulation. Furthermore, this work sets the road for the application of Model Predictive Control (MPC) approaches in hydropower production units by providing insightful analysis and a case study.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Introduction

This chapter covers the construction of a rockfill dam of the Genale Dawa III hydro power plant in Ethiopia. It also describes multiple techniques for adjusting the frequency of the Genale Dawa III hydropower plant. This chapter presents the basics of the MPC controller, an introduction of the software that is used, additional investigations that have been included, and a gap study.

In later a long time, power has ended up a basic portion of human life, and our reliance on power has quickly expanded. This abundance control era causes huge sums of nursery gas outflows and so contributes essentially to climate alteration. In this manner, the electricity industry is driving endeavors to extend power era from renewable vitality sources to diminish these climate alter impacts (Girgibo, 2022).

Based on renewable vitality activities, a few created nations have effectively coordinated huge sums of renewable vitality into their national power grids. Hydropower, wind, and sun-oriented control are the most renewable energy sources these nations utilize to produce power (Lee et al., 2023). Hydropower may be a renewable vitality source that depends on the worldwide water cycle.

Electrical energy is generated from hydroelectric power using a turbine generator set. Hydroelectric turbines are powered by the potential energy of flowing water, which is created by the height difference between the reservoir and the turbine inlet, also known as the head.(Weldcherkos et al., 2021).

Hydro power, also referred to as hydroelectric power, is a sustainable energy source that generates electricity through the utilization of flowing water's force. This eco-friendly and enduring energy form is created by constructing dams on rivers and utilizing the water to rotate turbines, which in turn produce electricity(H. Zhang et al., 2022).

Hydro power stands out as a dependable energy source that doesn't emit harmful greenhouse gases, making it environmentally beneficial. Furthermore, hydro power facilities can be established on a range of sizes, from large dams to smaller run-of-river projects, offering a flexible solution to meet energy demands. hydropower is a critical component of the renewable energy portfolio and serves a fundamental role in lessening our reliance on fossil fuels. (Y. Zhang et al., 2021).

Hydropower, also known as hydroelectric power, utilizes the kinetic energy of moving water to generate electricity. It represents a mature and significant source of renewable energy globally, contributing roughly 16% of worldwide electricity production and 69% of all renewable electricity generation (Bogdanov et al., 2021).

2.2 Hydropower Development

To delve into hydropower, explore the following various dimensions:

1. Technological Principles:

Conversion Mechanisms is Understand the fundamental principles of kinetic energy (KE) conversion into electricity through turbines and generator and turbine. Analyze factors influencing power generation like water flow rate, head (elevation difference), and turbine efficiency.

Plant Types is Explore different hydropower plant configurations, including run-of-river, dam-based, pumped storage, and tidal. Analyze their respective advantages and limitations in terms of power generation capacity, environmental impact, and operational flexibility.

Hydropower Integration: Investigate the challenges and opportunities of integrating hydropower with other renewable energy sources like solar and wind. Explore grid balancing mechanisms and the role of hydropower in providing essential ancillary services like frequency regulation.

2. Environmental and Social Impacts:

Sustainability is evaluating the environmental sustainability of hydropower plant, considering factors like water use, reservoir sedimentation, impacts on aquatic ecosystems, and greenhouse gas emissions. Analyze various mitigation strategies and best practices for sustainable hydropower development during project.

Social and Economic Considerations is Assess the social and economic impacts of hydropower projects on local communities, including resettlement, livelihood changes, and cultural heritage preservation. Explore stakeholder engagement strategies and benefit-sharing mechanisms to ensure equitable development.

Policy and Governance which is analyze the role of policies and regulations in promoting sustainable and responsible hydropower development. Evaluate international frameworks and national policies governing hydropower project development and operation.

Future Trends and Innovations are Emerging Technologies are Explore advancements in hydropower technologies like small scale hydro, marine energy devices, and advanced turbine designs. Analyze their potential to improve efficiency, address environmental concerns, and expand hydropower's reach.

Data-Driven Optimization are investigating the application of data analytics and machine learning in hydropower operations to optimize power generation, improve efficiency, and predict maintenance needs.

Integration with Smart Grids are analyzing the role of hydropower in the context of smart grids, including demand-side management, distributed generation, and microgrids.

2.3 Hydro Turbine Governor Task of Hydro Turbine Regulation

The hydroelectric generating unit transforms hydraulic energy into electric energy for users while ensures safe power supply and keeps frequency of electric energy and pressure in certain ranges closing to the rated values so as to meet requirements of users since the large deviation of the frequency shall directly affect quality of products of the users. The frequency fluctuations shall not exceed± 0.4% (± 0.2 Hz) for bulk power system and shall not exceed± 1% (± 0.5 Hz) for small and medium-sized power system.

Load of the power system keeps varying. Some loads varying randomly shall be unpredictable, and some varying periodically with two peaks in the morning and at night, and two troughs at noon and late night respectively shall be predictable.

Load changes caused frequency changes in the grid

The hydroelectric generating unit frequency f and speed n are related as follows:

$$f = \frac{n \times p}{60} \tag{2.1}$$

f： Generator frequency（ Hz）

n： Speed of the hydroelectric generating unit（ r/min）

P： The Magnetic pole logarithm on the generator

In order to make a constant frequency, it is necessary to make constant unit speed Motion equation of the set is as below shown.

$$J\frac{d\omega}{dt} = M_t - M_g \tag{2.2}$$

$$J = \frac{GD^2}{4g} \tag{2.3}$$

J stands for the inertia moment for rotating part of the set

GD^2 stands for the moment for flywheel of the set.

$\omega = \frac{n\pi}{30}$ stands for angular speed.
M_t _ stands for active moments of the hydro-turbine,
M_g _ stands for the resistance moment of the generator.
n _ stands for unit speed.

In order to make a constant frequency, it is necessary to make constant unit speed. Namely, increment dω of angular speed shall be kept at 0; thus, active moment Mt of the hydro turbine and resistance moment of the generator Mg shall be kept in balance, namely, the resistance moment varies along with the load; the active moment output by the set shall be regulated to main constant frequency.

Basic task for hydro-turbine regulation: Active power output of the hydroelectric generating unit shall be regulated (controlled) continuously according to variation of load so as to make the speed (frequency) of the unit within the prescript range.

The most effective method and approach for regulating active moment output by the hydro-turbine, namely regulating output power of the hydro-turbine are to change opening of the guide vane (spray nozzle) via regulating (controlling) flow rate of the hydro turbine. The flow rate shall be regulated by cooperatively regulating the guide vane and the blade regarding to the Kaplan turbine, and shall be controlled through cooperatively regulating the spray needle and the deflector regarding to the impulse turbine.

2.3.1 Composition and Feature of Hydro-Turbine Regulating System

The hydro-turbine regulating system comprises governor and regulation objects which refer to the hydroelectric generating unit (Figure 2.1), and further comprises water diversion system and power system connected with said unit to a broader extent. Control device for such regulation (control) is the hydro-turbine regulator (also called hydro-turbine controller).

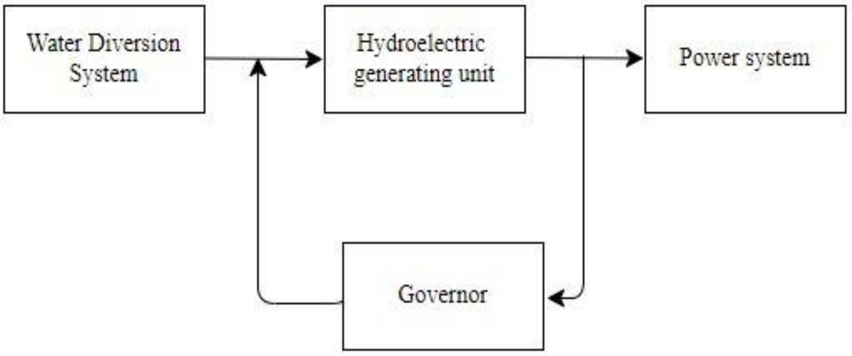


Figure 2.1: Block diagram of hydro-turbine regulating system

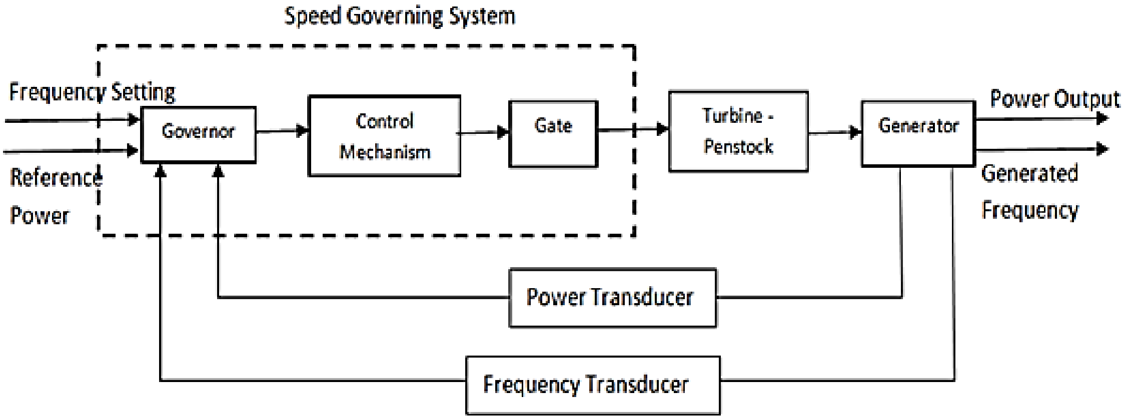


Figure 2.2:A Functional block diagram of a hydraulic system (Mushiri & Mbohwa, 2016).

2.3.2 Features of Hydro-Turbine Regulation

(1) Lag of regulation from the hydro-turbine regulating system will cause overshoot, which is bad for stability of the system. The hydraulic amplification actuating mechanism of governor has rather large time constant and the regulation object also has rather large inertia time constant Ta, causing lag of regulation and over regulation which makes the hydro-turbine regulating system become unstable.

(2) The hydro-turbine governor must have ample regulation power. The flow rate shall be kept rather high and the dimensions of hydro-turbine and the distributor thereof shall be enlarged correspondingly so as to generate more energy for the water head at the hydroelectric station is usually within the ranges from several meters to hundreds of meters, and pressure before the hydro-turbine is only within the range from a few tenths MPa to several MPa. Ample regulatory work together multi-stage hydraulic amplification (normally two stages) and additional energy sources (oil pressure device) shall be provided for pushing the heavy distributor

(3) Counter-regulation effect of water attach not only seriously deteriorates dynamic quality of the regulating system, but also adversely acts stability of the regulating system. Constrained by the natural conditions, the hydropower station also possesses long pressure water pipes, thus having large water current inertia; therefore, the adjustable-blade unit with low water head shall have large water current inertia because the huge water head, and have large T_W accordingly, thus to the counter-regulation effect of water attack shall become more obvious which shall even adversely affect stability of the hydro-turbine regulating system of such hydroelectric station and deteriorate dynamic quality of the regulating system at the meanwhile.

$$T_w = \frac{\Sigma LV}{gH_r} = \frac{Q_r}{gH_r} \bullet \frac{\Sigma L_i}{F_i} \qquad (2.4)$$

(4) Some hydro-turbine governor may be further provided with dual-regulation mechanism, which will cause the structural of the governor more complex.

For the adjustable-blade turbine and straight flow turbine, opening of the blade shall be regulated together with the distributor so as to improve efficiency of hydro-turbine and ensure to gains high operation efficiency under different water head conditions.

2.4 Functions of Hydro Turbine Governor

One of the important control devices of the hydropower station, the hydro-turbine governor has the following functions:

- Keep rotating speed of the unit constant during the single-unit operation (regulating according to frequency
- Be responsible for starting, stopping, synchronizing and closing, load increasing and decreasing operations (control） of the unit.
- During the synchronizing and closing operation, distribute load among the units according to the speed droop characteristics so as to realize power-based, opening-based, frequency-based and water level-based regulations.
- Act as one of the executive devices of the safety monitoring system for the hydropower station.

- It can quickly cut off the water flow with the guide vane (deflector） in an accident so as to stop the unit and protect it and the hydropower station.

2.5 Hydro Turbine Governor Tuning Techniques

The tuning of a hydro turbine governor is crucial for optimizing the performance and efficiency of the turbine.

2.5.1 Importance of Proper Governor Tuning

Tuning the governor of a hydro turbine is vital as it directly affects the performance, efficiency, and overall operation of the turbine. Proper governor tuning ensures that the turbine responds accurately to changes in load and frequency, thereby maintaining system stability and reliability. Additionally, well-tuned governors contribute to extending the lifespan of the equipment and reducing maintenance costs(Obradovic et al., 2020).

2.5.2 Factors Affecting Governor Tuning

Several factors influence the tuning of a hydro turbine governor, including the type of turbine, load characteristics, and system requirements. Understanding these factors is essential for achieving an optimal tuning configuration that aligns with the specific operating conditions and goals of the hydro power plant. Tuning techniques may vary depending on the complexity of the governing system and the desired performance outcomes(Borase et al., 2021).

2.5.3 Tuning Techniques

There are various techniques and approaches used in the tuning of hydro turbine governors. These methods encompass a range of parameters such as proportional gain, integral gain, and derivative gain, as well as time constants and droop settings. Additionally, advanced tuning techniques may involve the use of simulation tools and real-time data analysis to achieve precise and dynamic governor performance(Borase et al., 2021).

2.5.4 Advantages of Advanced Governor Tuning

Implementing advanced tuning techniques for hydro turbine governors can yield numerous benefits, including improved transient response, enhanced stability during load variations, and optimized power system behavior (Amir & Singh, 2024). Furthermore, advanced tuning enables the governor to adapt to changing operational conditions, thereby maximizing the overall efficiency and output of the hydro power plant. By delving deeper into the intricacies of hydro turbine governor tuning, plant operators and engineers can unlock the full potential of their turbines, leading to enhanced performance and operational excellence.

As we delve deeper into the realm of genetic algorithm optimization, it becomes essential to understand the foundational principles that drive this powerful method. At its core, GA optimization is inspired by the process of natural selection, where the fittest individuals are more likely to survive and pass on their genetic traits to the next generation. This concept forms the basis of the evolutionary approach that GA takes towards finding optimal solutions to complex problems(Nagaraj & Murugananth, 2010).

In addition, understanding the various parameters and operators employed in genetic algorism optimization, such as the selection mechanism, crossover techniques, mutation rates, and fitness evaluation, is crucial for harnessing the full potential of this approach in solving real-world problems. Each component plays a vital role in shaping the behavior of the algorithm and influencing the quality of the solutions it produces(Wadi et al., 2024)

As we proceed with our exploration of genetic algorism optimization, it is imperative to delve into the nuances of these components and their interdependencies to gain a comprehensive understanding of how to effectively apply GA in tackling optimization challenges across diverse domains. Optimizes the PID gains to improve controller performance (Pano & Ouyang, 2016).To assess which PID controller is optimal for the system, an objective function is needed. To identify a PID controller that provides the least overshoot, fastest rising time, or quickest settling time, an objective function might be developed.

