UNIVERSITY of RWANDA COLLEGE OF SCIENCE AND TECHNOLOGY ACE-ESD AFRICAN CENTER OF EXCELLENCE IN ENERGY FOR SUSTAINABLE DEVELOPMENT

STUDY ON POWER STABILITY IMPROVEMENT OF A MINI-HYDRO PLANT, CASE STUDY OF MUSARARA MINI-HYDROPOWER PLANT.

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Done by

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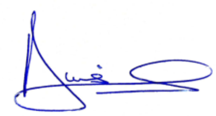
DECLARATION

I, the undersigned, declare that this study on improving power stability in a mini-hydropower plant; case study of Musarara Mini- hydropower plant located in Gakenke/Rwanda is my own original work and has not been submitted or presented for a degree at University of Rwanda or any other Masters program. All sources of materials used in the thesis work will have been properly acknowledged.

Names: Denyse ISHIMWE Signature: 

APPROVAL

Date of Submission: 06/11/2021

This thesis work has been submitted for examination with my approval as a university advisor.

Dr.-Ing. Getachew Biru Worku

Thesis Supervisor Signature

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ABSTRACT

Mini grid-connected hydropower plants contain small synchronous generators connected parallel to the grid. Voltage and frequency are the major variables which should be controlled to maintain the power stability of the system. The case study of my thesis is Musarara mini-hydropower plant which contains continuous voltage variation and frequency deviations. The plant