- Key components GA:
    - Population: A set of candidates PID controllers represented by chromosomes (parameter values).
    - Fitness function: Evaluates each controller's performance based on control objectives.
    - Selection: Chooses better-performing controllers for reproduction.
    - Crossover and Mutation: Combine and modify chromosomes to create new generations.
- Information exchange:
    - PID performance data: Fed back to the GA for fitness evaluation.
    - Optimized PID parameters: Sent from the GA to update the PID controller.

Benefits:

- Adaptability: Handles complex systems and changing operating conditions.
- Robustness: Less sensitive to parameter variations and disturbances.

- Improved performance: Achieves better control objectives compared to static PID controllers.

The GA-based tuning technique has been widely employed in applications such as industrial process control, robotics, and power systems. It may be applied to a variety of controller types, including PID, fuzzy logic, and more sophisticated control algorithms.

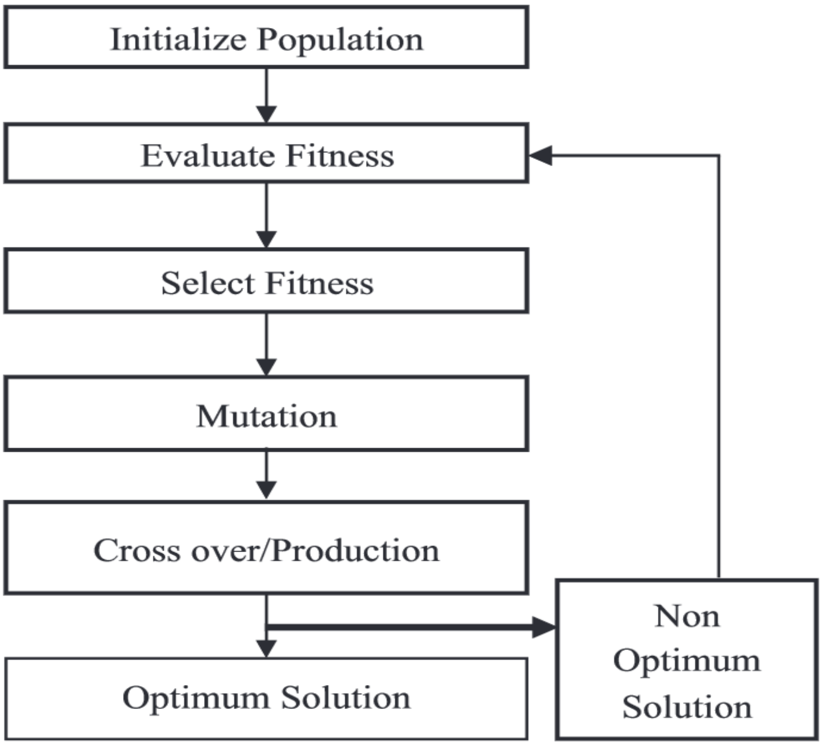


Figure 2.3: Flow chart of GA PID tuning

2.6 Applications of MPC in Hydro Turbine Governors

Model Predictive Control (MPC) is an advanced control strategy that has become more popular in various industrial processes over the years. MPC uses a dynamic mathematical model to predict system behavior and calculate control actions that optimize an objective function. It can handle various control objectives, improve efficiency and productivity, and is an emerging trend for Load Frequency Control in power systems

MPC relies on dynamic models of the process. These models predict how changes in control inputs will affect the system's dependent variables (e.g., pressure, flow, speed, generated power temperature). At each time step, MPC solves an optimization problem. It aims to find the optimal control action that drives the predicted plant output as close as possible to the desired reference while satisfying constraints. Unlike PID controllers, MPC can anticipate future events and adjust control actions accordingly. MPC holds promise for improving the performance and efficiency of hydro turbine governors(Beus & Pandžić, 2018).

2.7 Working Steps of MPC

Model Predictive Control (MPC) is a process control method that involves the optimization of a performance index with respect to some future control sequence, using predictions of the output. The working steps of MPC can be summarized as follows:

Step 1: Predictive Model: The predictive model of the process is used to predict the future outputs of the system. This model is typically a dynamic model that represents the behavior of the system over a future time horizon.

Step 2: Optimization: The sequence of future control signals is computed to optimize a performance criterion, often to minimize the error between a reference trajectory and the predicted process output. The control effort is usually included in the performance criterion.

Step 3: Control Signal Selection: Only the first control signal in the calculated sequence is transmitted to the process. The rest of the sequence is discarded.

Step 4: Feedback and Recursion: The process output is measured, and the process is updated. The predictive model is then updated with the new information, and the process repeats from Step 1.

This recursive process ensures that the control system adapts to changes in the process and maintains optimal performance over time.

2.8 Related Works

In (Sahoo & Panda, 2018) suggested a method to improve the design of a fuzzy-assisted controller by utilizing an advanced grey wolf optimization algorithm. The proposed technique was developed for the purpose of regulating the frequency of a power system. The gains of the PID controller were optimized utilizing the IGWO optimization algorithm. The research applies and evaluates the frequency control algorithm on two distinct six-unit test systems, each powered by a different energy source. Additionally, a three-area non-linear system is taken into account in the study. The outcomes are contrasted with established AI methods like grey wolf optimization (GWO), gravitational search algorithm (GSA), and particle swarm optimization (PSO), clearly demonstrating the superiority of the new technique over these approaches. Moreover, the suggested method successfully regulates the frequency of the mentioned test systems when faced with uncertainties and load disturbances.

In (Hammid et al., 2018) Proposed is a method for fuzzy control aimed at regulating the water intake of a hydropower plant. In this research, right-angle triangle membership functions were employed to simplify process the tuning of membership functions within the fuzzy inference system, utilizing a Mamdani-type model. The fuzzy controller was evaluated with randomized input variables to simulate water intake uncertainty. Results confirm its ability to maintain stable flow of water under different condition.

The authors (Ofosu et al., 2019) introduce a novel approach to electronic load control, leveraging a fuzzy PI controller. The fuzzy logic controller's performance is improved by optimizing its membership functions with a technique called Bacterial Foraging Algorithm (BFA).The implemented controller targets the system's frequency, ensuring its operation remains within the established reference range The controller actively manages system frequency deviations by dynamically transferring excess load to a designated 'damper load' mechanism when fluctuations in overall system demand occur The proposed electronic load controller (ELC) prioritizes economic viability by employing a microcontroller architecture. Furthermore, extensive testing under diverse conditions has established the ELC's capability to effectively regulate system frequency. These results underscore the potential of the proposed controller as a robust and cost-competitive solution.

In (El Hamdaouy et al., 2020) introduced a new Controller, Management, and Security System (CMSS) to oversee the overall functioning of Hydro power plant . The CMSS was developed to create a cost-effective and comprehensive control system for independent HPPs. This integrated system can be utilized to fulfill different control needs such as frequency and load regulation, system startup, and emergency shutdown. Utilizing microcontrollers, sensors, and a PI control scheme, the CMSS was constructed. Through testing in various scenarios with different conditions, the effectiveness of the proposed CMSS was demonstrated. The results indicate that the CMSS effectively manages the system's frequency amidst load fluctuations and safeguards the PHPP from electrical and mechanical issues, enhancing its reliability.

A fuzzy logic control (FLC) system that is based on Mamdani's method propose in (Kang et al., 2022). The purpose of this system is to control the charging process of a Battery Energy Storage System (BESS) that is integrated with a Hydropower system. The authors highlight the inefficiency of traditional electronic load controllers (ELCs) that waste energy by discarding excess load in order to maintain frequency during peak demand. To address this issue, the authors propose the integration of a BESS with the Pico Hydro system, along with the use of a Mamdani-based FLC that incorporates 25 membership functions to manage the charging process. The main objective of this system is to optimize energy utilization by storing excess energy during periods of low demand and using it during periods of high demand. The authors implement their proposed model on SIMULINK and demonstrate its effectiveness in managing the operation of the Hydropower system.

Building on the work of (Asoh et al., 2022), this study examines a frequency and load control scheme for SHPs(small hydropower plants) using artificial intelligence (AI).A unique one-input fuzzy logic control strategy is introduced to minimize implementation costs. Linear and nonlinear plant models were simulated using SIMULINK. The performance of the controller was evaluated in various scenarios by comparing it to a conventional PI or PID controller. The results show a significant reduction in overshoot and settling time, indicating improved dynamic stability and efficient LFC.

Model Predictive Control (MPC) for Variable Speed Hydropower (VSHP) plant aims to enhance the controller design for variable speed hydropower (VSHP) plants in (Reigstad & Uhlen, 2020). The objective is to optimize performance and enable a swift response to frequency deviations, while also adhering to electrical and hydraulic limitations. The implementation of Model Predictive Control (MPC) coordinates the turbine controller and the virtual synchronous generator (VSG) control. This allows the VSG to efficiently utilize rotational energy in order to deliver a rapid power response. The MPC also adjusts the guide vane opening to ensure speed recovery, or modifies the VSHP power output through the VSG reference if hydraulic constraints delay the recovery process.

In (Schwenzer et al., 2021) propose Model predictive control (MPC) leverages a process model to predict future behavior and optimize control by solving an optimization problem. This simplifies controller design by focusing on modeling rather than control law development. Its intuitive structure allows for easier tuning and enables control of systems beyond conventional methods.

2.9 Research Gap

There is a need to develop an intelligent flow control technique for hydro turbines to enhance and sustain their output performance by controlling the water flow speed. Another need is to develop a load frequency control technique to address variations in consumer load and analyze the system's performance during these load changes. The search results indicate that current hydro turbine designs encounter difficulties in maintaining optimal performance due to fluctuations in water flow and consumer loads. By developing advanced load frequency control techniques, and by using MPC governor controller these issues can be addressed, leading to improved overall performance and reliability of hydropower systems.

2.10 Summary

Hydropower plants are usually operated in standalone off-grid mode and grid-connected mode supply electricity to large number of consumers. The degree of variation in load demand of these power systems is very high. These variations render the system unstable as they are directly related to the 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 a swinging phenomenon in the electrical system. Therefore, an 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 2.8 of this chapter. However, majority of the load frequency management techniques are design for small or micro hydropower. Hydropower plants are more sensitive to changes in consumer load due to their small generator size and irregular water flows. Therefore, an efficient load frequency management scheme designed specifically for hydropower plants is yet to be investigated.

CHAPTER THREE

3 MATERIALS AND METHODS

3.1 Materials

In this thesis work, software such as MATLAB/R2021 and Concept Draw DIAGRAM are used. MATLAB is a programming tool that was created specifically for engineers and scientists to study and design systems and products that will change the world. Concept Draw DIAGRAM is drawing software that includes a professional set of drawing tools, ready-to-use templates, a large object library, and a range of custom printing and file export options.

3.2 Methods

3.2.1 System Design

The Unit Generator Power Method is a modeling approach used to focus on the individual generators within a hydropower plant. This method simplifies the complex interactions between the hydraulic turbine, governor, and generator components by breaking them down into separate models. The generator model specifically considers the electromagnetic behavior of the generator, taking into account factors like voltage, frequency, and torque. By using the unit generator method, engineers can analyze the performance of individual generators within the larger hydropower plant. This provides valuable information for fault diagnosis, maintenance planning, and operational optimization(Hu et al., 2023).

For the analysis of a hydro turbine combined cycle in GD3 power plant, a specific model has been integrated into Simulink within MATLAB software. This implementation encompasses several interconnected dynamical subsystems or models:

- The hydrodynamic system
- Model of Turbine
- Actuator Hydraulic
- Regulator for turbine governor (MPC and PID controller)

The diagram that represents the block schemes for the entire model together with its sub model is demonstrate in Figure 3.1.

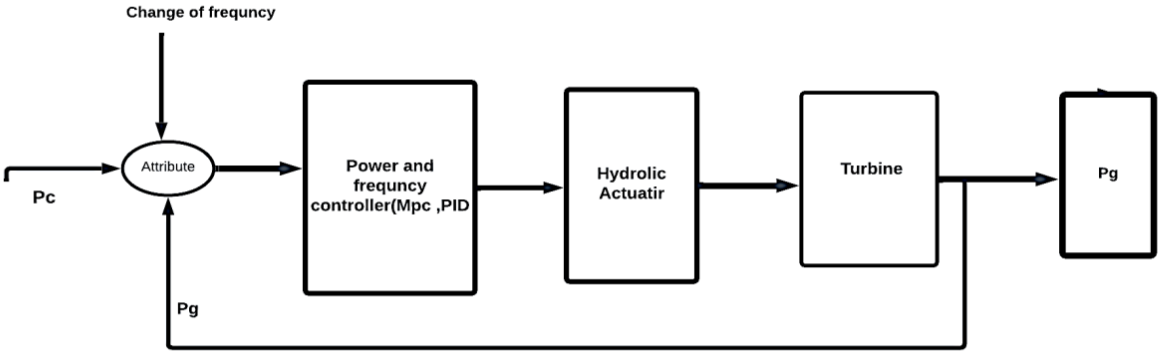


Figure 3.1: General structure of the sub mode

All values are expressed in per unit (Pu), a convention that facilitates the interaction among various components and simplifies the modeling of algorithms. To compute the per unit value, utilize the following formula.

$$Per\ unit = \frac{actual\ value}{base\ value} \tag{3.1}$$

3.2.1.1 Modelling of the Hydraulic System

In a hydroelectric power plant, water is stored in a reservoir at a high elevation. When the water is released from the reservoir, it flows down a pipe or channel and turns a turbine, which drives a generator to produce electricity. The potential energy (PE) of the water at the high elevation is converted into kinetic energy as it flows down, and this kinetic energy (KE) is then converted into electrical energy through the process of electromechanical conversion. The turbine governor is an important component of a hydroelectric power plant (HEPP). It is responsible for regulating the amount of water flowing into the turbine, which in turn controls the speed of the turbine and the amount of electrical power generated.

The governor works by monitoring the speed of the turbine and comparing it to a predetermined set point. If the turbine is spinning too quickly, the governor will reduce the amount of water flowing into the turbine by closing the gates or nozzles. If the turbine is spinning too slowly, the governor will increase the amount of water flowing into the turbine by opening the gates or nozzles.

By controlling the flow of water into the turbine, the governor helps to maintain a constant speed and output power, even when there are fluctuations in the amount of water available or changes in the electrical load on the system. This is important for maintaining the stability of the power grid and preventing blackouts (Yu et al., 2016).

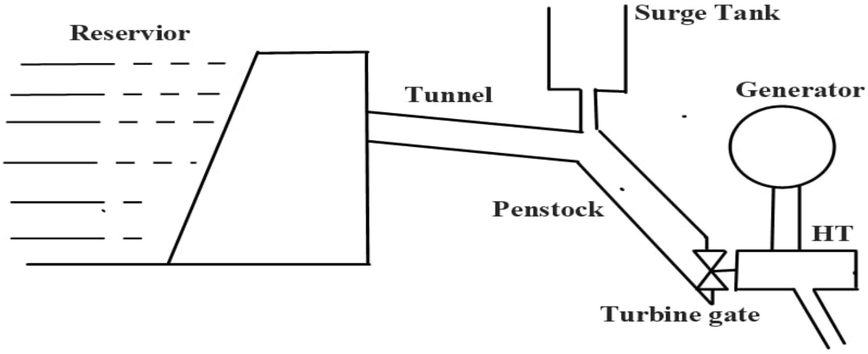


Figure 3.2: Structure of Genale Dawa III hydropower plant.

Figure 3.2 depicts the basic design of a hydroelectric plant, which consists of a reservoir, the high-pressure penstock, an opening, a surge tank, a hydro turbine, with a generator. The reservoir's purpose is to hold water and create a head. Water released from the reservoir travels via the penstock and reaches the turbine inlet, where it activates the turbine generating unit. It then goes into the turbine's scroll casing, which uniformly distributes the water over the running the blades. Between the generator installed on the common shaft and the turbine runner is where the electromechanical power conversion occurs.

The governor is responsible for controlling the wicket gates, which in turn control the water flow to the turbine. The gates open and close based on the different electrical load linked to the generator and the shaft speeds. The hydropower plant has numerous basic components, including a turbine, a penstock, a generator, and a load. In practice, a linear (or linearized) model is utilized to characterize the plant and design the control system. The dynamic features of the plant are given in the figure below.

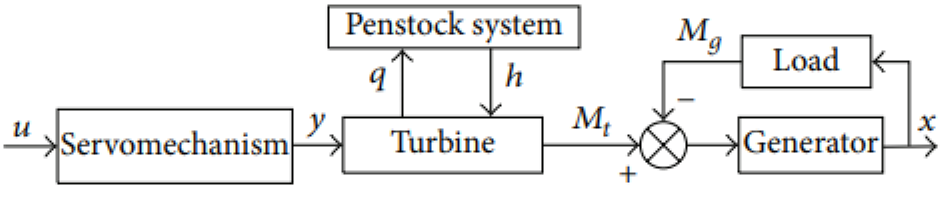


Figure 3.3: Hydro-turbine generator regulating system.

Three units typically make up the hydraulic system that from the Genale Dawa III dam to each individual turbine. Included are the fundamental parts, such as the generator and power system, the valve and its servomotor, the turbine and its feeding penstock.

3.2.1.2 Mathematical Model of Penstock

the penstock is a critical component that ensures a reliable supply of pressurized water to the turbines, allowing the hydropower plant to generate electricity efficiently and on demand.

Its design and operation are crucial for the overall performance and safety of the hydropower system. To exclude debris from entering the water intake of a hydroelectric plant, a grid of bars known as a trash rack is installed at an incline from the horizontal before the penstock. Although crucial, trash rack design is beyond the scope of this study's hydraulic turbine mathematical design considerations. The installation of the penstock for the Genale Dawa III plant is subterranean, influenced by factors such as ground conditions, material properties, ambient temperature, and environmental regulations. The mathematical design of the penstock and tunnel hydrodynamics falls under the purview of the pu concept, with water flow dynamics within the penstock being a key factor in turbine response time delay.

$$\frac{\Delta h(s)}{\Delta q(s)} = -Tws, \tag{3.2}$$

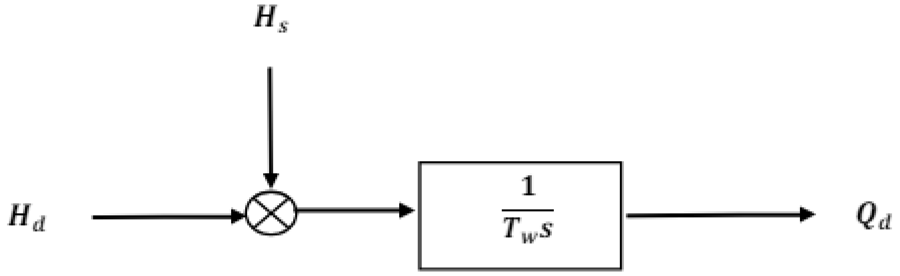


Figure 3.4: Block of Penstock Water Dynamics.

Where, Q_d is the dynamic flow of water and T_w is the water starting time of the pipe segment. T_w is defined. $Hloss$ is the head loss in the system due to the frictional coefficients which is considered as zero in the thesis for the simplicity of calculation.

3.2.1.3 Hydraulic Turbine Modeling

This study focuses on the energy conversion process within a Francis turbine deployed at the GD3 hydropower plant, characterized by a high head of 240 meters. The Francis turbine selection is driven by its suitability for high-head applications. To quantify mass and energy transfer through the turbine, the analysis will center on two key parameters: water flow rate (Q) and the turbine moment (M) transmitted to the coupled electrical generator (Barsi et al., 2023).

3.2.1.4 The linear Francis Hydro Turbine Model

Figure 3.4 depicts the subsystems of the hydropower scheme, and the simplified transfer function represents the dynamic behavior of the penstock in equation (3.2)

Where The water flow through the turbine represented by q, deviation is denoted by Δ the water beginning constant is represented by Tw, the Laplace domain is indicated by s, and the dynamic pressure at the penstock's end (head) is represented by h.

The Francis's turbine model, which represents the water flow through a turbine and the mechanical power production, is expressed as (3.3) and (3.4)

$$\mathrm{q} = \mathrm{y}\sqrt{\mathrm{h}} \quad (\mathrm{p.u.}), \tag{3.3}$$

$$\mathrm{M} = \mathrm{At}(\mathrm{qT} - \mathrm{qNL})\mathrm{h} - \mathrm{Da}{*}\mathrm{y}{*}\Delta\mathrm{w} \quad (pu), \tag{3.4}$$

where At is an attribute on the volt ampere base of the generator that takes into account turbine gain and transforms gate opening to per unit turbine output, The no-load flow is represented by qNL, the turbine damping coefficient by Da, and the turbine runner speed variation by Δw.

The linearized model provides a local linear approximation of the nonlinear turbine behavior around the specified operating point, which can be useful for analysis and control design. From equation (3.3) and (3.4) makes it evident that the turbine model is nonlinear and therefore, in order to produce a linearized.

For system stability studies, the most popular representation of a hydraulic turbine is a transfer function that is produced by linearizing the turbine characteristic curves around an operating point. Changing the operational point allows one to see the dynamics of the system under analysis with regard to that point.

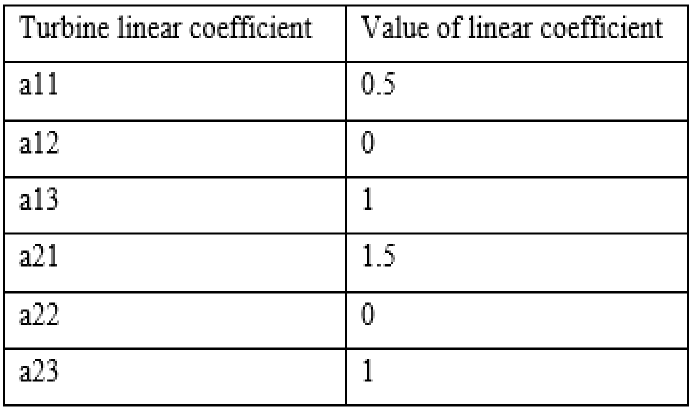
In order to characterize mass and energy transfer in the turbine, we will take into account the produced moment (M) and the water flow (Q). After that, the created moment is sent to the electrical generator so that the linear synthesis technique may be used to create the controller. Equations (3.3) and (3.4) can be approximated by using the Taylor series. The process of linearizing the turbine model's properties around an operating point leads to its simplification. The head increment (Δh), rotational speed increase (Δn), gate opening increment (ΔG), and mechanical torque increment (Δm) in hydro-turbine systems are all dependent on each other. The turbine is well-represented by the following linearized equations for small perturbations around a steady-state condition linearization is thus made.

$$\begin{aligned} \vartriangle q &= a11\vartriangle h + a12\vartriangle n + a13\vartriangle G \\ \vartriangle m &= a21\vartriangle h + a22\vartriangle n + a23\vartriangle G \end{aligned} \tag{3.5}$$

$$a11 = \frac{\delta q}{\delta h}; \quad a12 = \frac{\delta q}{\delta n}; \quad a13 = \frac{\delta q}{\delta G}$$

$$a21 = \frac{\delta m}{\delta h} \ ; \ a22 = \frac{\delta m}{\delta n} \ ; \ a23 = \frac{\delta m}{\delta G}$$

Table 3.1: Turbine coefficient based on IEEE model(Mushiri & Mbohwa, 2016)



Turbine linear coefficient	Value of linear coefficient
a11	0.5
a12	0
a13	1
a21	1.5
a22	0
a23	1

After adding (3.3) and (3.4), the linearized unit's mechanical power is as follows.

$$\Delta \mathrm{Pm} = \mathrm{a22}\Delta \mathrm{wn} + \mathrm{a23}\Delta \mathrm{y} - \frac{\mathrm{a21}\left(\mathrm{a12}\Delta \mathrm{wn} + \mathrm{a13}\Delta \mathrm{y}\right)\left(-\mathrm{sTw}\right)}{-1 + \mathrm{a11}\left(-\mathrm{sTw}\right)} \tag{3.6}$$

The dynamics of the water passing through the penstock of a hydro turbine determine its tangent characteristic. Given that the system experiences only minor fluctuations while operating normally, the linear model is adequate for the hydro-turbine's dynamic depiction. by Eq. (3.6) (Saha and Saikia, 2018).

Lastly, the following is the expression of the transfer function that characterizes the mechanical power output of the turbine as a function of the guide vane (gate) Opening.

$$\frac{\Delta \mathrm{Pm}}{\Delta \mathrm{G}} = \frac{\mathrm{a23} - \left(\mathrm{a13k21} - \mathrm{a11a23}\right)\mathrm{Tws}}{1 + \mathrm{a11Tws}} \tag{3.7}$$

After substituting the coefficients in Eq. (3.6), we obtain a generalized transfer function of the hydro-turbine model for an ideal Francis type turbine.

$$\frac{\Delta \mathrm{Pm}}{\Delta \mathrm{G}} = \frac{1-(1*1.5-0.5*1)TwS}{1+0.5TwS} = \frac{1-TwS}{1+0.5TwS} \tag{3.8}$$

Where, ΔPm - represents the change in mechanical power

ΔG - indicates the position of the gate

Tw - represents the water time constant.

3.2.1.5 Popular Model of Turbine

This study investigates the significant impact of hydraulic turbine dynamics on the dynamic stability of power systems. To illustrate this, Figure 3.5 presents a block diagram depicting the essential components of a hydro turbine integrated within the power system environment.

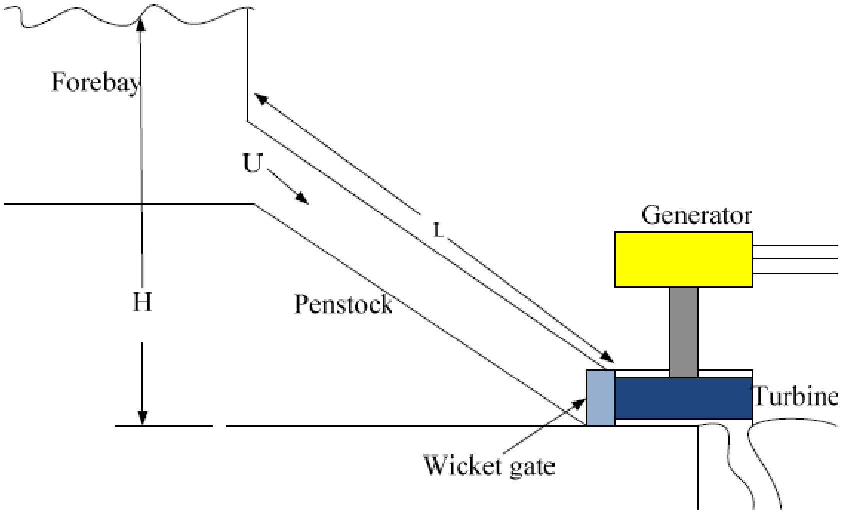


Figure 3.5: Block diagram illustrating the key elements of a hydropower (Blakers et al., 2021).

The coupled dynamics of the turbine and penstock in a hydropower system are governed by a fundamental set of three equations is

a) Water's speed in the penstock
b) Mechanical power of turbines
c) Water level acceleration

The speed of water in the penstock is given by

$$U = K_u G \sqrt{H} \tag{3.9}$$

Where U represents the water speed, G indicates the gate location, and H represents the head at the gate, which measures the hydraulic head. Additionally, Ku is a proportionality constant that is crucial for calculations.

To minimal deviations in proximity to an operational state,

$$\Delta U = \frac{\partial U}{\partial H}\Delta H + \frac{\partial U}{\partial G}\Delta G \tag{3.10}$$

$$U_0 = K_u G_0 \sqrt{H_0} \tag{3.11}$$

These equations yield

$$\frac{\Delta U}{U_0} = \frac{\Delta H}{2H_0} + \frac{\Delta G}{G_0} \tag{3.12}$$

$$\Delta \bar{U} = \frac{1}{2}\Delta \bar{H} + \Delta \bar{G} \tag{3.13}$$

where the super bar "_" represents normalized values based on steady-state operating values, the prefix Δ indicates tiny deviations, and the subscript 0 identifies beginning steady-state values. Since the mechanical power of a turbine is proportional to the product of flow and pressure,

$$P_m = K_p H U \tag{3.14}$$

Linearizing by considering small displacements, and normalizing by dividing both sides by

$$P_{m0} = K_p H_0 U_0$$

we have,

$$\frac{\Delta P_m}{P_{m0}} = \frac{\Delta H}{H_0} + \frac{\Delta U}{U_0} \tag{3.15}$$

Or

$$\Delta \bar{P}_m = \Delta \bar{H} + \Delta \bar{U} \tag{3.16}$$

Substituting for $\Delta\bar{U}$ from equation $\Delta\bar{U} = \frac{1}{2}\Delta\bar{H} + \Delta\bar{G}$ yields

$$\Delta \bar{P}_m = 1.5\Delta \bar{H} + \Delta \bar{G} \tag{3.17}$$

Alternatively, by substituting for ΔH from equation $\Delta\bar{U} = \frac{1}{2}\Delta\bar{H} + \Delta\bar{G}$ we may write

$$\Delta \bar{P}_m = 3\Delta \bar{U} - 2\Delta \bar{G} \tag{3.18}$$

According to Newton's second law of motion, the acceleration of the water column caused by the change in head at the turbine may be written as

$$\rho L A \frac{d\Delta U}{dt} = -A(\rho a_g)\Delta H \tag{3.19}$$

Where L= conduit's length

A= pipeline area

ρ = density of mass

a_g= acceleration brought on by gravity.

ρLA = volume of water within the pipe

$\rho a_g \Delta H$ = gradual shift in pressure at the turbine gate

t = the servo motor's time

By dividing both side by $a_g H_0 U_0$, the acceleration equation in normalized form becomes

$$\frac{LU_0}{a_g H_0}\frac{d}{dt}\left(\frac{\Delta U}{U_0}\right) = -\frac{\Delta H}{H_0} \tag{3.20}$$

Or

$$T_w \frac{d\Delta\bar{U}}{dt} = \Delta\bar{H} \tag{3.21}$$

Here, we use the term "water starting time" to refer to the time it takes for the water to begin flowing. This refers to the time that takes for the flow of water in the penstock to accelerate from a standstill to its desired velocity. It's important to note that this time can vary depending on the load. Typically, at full load, the water starting time ranges from 0.5 seconds to 5.0 seconds.

The mentioned equation represents a significant characteristic of the hydraulic plant. In simpler terms, if we apply back pressure at the end of the penstock by closing the gate, the water in the penstock will slow down. In other words, a positive change in pressure will result in a corresponding negative change in acceleration.

By utilizing the equation $\Delta\bar{P}_m = 3\Delta\bar{U} - 2\Delta\overline{G}$ and $T_w \frac{d\Delta\bar{U}}{dt} = \Delta\bar{H}$, we can express the correlation between velocity and gate location can be expressed as follows:

$$T_w \frac{d\Delta\bar{U}}{dt} = 2(\Delta\bar{G} - \Delta\bar{U}) \tag{3.22}$$

Replacing $^{d}/_{dt}$ with the Laplace operator s, we may write

$$T_w s\Delta\bar{U} = 2(\Delta\bar{G} - \Delta\bar{U}) \tag{3.23}$$

Or

$$\Delta\bar{U} = \frac{1}{1+\frac{1}{2}T_w s}\Delta\bar{G} \tag{3.24}$$

Substituting for $\Delta\bar{U}$ from Equation (3.22) and rearranging, we obtain

$$\frac{\Delta P_m}{\Delta G} = \frac{1-T_w s}{1+0.5T_w s} \tag{3.25}$$

The above equation (3.30) represent in block diagram is shown in Figure (3.6) .

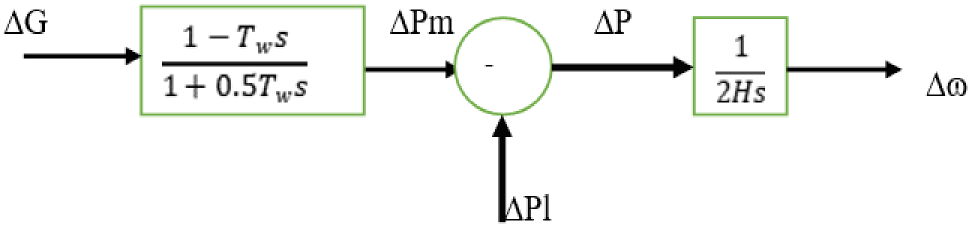


Figure 3.6: Block diagram of HT and a generator

The equation represents the transfer function of a hydraulic turbine. It illustrates how the power output of the turbine changes when there is a modification in the gate opening or when the turbine operates without any losses.

3.2.1.6 Modeling the Load

The synchronous generator's electrical load, as shown in Figure 3.7, is a consumer load. The consumer load is what causes variations in the overall electrical load.

$$\Delta P_e = \Delta P_{CL} \tag{3.26}$$

where ΔP_{CL} the consumer load has changed.

The consumer load of a hydropower system comprises different electrical devices. These devices can be classified into two main categories: non-frequency sensitive loads and frequency sensitive loads. Non-frequency sensitive loads, such as lighting and heating, remain unaffected by changes in frequency. On the other hand, motor loads are responsive to fluctuations in frequency. The extent to which a load is influenced by frequency depends on the combined speed-load characteristics of all the devices being powered.

Given a mixed load, the speed load characteristic is given by

$$\Delta P_{CL} = \Delta P_L + D\Delta\omega \tag{3.27}$$

where ΔP_L and $D\Delta\omega$ are variations in the consumer load that are non-frequency-sensitive and frequency-sensitive, respectively. The load damping constant, or D, is calculated by dividing the percentage change in load by the percentage change in frequency.

$$\Delta\omega(s) = \frac{1}{2H_s}\left[\Delta P_m(s) - \Delta P_L(s) - D\Delta\omega(s)\right] \tag{3.28}$$

The formula that has been simplified is

$$\Delta\omega(s) = \frac{1}{2H_s + D}\left[\Delta P_m(s) - \Delta P_L(s)\right] \tag{3.29}$$

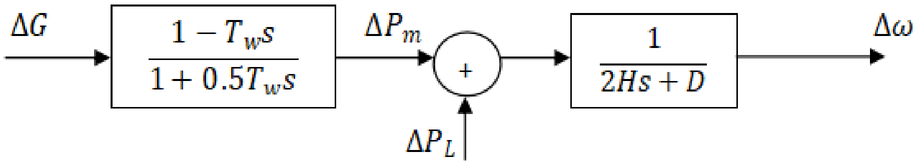


Figure 3.7: Loads, generator and turbine block diagram

3.2.1.7 Hydraulic Governor Model

The governor control system is used for hydraulic turbines in hydroelectric installations. Its main purpose is to monitor and regulate the power output and speed of the generating unit by adjusting the position of the wicket gate. The system compares the actual operating point with a reference point and makes necessary adjustments. It efficiently manages the speed and power output of the hydroelectric turbine. It consists of two main sections: the control section and the actuator mechanism sections.

The actuator used in this thesis to regulate the opening of the wicket gate in the hydraulic turbine can be either a hydraulic controller or a motor controller. The hydro turbine governor is a crucial component of a hydro power plant, serving two primary functions: controlling the mechanical power at the generator shaft to produce electrical power, and regulating the generator's speed variation to maintain a constant system frequency.

In order to regulate the system and generators frequency are equipped with governor control. In this setup, the input Δf is responsible for influencing the change in the turbine's gate valve position, ΔY. Consequently, this change in position directly affects the mechanical power ΔPm, as illustrated in Figure (3.8).

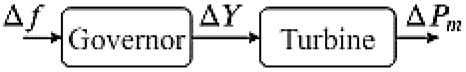


Figure 3.8: Block of HTG

There are different types of governor controllers, but the standard design consists of separate components for transient and steady-state performance. The inclusion of servo dynamics depends on the type of governor being used, such as mechanical or digital. This thesis is considering Digital governor with control is a PID type, a steady-state droop (EP), a transient PID controller with properties [K_P, K_I, K_D, T_f], and a servo dynamic with a first-order filter of time constant Ta.

Figure (3.9) illustrates a block diagram of the hydro turbine governor. The first component is a PID controller, which takes the speed error and power deviation as input and produces the desired gate position as output. This gate position serves as the input for the hydroelectric servo motor. PID controllers provide both transient and steady-state response, ensuring a faster speed response. In isolated micro-grid operation, the derivative term (Kd) of the PID controller plays a critical role in system stability. However, in an interconnected hybrid system, a high derivative gain can result in oscillations or instability mostly it is 0 value. In this system derivative term (Kd) is considered as zero. Based on the input signal, the servo motor regulates the gate opening, which subsequently controls the water flow rate and helps maintain the system frequency.

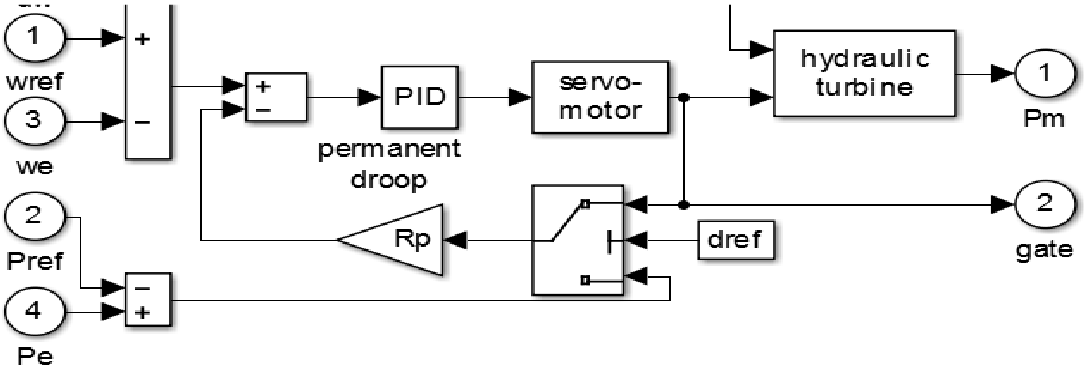


Figure 3.9: Simulink structure of hydraulic turbine speed governor

The hydraulic guide vane (gate) servo moto in Simulink representation in figure (3.8) for the Genale Dawa Three hydro power plant (Ta=0.5second) is based on the gate servomotor reaction time (ta). Figure (3.10) depicts a second-order system that is used to mimic the guide vane servomotor.

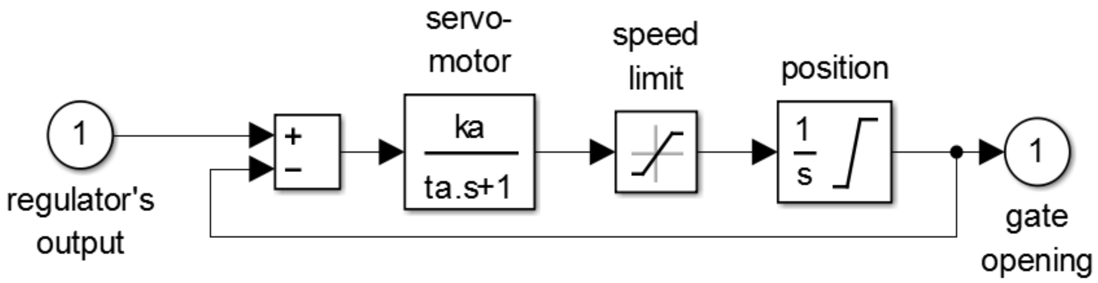


Figure 3.10: Block of servomotor model.

In electrical-hydraulic servo system, electrical-hydraulic servo valve is a key element. It is a element for electrical/displacement transition and hydraulic power amplification. It is used to convert comprehensive electrical signal output from electrical part to mechanical displacement signal with certain operating force and displacement or convert to flow signal of certain pressure.

The servo motor adjusts the position of the gate to maintain a constant frequency by responding to speed changes at the generator shaft. the general transfer function of a hydroelectric servo motor can be represented as:

$$G(s)=\frac{Ka}{(Js^2+Bs+K)} \tag{3.30}$$

Where: K is the motor constant is the moment of inertia, and B is the viscous damping coefficient.

Similar to the case of a standard servo motor, the term Js^2 can often be neglected compared to the Bs term, especially at lower frequencies. This allows the transfer function to be simplified to a first-order system:

$$G(s)=\frac{1}{(Tas+K)} \tag{3.31}$$

This first-order transfer function has a single time constant, Ta= B/K, which characterizes the dynamic response of the hydroelectric servo motor.

This simplification is commonly used in the modeling and control of hydroelectric servo motors, as it provides a good balance between accuracy and computational complexity. The advantage of reducing the transfer function to a first-order system is that it simplifies the analysis and design of the control system.

3.2.2 PID Controller

PID governor for load frequency control components are Speed governor which is manages the turbine output based on the frequency error signal, turbine Converts the water flow into mechanical power to drive the generator, Generator is Converts the mechanical power into electrical power, and Load which is represents the electrical demand on the system.

The PID controller is used to regulate the frequency by adjusting the governor setpoint. The proportional term provides a frequency-dependent correction, the integral term eliminates steady-state errors, and the derivative term improves stability and transient response.

The frequency error, which is the difference between the actual and desired frequencies, is fed into the PID controller. The PID output adjusts the governor valve position to change the turbine power and correct the frequency deviation. Tuning the PID gains is critical for optimal performance. The PID governor block diagram captures the key elements of a single area load frequency control system, with the PID controller regulating the turbine output via the speed governor to maintain frequency stability.

PID-based hydro turbine governor is an essential component in modern hydroelectric power plants, ensuring efficient, reliable, and stable operation. Its benefits include improved stability, increased efficiency, reduced wear and tear, and better response to changing load demands.

At present, although there are many kinds of microcomputer-based regulator both in all over the world, but most of them adopt PID regulation law and only some adopt adaptive parameter-varying PID while microcomputer-based governors with real high regulation law are only limited to research and test stage. Digital PID microcomputer-based governor may be divided into position type, increment type and analog increment type according to different algorithm, and may be divided into electrical-hydraulic servo system type and digital-hydraulic servo system type according to different servo systems. Microcomputer-based governors of different algorithms are described briefly as follows.

3.2.3 The Hydro Power Plant Operating Principle of a Machine

3.2.3.1 IN-line (Grid Connected) Operation

The regulator loop is power-dependent and the governor is responsible for regulating towards a power reference and droop characteristics. It is important to note that altering the grid frequency value will have an impact on the system's stability. As a result, the system will automatically modify the turbine power output to align with the value determined by the droop.

When operating after connected with grid (when system is large enough), governor increases or decreases load with power preset; it is equivalent to open-loop control because system frequency does not change at this moment; increase/decrease of load with power preset only changes load brought by generator set it.

3.2.3.2 Stand-Alone (off line) Operation

In the isolated or standalone operating mode, the system's primary control task is to regulate the frequency deviation (ΔF). In this mode, the control system only needs to monitor and adjust the frequency deviation to ensure stable operation of the isolated system. Since there is no grid connection, the main focus of the control system is solely on regulating the frequency, without the need to balance power flow to the grid. The control system must ensure that the frequency remains within acceptable limits by adjusting the generator output to match the local load demands, using techniques such as governor control.

The model incorporates a modification in the reference frequency value. This value is transmitted to a summation block, where it is deducted from the process frequency value, yielding the value e. The e value is subsequently relayed to both the PID controller and the MPC controller.

Subsequently, the controller converts the signal, which is denoted as the guide vane opening G. The guide vane opening, in turn, determines the magnitude of the flow q through the turbine dynamics. Ultimately, the flow water is directed into the hydraulic system.

Frequency regulation mode is suitable for no-load automatic operation of generator set, operation of single generator set with isolated load or generator set being connected with small grid and operation of frequency adjustment mode for generator being connected with large grid.

CHAPTER FOUR

4 CONTROLLER DESIGN

4.1 GD3 Existing PID governor

During the model's simulation, the electrical power and mechanical turbine rotor speed were compared in terms of units (Pu). The error accumulation system's architecture is shown in Figure 4.1 It also provides the error signal that the PID controller uses as an input.

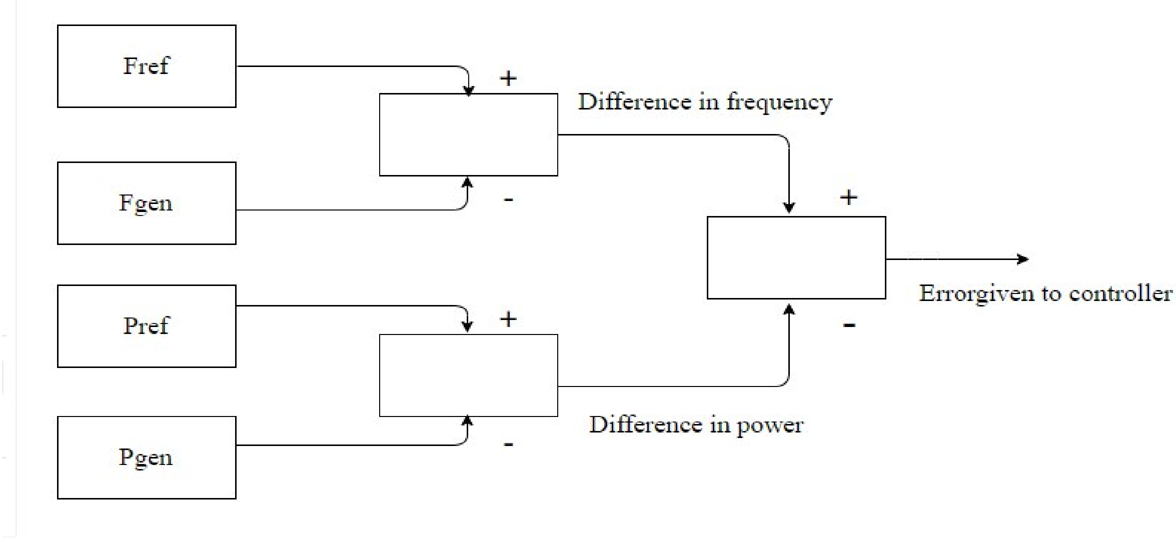


Figure 4.1: Block error collection (acquisition) given to controller

The frequency error is determined by comparing the reference frequency to the actual frequency produced by the generator. The power error is obtained by comparing the reference power to the active power output of the generator. The summation of the frequency error and power error is then input into a PID controller. In a stable system, this error should ideally be zero. The PID controller utilizes the discrepancy in frequency and power to initiate corrective actions, thereby ensuring the stabilization of power generation.

PID Controller

A PID-based hydro turbine governor is a type of control system that uses a Proportional-Integral-Derivative (PID) controller to regulate the speed of the turbine. The PID controller receives feedback from sensors that measure the turbine's speed, flow rate, and other parameters. Based on this feedback, the PID controller adjusts the output signal to control the turbine's speed, taking into account factors such as load demand, turbine speed.

The outer loop controller is used to get the power deviation reference for controlling the gate opening deviation. Outer loop controller takes desired speed and frequency deviations, then gives the power deviation of turbine that must be to meet the desired speed and frequency deviations. These reference power deviations are then used to control the gate position of the turbine.

To meet the desired specifications, PID controllers are designed to set the reference gate positions based on the reference power deviation. There is one internal PID gate position controller. The outer loop controller gives power deviation reference as

$$\varDelta P^{*} \tag{4.1}$$

The errors between the reference and turbine power deviations are described as below.

$$e_{\varDelta P} = \varDelta P^{*} - \varDelta P \tag{4.2}$$

PID controller gains be k_P,kd and k_d

The PID controller attempts to minimize the error between a measured process variable and a desired set point by calculating and outputting a corrective action to adjust the process accordingly. The proportional, integral, and derivative terms determine the reaction based on the current error, the sum of recent errors, and the rate of change in the error, respectively. Tuning the three PID constants allows the controller to meet specific process requirements. However, using the PID algorithm does not guarantee optimal control or system stability. The values of Kp, Ki, and Kd are typically determined through a trial-and-error method, with the input for the PID controller in the GD3 hydropower plant being taken from the plant manual and tuned during operation.

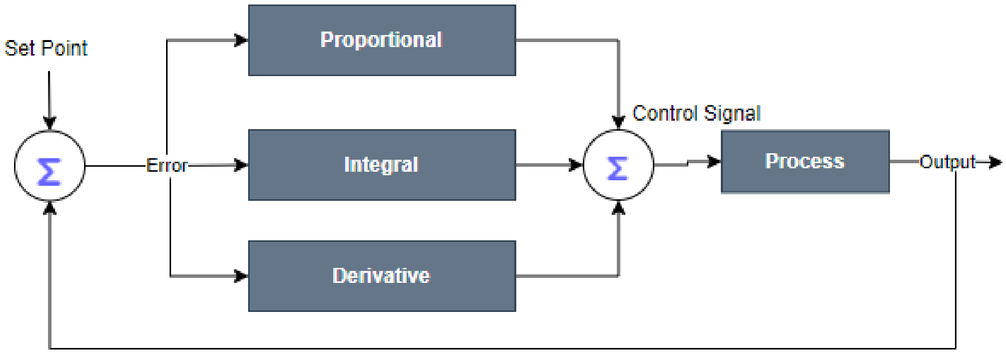


Figure 4.2: The block diagram of PID controller

The specific values for the P, I, and D parameters will depend on the characteristics of the unit, the process being controlled, and the desired performance objectives. It's recommended to start with a conservative set of PID values and then gradually adjust them through iterative tuning and testing to achieve the optimal control performance for your application. Mostly use the following PID parameter.

Table 4.1: Existing PID gain collect from site

Grid connected	Kp = 4	K i=0.25	Kd=0
Standalone plant	Kp = 4	Ki=0.25	Kd=0.02

The manual tuning method for PID controllers involves physically testing the system's response and adjusting the PID gain parameters until satisfactory performance is achieved. This empirical approach includes observing the system's behavior and iteratively tweaking the proportional, integral, and derivative gain values to obtain the desired control characteristics.

Engineers may start with approximate PID gain values as a baseline and then systematically fine-tune them through a manual process. They carefully monitor the system's response and make incremental adjustments to the PID gains. The goal is to achieve the required level of control performance, such as stable operation, minimal overshoot, reduced settling time, or meeting other operational targets.

When generator set is under automatic working condition, regulator implements PID operation according to frequency difference and permanent speed droop bp of governor is zero. After generator set is connected with grid, permanent speed droop bp of governor is certain preset value (usually is preset by system control) in order to realize difference regulation; if it operates with base load, it may be put into manual failure zone (that is frequency dead zone, opening dead zone or power dead zone). At the same time, cut off differential action and change PID operation to PI operation.

The manual tuning method is commonly used because it allows engineers to apply their domain expertise and empirical understanding of the system's dynamics. By directly observing the system's behavior and making manual adjustments, engineers can often achieve a well-tuned PID controller that meets the application's needs, even in complex or non-linear systems where automated tuning methods may struggle. PI controller equation basically express in below equation (4.3) the gate position deviation is:

$$\Delta G = k_P e_{\Delta P} + k_I \int e_{\Delta P} dt \tag{4.3}$$

The output from PI controller (gate position) is used for controlling the power output of the turbine.

4.2 Linear Model Predictive Governor Controller

The generator speed change and the mechanical power developed by the turbine are related by equation 4.4 given below.

$$\text{Ä}P(s) = (Ms + D)\text{Äù}(s) \tag{4.4}$$

$$\text{Äù}(s) = \frac{1}{Ms+D}\text{Ä}P(s) \tag{4.5}$$

The mechanical power also depends on the gate opening position and the relationship between these two terms is expressed in equation 4.6.

$$\Delta P_m = \frac{1-T_w s}{1+0.5T_w s}\Delta y \tag{4.6}$$

where, Δy is the guide vane opening.

The guide vane is also controlled servomotor which depends on the control signal u produced by the governor.

$$\Delta y = \frac{1}{1+T_a s}u \tag{4.7}$$

where, T_a is the time constant of the servomotor dynamics.

When we combine the above three equations to develop an overall model, we reach to an expression which has the control signal u as input and the speed change of the turbine as output. Hence equation 4.8 gives the overall expression used for the controller development.

$$\frac{\Delta\omega}{u} = \frac{1}{D+Ms}\times\frac{1-T_w s}{1+0.5T_w s}\times\frac{1}{1+T_a s} = \frac{1-T_w s}{0.5MT_wT_a s^3 + \left(0.5MT_w + 0.5DT_wT_a + MT_a\right)s^2 + D} \tag{4.8}$$

The transfer function which is given in equation 4.8 is then converted to state space representation and shown in equations 4.9 and 4.10.

$$\dot{x}(t) = A_c x(t) + B_c u(t) \tag{4.9}$$

where, $x(t) = states, u(t) = control\ signal.$

The output of the generator is the frequency deviation and the output equation is given as:

$$y(t) = C_c x(t) \tag{4.10}$$

where, $y(t) = Äf(t), C_c = \frac{1}{2ð}$.

In order to design MPC, the linear model of the generator is discretized as:

$$x(k+1) = A_d x(k) + B_d u(k) \tag{4.11}$$

$$y(k) = C_d x(k) + D_d u(k) \tag{4.12}$$

Using the expression $Äx(k) = x(k) - x(k-1), Äu(k) = u(k) - u(k-1)$,

state increments are given as

$$Äx(k+1) = A_d Äx(k) + B_d Äu(k) \tag{4.13}$$

Similarly, using the state and input increments, the output equation is redefined as follows

$$y(k+1) = y(k) + C_d A_d Äx(k) + C_d B_d Äu(k) \tag{4.14}$$

The augmented system is developed as

$$\begin{bmatrix} Äx(k+1) \\ y(k+1) \end{bmatrix} = \begin{bmatrix} A_d & 0 \\ C_d A_d & 1 \end{bmatrix} \begin{bmatrix} Äx(k) \\ y(k) \end{bmatrix} + \begin{bmatrix} B_{du} \\ C_d B_{du} \end{bmatrix} Äu(k) \tag{4.15}$$

Let new state is defined as

$$z(k) = \begin{bmatrix} Äx(k) \\ y(k) \end{bmatrix}$$

Using the new state, the augmented expression, Equation (4.37) is written as

$$z(k+1) = Az(k) + BÄu(k) \tag{4.16}$$

$$y(k) = Cz(k) \tag{4.17}$$

where, $A = \begin{bmatrix} A_d & 0 \\ C_d A_d & I \end{bmatrix}$, $\mathrm{B} = \begin{bmatrix} B_d \\ C_d B_d \end{bmatrix}$, $\mathrm{C} = [(0)_{\text{size of } x(k)} \quad I_{size \text{ of } y}]$

As shown in equation, the augmented system is influenced by the previous states and change of the control signal.

Define a control horizon (Nc) as number of parameters used to determine the future control trajectory. The future control trajectory can be denoted by:

$$Äu(k)\,, \Delta u(k+1)\,, \Delta u(k+2)\,, \dots \Delta u(k+N_c) \tag{4.18}$$

Another parameter is called prediction horizon, Np, defined as the length of the optimization window. The predicted states can be denoted as:

$$z(k+1|k)\,,z(k+2|k)\,,z(k+3|k)\,,\dots z(k+N_P|k)$$

For given prediction horizon, the predictions of the augmented system for three consecutive time steps are given as

$$z(k+1|k) = Az(k) + B\ddot{A}u(k)$$

$$z(k+2|k) = Az(k+1|k) + B\ddot{A}u(k+1) = A^2z(k) + \sum_{i=0}^{2-1} A^{2-i-1}B\ddot{A}u(k+i)$$

$$z(k+3|k) = Az(k+2|k) + B\ddot{A}u(k+2) = A^3z(k) + \sum_{i=0}^{3-1} A^{3-i-1}B\ddot{A}u(k+i)$$

For any arbitrary future time step n, Equation __ shows the system predicted expression.

$$z(k+n|k) = A^n z(k) + \sum_{i=0}^{n-1} A^{n-i-1}B\ddot{A}u(k+i)\,, \text{if } n < N_c$$

$$z(k+n|k) = A^n z(k) + \sum_{i=0}^{n-N_c-1} A^{n-i-1}B\ddot{A}u(k+i)\,, \text{if } n \geq N_c$$

Similarly, the last prediction made on the system is given by Equation (4.43)

$$z\big(k+N_p|k\big) = A^{N_p}z(k) + \sum_{i=0}^{N_p-1} A^{N_p-i-1}B\ddot{A}u(k+i)\,, \text{if } N_p = N_c$$

$$z\big(k+N_p|k\big) = A^{N_p}z(k) + \sum_{i=0}^{N_c-1} A^{N_p-i-1}B\ddot{A}u(k+i)\,, \text{if } N_p > N_c$$

and, the predictions of the outputs of three consecutive time steps are developed as:

$$y(k+1|k) = Cz(k+1|k) = CAz(k) + CB\ddot{A}u(k)$$

$$y(k+2|k) = Cz(k+2|k) = CA^2z(k) + \sum_{i=0}^{2-1} CA^{2-i-1}B\ddot{A}u(k+i)$$

$$y(k+3|k) = Cz(k+3|k) = CA^3z(k) + \sum_{i=0}^{3-1} CA^{3-i-1}B\ddot{A}u(k+i)$$

Hence, for an arbitrary time step instance, n, the output prediction becomes

$$y(k+n|k) = Cz(k+n|k) = CA^{n}z(k) + \sum_{i=0}^{n-1} CA^{n-i-1}B\ddot{A}u(k+i)\,, \text{if } n < N_c$$

$$y(k+n|k) = Cz(k+n|k) = CA^{n}z(k) + \sum_{i=0}^{N_c-1} CA^{n-i-1}B\ddot{A}u(k+i)\,, \text{if } n \geq N_c$$

In summary, the last output prediction made at time step equal to the prediction horizon, N_P, is expressed as

$$y\left(k+N_p|k\right) = Cz\left(k+N_p|k\right) = CA^{N_p}z(k) + \sum_{i=0}^{N_p-1} CA^{N_p-i-1}B\ddot{A}u(k+i)\,, \text{if } N_p = N_c$$

$$y\left(k+N_p|k\right) = Cz\left(k+N_p|k\right) = CA^{N_p}z(k) + \sum_{i=0}^{N_c-1} CA^{N_p-i-1}B\ddot{A}u(k+i)\,, \text{if } N_p > N_c$$

In general, the vector of predictions on the output is defined as:

$$Y = Ez(k) + F\ddot{A}U \tag{4.19}$$

where, $Y = \begin{bmatrix} y(k+1|k) \\ y(k+2|k) \\ \vdots \\ y(k+N_P|k) \end{bmatrix}$, $\Delta U = \begin{bmatrix} \ddot{A}u(k) \\ \ddot{A}u(k+1) \\ \vdots \\ \ddot{A}u(k+Nc-1) \end{bmatrix}$

$$E = \begin{bmatrix} CA \\ CA^{2} \\ \vdots \\ CA^{N_p} \end{bmatrix},\; F = \begin{bmatrix} CB & 0 & \cdots & 0 \\ CAB & CB & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ CA^{N_P-1}B & CA^{N_P-2}B & \cdots & CA^{N_P-N_C}B \end{bmatrix}$$

The next step in LMPC development is stating the cost function and list the constraints that apply on the system variables.

In optimal control, the optimization is considered in reducing the error between the set point value and the predicted state output. Since the final value is defined, the optimization is done as a fixed final state optimization. It can be written as:

$$J = \frac{1}{2}\int_0^{\infty}((R_s - Y)^{T}Q(R_s - Y) + \ddot{A}U^{T}R\ddot{A}U)dt \tag{4.20}$$

where, R_S is the vector of desired frequency deviation (set point). Q and R are the weighting matrices of the output errors and input increments.

MPC is a type of controller in which different constraints can be used for better control performance. In this project there are three constraints are defined:

i. Constraint on input control signal, u
ii. Constraint on the increment of the input signal, Δu
iii. Constraint on the output, y

The input constraint is bounded in between minimum and maximum values of the power deviation (that means u_{min} and u_{max}, respectively). The predicted input signals for three consecutive time steps can be expressed as:

$$u(k) = u(k-1) + \ddot{A}u(k)$$
$$u(k+1) = u(k) + \ddot{A}u(k+1) = u(k-1) + \ddot{A}u(k) + \ddot{A}u(k+1)$$
$$u(k+2) = u(k+1) + \ddot{A}u(k+2) = u(k-1) + \ddot{A}u(k) + \ddot{A}u(k+1) + \ddot{A}u(k+2)$$

For any time-step n which is less than the number of the control horizon, the future control value is given calculated as

$$u(k+n) = u(k+n-1) + \ddot{A}u(k+n) = u(k-1) + \sum_{i=0}^{n} \ddot{A}u(k+i)$$

In addition, the last future control value is found to be

$$u(k+N_c-1) = u(k-1) + \begin{bmatrix} 1 & 1 & \cdots & 1 \end{bmatrix}_{1\times N_c} \begin{bmatrix} \ddot{A}u(k) \\ \ddot{A}u(k+1) \\ \vdots \\ \ddot{A}u(k+N_C-1) \end{bmatrix}$$
$$u(k+N_c-1) = u(k-1) + \begin{bmatrix} 1 & 1 & \cdots & 1 \end{bmatrix}_{1\times N_c} \ddot{A}U$$

Assume that control constraints are applied at any instant prediction, n, which is less than the size of the control horizon, then it is described as follows.

$$u_{\min} \le u(k+n) \le u_{\max}$$
$$u_{\min} \le u(k-1) + \sum_{i=0}^{n} \Delta u(k+i) \le u_{\max}$$
$$u_{\min} - u(k-1) \le \sum_{i=0}^{n} \Delta u(k+i) \le u_{\max} - u(k-1)$$

In general, for sequence of future control increments, ΔU, the constraints are summarized below. The coefficient matrix that multiplies sequences of control increments is composed of identity matrices, I, with size of 2×2 because of the control signals are two.

$$\begin{bmatrix} & u_{min} & \\ & u_{min} & \\ & \vdots & \\ u_{min}[] \begin{bmatrix} I & 0 & \cdots & 0 \\ I & I & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ I & I & \cdots & I \end{bmatrix} & \begin{bmatrix} \ddot{A}u(k) \\ \ddot{A}u(k+1) \\ \vdots \\ \ddot{A}u(k+N_c-1) \end{bmatrix} & \begin{bmatrix} u_{max} \\ u_{max} \\ \vdots \\ u_{max}[] \end{bmatrix} \end{bmatrix}$$

It can also be designed as

$$\begin{bmatrix} I & 0 & \cdots & 0 \\ I & I & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ I & I & \cdots & I \end{bmatrix} \begin{bmatrix} \ddot{A}u(k) \\ \ddot{A}u(k+1) \\ \vdots \\ \ddot{A}u(k+N_c-1) \end{bmatrix} \leq \begin{bmatrix} u(k-1)_{max} \\ u(k-1)_{max} \\ \vdots \\ u(k-1)_{max}[] \end{bmatrix} \begin{bmatrix} -I & 0 & \cdots & 0 \\ -I & -I & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ -I & -I & \cdots & -I \end{bmatrix} \begin{bmatrix} \ddot{A}u(k) \\ \ddot{A}u(k+1) \\ \vdots \\ \ddot{A}u(k+N_c-1) \end{bmatrix} \leq \begin{bmatrix} -u(k-1)_{min} \\ -u(k-1)_{min} \\ \vdots \\ -u(k-1)_{min}[] \end{bmatrix}$$

From the last two expressions, a compact form is written as:

$$M_1 * \ddot{A}U \leq N_1 \tag{4.21}$$

where, $M_1 = \begin{bmatrix} I & 0 & \cdots & 0 \\ I & I & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ I & I & \cdots & I \\ -I & 0 & \cdots & 0 \\ -I & -I & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ -I & -I & \cdots & -I \end{bmatrix}$, $N_1 = \begin{bmatrix} u_{\max} - u(k-1) \\ u_{\max} - u(k-1) \\ \vdots \\ u_{\max} - u(k-1) \\ -u_{\min} + u(k-1) \\ -u_{\min} + u(k-1) \\ \vdots \\ -u_{\min} + u(k-1) \end{bmatrix}$

The increment of the input signal, Δu, is taken to be in the range of Δu_{min} and Δu_{max}. Constraints on arbitrary increment is described below.

$$\Delta u_{\min} \leq \Delta u(k+n) \leq \Delta u_{\max}$$

These can be expressed in compact matrix form as:

$$\begin{bmatrix} & \ddot{A}u_{min} & \\ & \ddot{A}u_{min} & \\ & \vdots & \\ \ddot{A}u_{min}[] \begin{bmatrix} I & 0 & \cdots & 0 \\ 0 & I & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & I \end{bmatrix} & \begin{bmatrix} \ddot{A}u(k) \\ \ddot{A}u(k+1) \\ \vdots \\ \ddot{A}u(k+N_c-1) \end{bmatrix} & \begin{bmatrix} \ddot{A}u_{max} \\ \ddot{A}u_{max} \\ \vdots \\ \ddot{A}u_{max}[] \end{bmatrix} \end{bmatrix}$$

This expression is also written into two expressions.

$$\begin{bmatrix} I & 0 & \cdots & 0 \\ 0 & I & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & I \end{bmatrix} \begin{bmatrix} \ddot{A}u(k) \\ \ddot{A}u(k+1) \\ \vdots \\ \ddot{A}u(k+N_c-1) \end{bmatrix}$$

$$\leq \begin{bmatrix} \ddot{A}u_{max} \\ \ddot{A}u_{max} \\ \vdots \\ \ddot{A}u_{max}[] \end{bmatrix} \Bigg| \begin{bmatrix} -I & 0 & \cdots & 0 \\ -I & -I & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ -I & -I & \cdots & -I \end{bmatrix} \begin{bmatrix} \ddot{A}u(k) \\ \ddot{A}u(k+1) \\ \vdots \\ \ddot{A}u(k+N_c-1) \end{bmatrix} \leq \begin{bmatrix} -\ddot{A}u_{min} \\ -\ddot{A}u_{min} \\ \vdots \\ -\ddot{A}u_{min}[] \end{bmatrix}$$

Again, in simplified form,

$$M_2 * \ddot{A}U \leq N_2 \tag{4.22}$$

where, $M_2 = \begin{bmatrix} I & 0 & \cdots & 0 \\ 0 & I & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & I \\ -I & 0 & \cdots & 0 \\ -I & -I & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ -I & -I & \cdots & -I \end{bmatrix}$, $N_2 = \begin{bmatrix} \Delta u_{\max} \\ \Delta u_{\max} \\ \vdots \\ \Delta u_{\max} \\ -\Delta u_{\min} \\ -\Delta u_{\min} \\ \vdots \\ -\Delta u_{\min} \end{bmatrix}$

Similarly, the output is set to be in between Y_{min} and Y_{max}.

$$Y_{\min} \leq Y \leq Y_{\max}$$

From Equation (4.15),

$$\begin{aligned} & Y_{\min} \leq Ez(k) + F\Delta U \leq Y_{\max} \\ & Y_{\min} - Ez(k) \leq F\Delta U \leq Y_{\max} - Ez(k) \\ & -F\Delta U \leq -Y_{\min} + Ez(k) \ \ , \ \ F\Delta U \leq Y_{\max} - Ez(k) \end{aligned}$$

In compact simplified form,

$$M_3 * \Delta U \leq N_3 \tag{4.23}$$

where, $M_3 = \begin{bmatrix} -F \\ F \end{bmatrix}$, $N_3 = \begin{bmatrix} -Y_{min} \\ Y_{max} \end{bmatrix}$

The expressions developed in are summarized in a single equation as:

$$M * \ddot{A}U \leq N \tag{4.24}$$

where, $M = \begin{bmatrix} M_1 \\ M_2 \\ M_3 \end{bmatrix}$, $N = \begin{bmatrix} N_1 \\ N_2 \\ N_3 \end{bmatrix}$

Due to constraints exist, the optimization problem becomes:

$$\underset{\ddot{A}U}{min} J = \frac{1}{2}\left((R_s - Y)^T Q (R_s - Y) + \ddot{A}U^T R \ddot{A}U\right) \tag{4.25}$$

$$such \text{ that } M * \Delta U \leq N$$

Hence, Hamiltonian equation is required for optimization.

$$H = \frac{1}{2}(R_s - Y)^T Q (R_s - Y) + \frac{1}{2}\ddot{A}U^T R \ddot{A}U + \ddot{e}^T (M * \ddot{A}U - N) \tag{4.26}$$

Since Y is determined in equation (4.42), the Hamiltonian equation is rewritten as

$$H = \frac{1}{2}(R_s - Ez(k) - F\ddot{A}U)^T Q (R_s - Ez(k) - F\ddot{A}U) + \frac{1}{2}\ddot{A}U^T R \ddot{A}U + \ddot{e}^T (M * \ddot{A}U - N)$$

$$H = \frac{1}{2}(R_s - Ez(k))^T Q (R_s - Ez(k)) + \frac{1}{2}\ddot{A}U^T (F^T Q F + R) \ddot{A}U - \ddot{A}U^T F^T Q (R_s - Ez(k)) + \ddot{e}^T (M * \ddot{A}U - N)$$

The necessary conditions for optimization are

$$0 = \frac{\partial H}{\partial \ddot{A}U} \quad , \quad 0 = \frac{\partial H}{\partial \ddot{e}}$$

Therefore, the necessary conditions will lead to

$$\frac{\partial H}{\partial \ddot{A}U} = F^T Q F \ddot{A}U - F^T Q (R_s - Ez(k)) + R\ddot{A}U + M^T \ddot{e} = 0$$

$$(F^T Q F + R)\ddot{A}U - F^T Q (R_s - Ez(k)) + M^T \ddot{e} = 0$$

$$\frac{\partial H}{\partial \ddot{e}} = M * \ddot{A}U - N = 0$$

$$M * \ddot{A}U = N$$

$$M^T M * \ddot{A}U = M^T N$$

$$\ddot{A}U = (M^T M)^{-1} M^T N$$

Since the constraint is inequality constraint, finding the optimal value of ΔU is difficult. So, a MATLAB built in function, *quadprog*, is used.

In conclusion, the optimal control signal is found from

$$\ddot{A}U = quadprog(\tilde{a}, \hat{a}, M, N)$$

where, $\tilde{a} = F^T * Q * F + R\ ,\ \hat{a} = -F^T * Q * (R_s - E * x)$

ΔU is a matrix of size $N_c \times 1$ which consists optimal control signal values (in our context, the duty ratio of the converter). But MPC is optimization technique where the first value of ΔU is applied on the system to determine the dynamics of the system. Hence, the optimal control increment value that is applied is given by:

$$\ddot{A}u(k) = [1 \quad 0 \quad \cdots \quad 0]_{1 \times Nc} \ddot{A}U \tag{4.27}$$

And the applied control is:

$$u(k) = u(k-1) + \ddot{A}u(k) \tag{4.28}$$

As said earlier, the output of the outer controller is the power deviation references used inside the PI gate opening controller. Therefore, *u(k)* is defined as

$$u(k) = \ddot{A}P^* \tag{4.29}$$

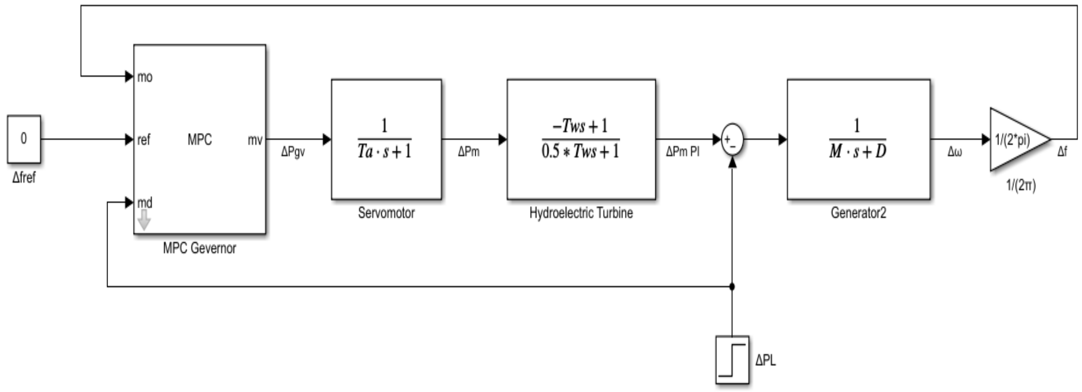


Figure 4.3: Overall system of the MPC controlled the hydro power plant

CHAPTER FIVE

5 SIMULATION RESULT

In the simulations presented in this section, the parameters of a GD3 hydropower system are examined. The total rated capacity of the generation unit is 84.7 kilowatts (kW), and the normal coefficient R is 10 hertz per per-unit kilowatt (Hz/pu·kW), with a load change of 10 %,20%, and 30%. Additionally, the nominal starting time of water in the penstock (Tw) is 4 seconds, as detailed in Appendix A. The inclusion of these typical parameters allows for a comprehensive analysis of the GD3 hydropower system's performance and behavior under various operating conditions and different scenario focuses on the response of controllers to changes in system load.

5.1 Performance of MPC

For this research, the prediction horizon selected is 5. This choice may have been determined through simulation to ensure that the controller can effectively track the desired response and anticipate constraint violations. Prediction horizon likely chosen based on the specific requirements of the system and the desired performance.

The constraints are shown below.

Constraints applied on the current references are

$$\Delta f_{\min} = -1pu,\ \Delta f_{\max} = 1pu,\ \Delta P_{\min} = -1pu,\ \Delta P_{\max} = 1pu$$

And the inequality constraints are defined as:

$$\Delta f_{\min} \le \Delta f \le \Delta f_{\max}$$
$$\Delta P_{\min} \le \Delta P \le \Delta P_{\max}$$

The set point used for closed-loop performance analysis is to make the frequency deviation to be within the range of -0.1pu and 0.1pu, and equal to zero.

$$\Delta f^{*} = 0pu$$

The state and control weight matrices (Q and R) are found to get better tracking performance and minimize the cost function. The state weight matrix, Q, penalize the state error found by the difference of the set point and the instant state (output). The control weight, R, is used to penalize the control signal and improves the cost function by optimizing the control variable. The values of Q and R are set by Bryson's:

$$\mathbf{Q=60},\ \boldsymbol{R = 0.005}$$

In terms of practicality, Bryson's rule allows for the calculation of initial values for the weighting matrices Q and R in the LQR controller. This is achieved by using the reciprocals of the squares of the maximum acceptable values of the state variables. By employing this method, the controller parameters can be effectively determined, which ultimately improves the stability and performance of the control system.

5.2 Machine Operating in Isolated Mode

A hydropower unit operating in island mode is specifically designed to ensure a stable frequency on an isolated electrical grid. It accomplishes this by adjusting its power output to match the load, thereby regulating the frequency and maintaining system stability without the need for support from a larger interconnected grid. This means that reliable electricity can be provided even when the main grid is not available. The single machine, single load setup provides a relatively simple testbed to compare the capabilities of PID and MPC control strategies in maintaining grid stability and power quality.

Model Predictive Control (MPC) as the optimization approach. Additionally, the same underlying model has been adapted and evaluated with existing PID controller

(a) When add the 10% load

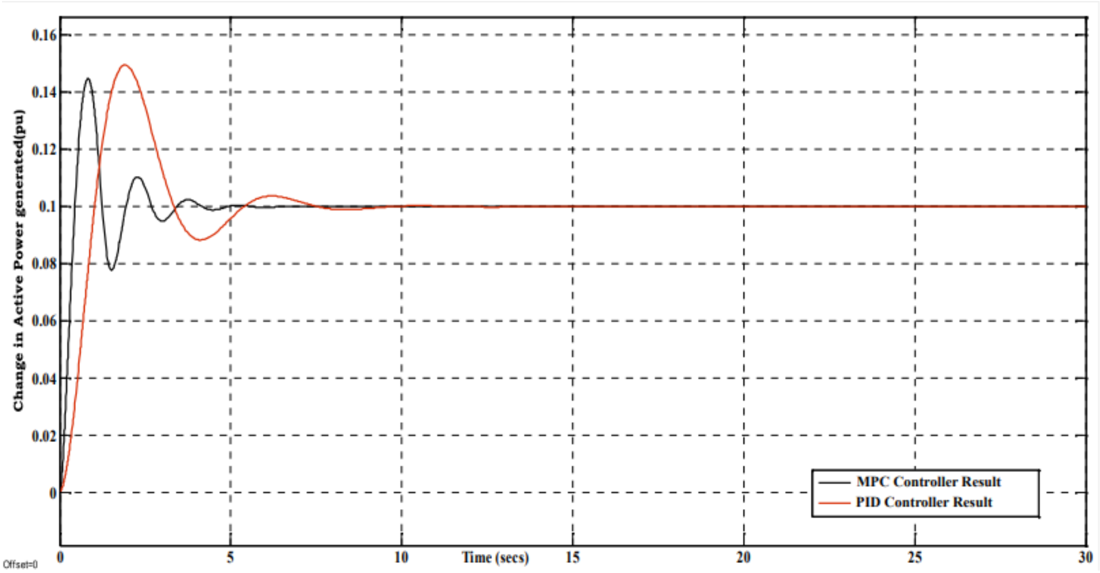


Figure 5.1: Response of change of power output when the 10% load add

(b) When add 0.2pu load

In an isolated electrical network, a 0.2 per unit increase in load can significantly impact the system frequency. To maintain system frequency stability, it is essential for the generation to closely match the load in real-time, especially in networks with limited interconnections. The load frequency control system is responsible for quickly detecting load changes and coordinating the necessary generation response to restore the frequency to the desired setpoint. Two commonly used control strategies for this purpose are PID (Proportional-Integral-Derivative) and MPC (Model Predictive Control).

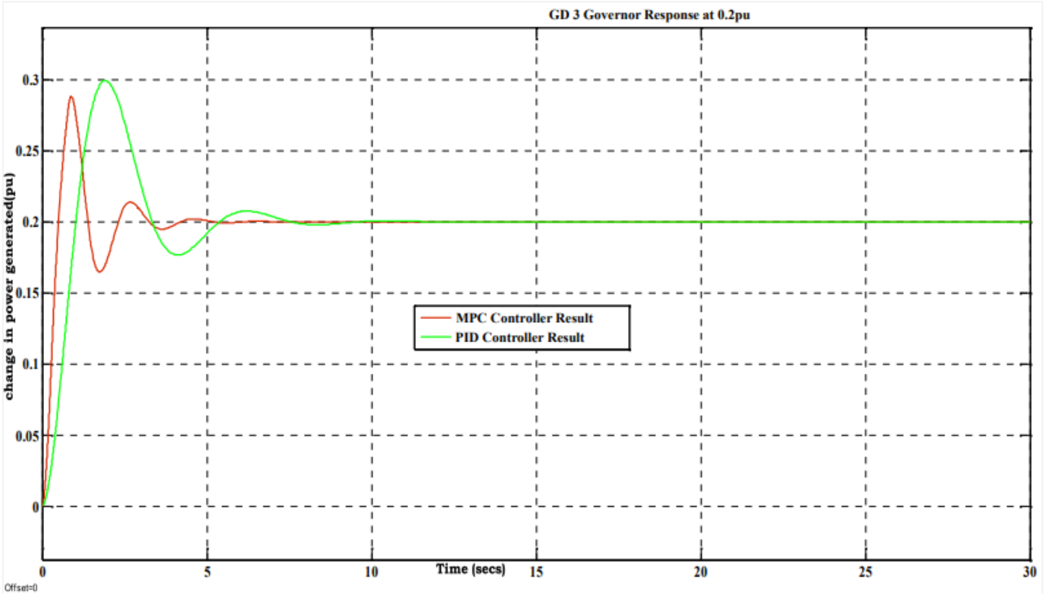


Figure 5.2: Response of change of power output when the 20% load add

Shown in Figure 5.2 MPC employs a system model to forecast the future actions of the generator and load, and then proactively optimize the generator's response. This proactive approach enables MPC to swiftly adapt to changes and disturbances, in contrast to the reactive nature of PID control. By incorporating the parameters of the existing PID controller, an MPC system can be fine-tuned to enhance the baseline performance.

During startup, the system steadily increases the production of power, peaking at 0.876 seconds. The value then peaks at 0.288pu before dropping to 0.21pu at 4.59 seconds. The MPC effectively stabilizes the system changed by 20 presents.

(c) When the load changes (add) by 0.3Pu

The MPC controller would offer a more precise, stable, and rapid response to the 0.3 pu load change, as opposed to the PID controller, in this power control application.

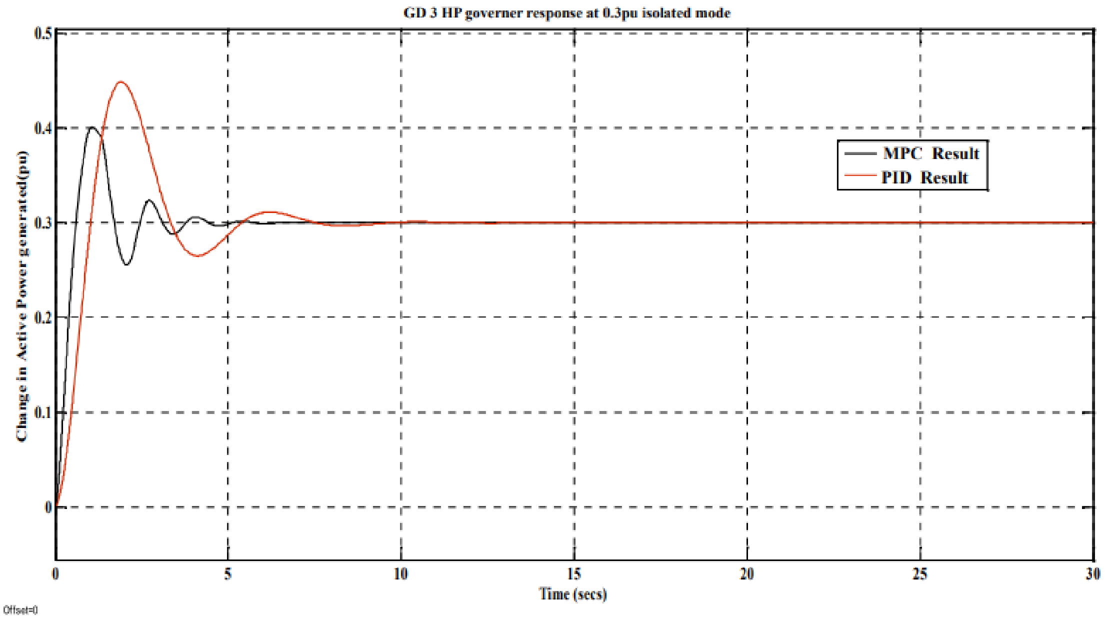


Figure 5.3: Response of change of power output when the 30%load add

Table 5.1: Response time of controller the load change (add 0.1pu,0.2pu and, 0.3pu)

Specification	MPC			PID		
	0.1 pu	0.2pu	0.3pu	0.1 pu	0.2pu	0.3pu
Setting time	4.9	4.9	5	5.66	5.8	7.8
Overshoot	43.9	44.2	44.6	51.1	50.8	52.1
Rise time	0.31	0.34	0.35	0.69	0.7	0.9

(d) The load reduces by 10%

MPC known to be more robust, offering faster and smoother responses with undershoot time, settling time, and overshoots compared to PID controllers and also Model Predictive Control provides optimal control signal for the future, leading to improved control performance compared to traditional PID control strategies.

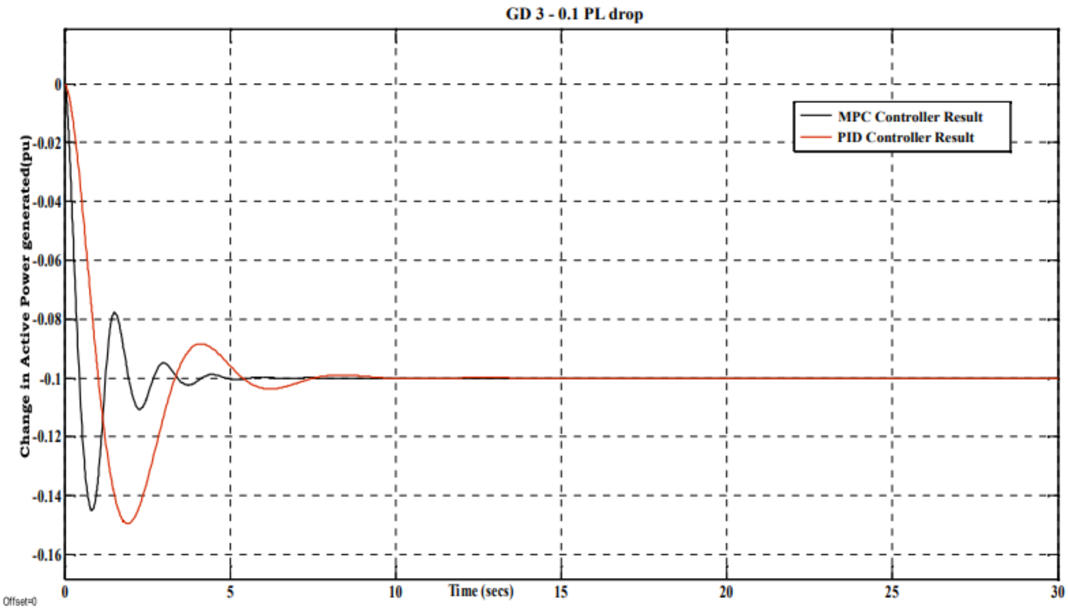


Figure 5.4: Response of change of power output when 10% load reduced

(e) 0.2 load reduced

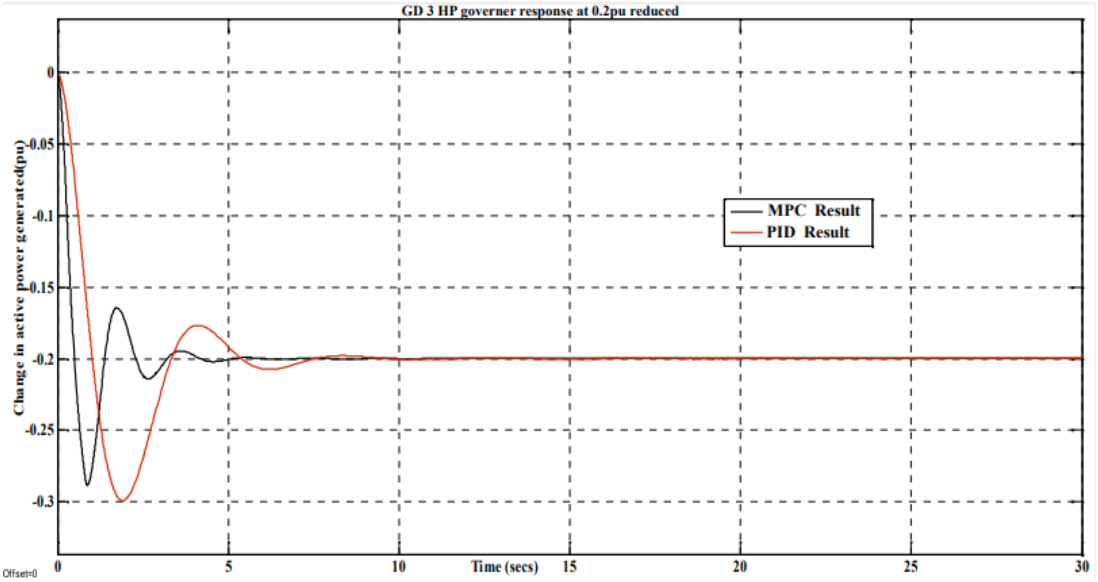


Figure 5.5: Response of change of power output when the 20 % load reduce

(f) Load reduced by 30 %

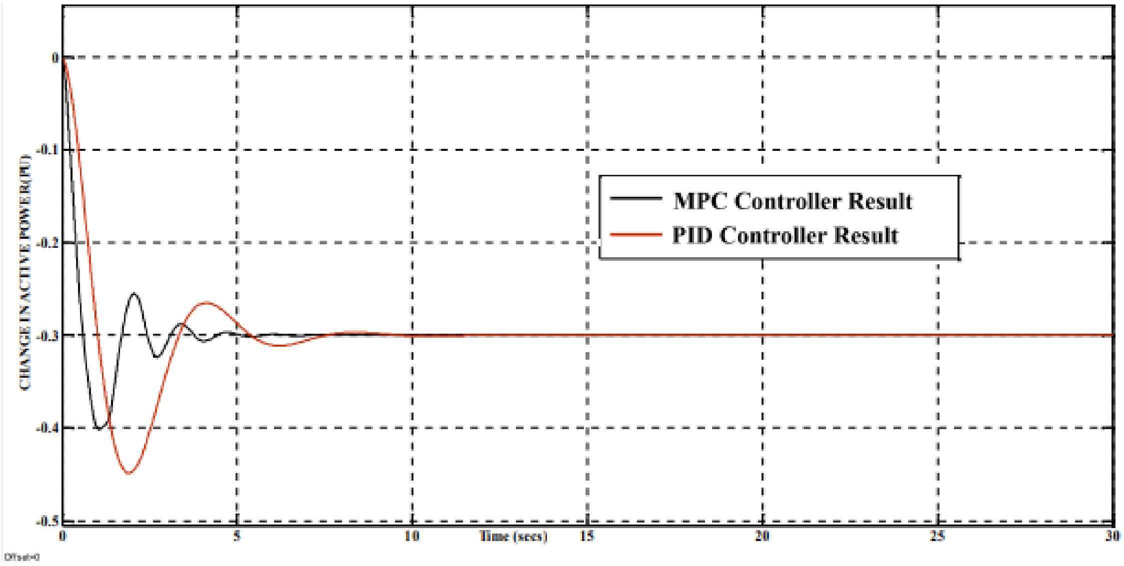


Figure 5.6: Response of change of power output when the 30%load reduced

Table 5.2: Response time of controller the load change (drop 0.1pu,0.2pu and, 0.3pu)

Specification	MPC			PID		
	0.10 pu	0.20pu	0.30pu	0.10pu	0.20pu	0.30pu
Setting time	4.70	2.1	4.8	8.3	4.3	6.1
Undershoot	45.8	44.3	34.5	51.2	51.5	50.8
Fall time	0.3	0.34	0.4	0.71	0.71	0.71

5.3 The Machin connected to Grid

When the machine(unit) connected to the grid have to mode frequency control mode and power control mode.

5.3.1 First Mode: Frequency Control Mode

In The GD3 Hydropower Station, after the unit is connected with power grid, the governor can also work in any kind of three modes artificially selected of (speed, opening and power control mode) be. Before connecting to the power grid, the governor works only under speed control mode.

Case one :1% Frequency added from a system

When the system frequency increases by 1%, this indicates that the generation is exceeding the load on the network. As a result, the system experiences a phenomenon called "droop" where the load on the system decreases in response to the higher frequency.

When 1% increase in frequency causes the load to droop, which in turn leads to a decrease in the power generated by the system, resulting in a 16.8 MW drop in power production from the 84 MW rated capacity

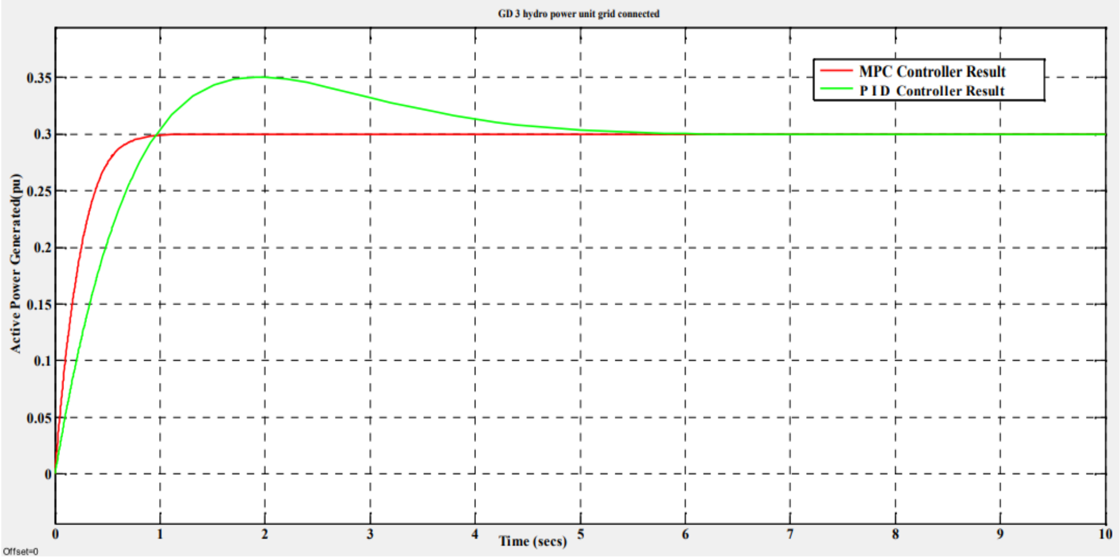


Figure 5.7 : Response of change of power output when frequency 1% add from a system

Case two :1% present drop frequency

the 1% decrease in frequency causes the generators to droop and reduce their power production to match the higher load on the network. The 1% decrease in frequency triggers an increase in power generation by 0.2 pu, resulting in a total 0.7 pu change in power output. The figure then compares the performance of different control approaches in managing this change in generation

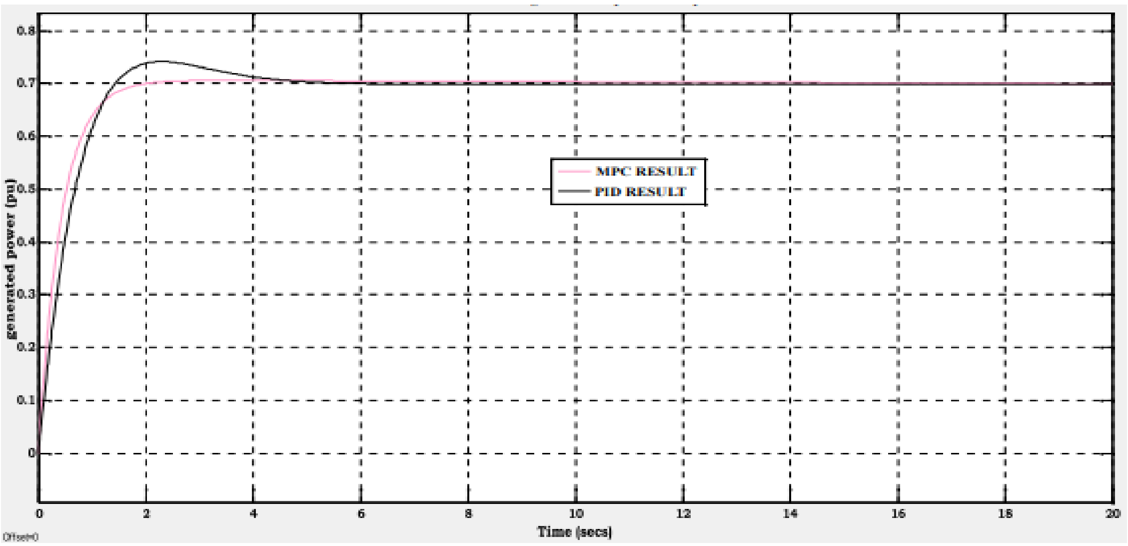


Figure 5.8 : Response of generated power the 1% decrease in frequency

Table 5.3: Response time of controller the l in frequency change

Case	1%f added		1%f drop	
Specification	MPC	PID	MPC	PID
Setting Time	2.780	5.790	2.98	4.30
Overshoot	0.5	16.9	0.5	6.2
Rise Time	0.44	0.71	0.92	0.97

5.3.2 Second Mode: Power Control Mode

Power regulation mode is a kind of regulation mode adopted with priority after generator set is connected with large grid. It is mainly used under base load working condition. Power regulation mode is especially suitable to automatic generating control working condition implemented by hydropower station. Such regulation mode, regulator allows generator set to change load through power preset Pc (or upper generator set issues power preset value). However, opening preset will not participate in closed loop load regulation; opening preset Yc only tracks opening value of guide vane servomotor in real time so as to guarantee to realize disturbance-free conversion when switching from this regulation mode over to “opening regulation” mode.

In the power control mode, the generator's governor adjusts the opening of the prime mover's inlet valve or gate (such as turbine guide vanes) according to received power signals. The power control mode serves a distinct purpose from other governor control modes, like speed control, which have different objectives. Specifically, the power control approach is employed to maintain a steady power output at a predetermined value. By utilizing this power control mode, the generator can seamlessly adjust its output to accommodate shifting grid conditions, guaranteeing a consistent power supply to the electrical network.

Case 1: Power Input Reference is 0.5

The power generation unit maintains a constant power output that matches a reference power of 0.5 per unit, regardless of load demand or frequency variations, when operating in power control mode

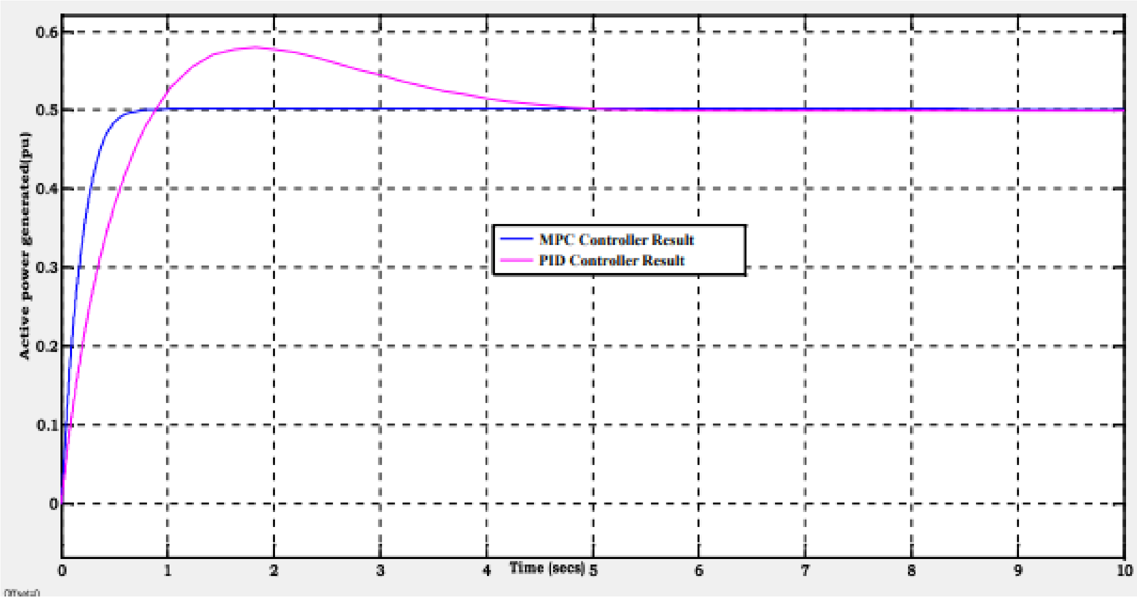


Figure 5.9: Active power generated when Pref=0.5

Case 2: Power Reference Input 0.9pu

The power generation unit in power control mode maintains a constant power output that matches the power reference signal, regardless of load demand or frequency variations. An operator provides the results of a model predictive control (MPC) and PID controller for power control at a reference power of 0.9 per unit for unit one of the GD3 hydropower plant.

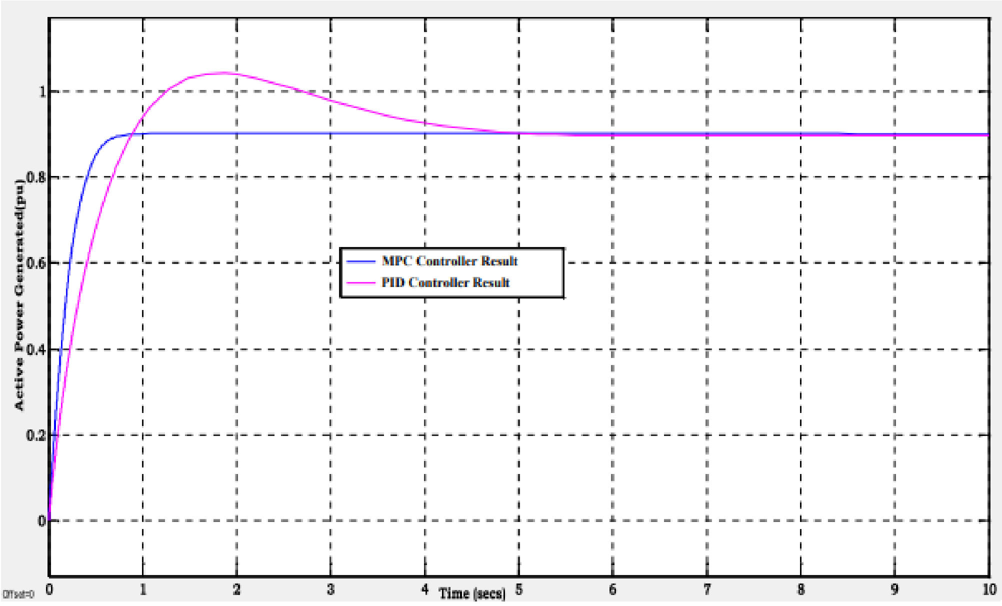


Figure 5.10: Active power generated when Pref=0.9

The table demonstrates that the model predictive control (MPC) controller outperforms the existing PID controller in power control modulation systems. It shows that the MPC controller has a lower percentage of overshoot, shorter settling time, and faster rise times

Table 5.4: Specification the reference power input

Case	0.5 reference		0.9 reference	
Specification	MPC	PID	MPC	PID
Settling time	1.080	4.080	1.07	4.31
Overshoot (%)	0.77	26.48	0.901	23.9
Rise Time	0.5	0.3	0.35	0.56

When generator outlet switch is closed, generator set is connected with grid and governor selects “power regulation” mode automatically at this moment. After generator set is connected with grid, any of the three regulation modes may be selected manually. The hydropower unit responds more effectively to smaller power reference values than to higher values. Model predictive control (MPC) provides a quicker response in power control mode compared to other control strategies.

Model Predictive Control (MPC) as the optimization approach. Additionally, the same underlying model has been adapted and evaluated with PID. On the other hand, the control system that uses MPC appears to maintain a stable and well-regulated response when dealing with this significant different load change load. The MPC-based controller effectively dampens and minimizes the frequency and magnitude of oscillations observed in the figure 5.1 to figure 5.6 response control approaches under the same load change conditions. This comparative analysis suggests that the MPC control strategy may be better suited to handle larger fluctuations in system load without compromising the stability and consistency of frequency regulation. The findings indicate that the MPC approach can adapt and respond more effectively to substantial changes in the operational conditions of the system, mitigating the oscillatory tendencies that are prevalent in alternative control techniques under these demanding load scenarios.

These insights provide valuable information about the relative performance and suitability of different control systems when dealing with significant changes in system load. This knowledge can guide the selection and implementation of the most appropriate control methodology for applications that may experience substantial variations in their operational load requirements. time. MPC showed its reliability, while other controllers had difficulty dealing with the problem of fluctuation consolidation.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

This thesis suggests a model predictive controller to regulate the frequency and active power of a HPP unit. The objective is to support the adoption of digital monitoring and control systems for power in Genale Dawa Three. The initial stage of the research included modeling the dynamics of the hydraulic system (including the penstock), the mechanical system (particularly the linearized hydro turbine), and the electrical system.

By comparing the dynamic response of a linear plant model applying a limited predictive control algorithm to that of an ordinary proportional-integral (PID) controller, the effectiveness of the recommended predictive algorithm was confirmed. The results show that the plant's reaction is greatly improved over its whole operating range by the predictive control algorithm.

This research successfully developed a control strategy that drives the predicted plant output remarkably close to the desired reference, demonstrating its effectiveness in achieving accurate system performance while satisfying constraints. MPC can anticipate future events and adjust control actions accordingly and holds promise for improving the performance and efficiency of hydro turbine governors.

MPC known to be more robust, offering faster and smoother responses with undershoot time, settling time, and overshoots compared to PID controllers and also Model Predictive Control provides optimal control signal for the future, leading to improved control performance compared to traditional PID control strategies.

The individual component of Genale Dawa 3 hydro power plant modeled to form hydro power plant and simulated for two operating condition grid connected and isolated operation. For grid connected operation simulate two types of control power and frequency and for isolated operation control frequency of the system using existing conventional controller. In this work model predictive controller controls frequency and active power generated under the system is in isolated operation and Grid connected operation, and the result of simulation is compared with existing Proportional Integral Derivative controller. The control performa nce of a Model Predictive controller is superior to existing conventional PID controller. MPC controllers can achieve superior performance in terms of faster response times, tighter control, and better disturbance rejection compared to PID controllers.

6.2 Recommendation

This thesis limits its evaluation of hydro power plant MPC controller by simulation only but for future work implemented practically hydropower system model by reducing model complexity means Balancing accuracy with computational efficiency remains a challenge. including model validation means verifying the model's accuracy against real world data is crucial, and the controller works on emerging technologies.it is integrating machine learning.

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APPENDIX A

Table A.1: Hydro power plant parameters and HTG

Parameter	Symbol	Unit	Value
Number of units			3
Water flow	Q	m^3/s	38.1
Rate height	H	m	270
Rated water flow	QR	m3/s	124
Friction factor tunnel	ft	pu	0
Servo time constant	TG	sec	0.5
Surge tank Friction factor	fp	pu	0.036
Water starting time	Tw2	sec	4
Rated speed	w	rm	427
Rated power	P	MW	85
Francis type turbine			
Inertia constant of system	H		3
Load damping factor	D		1%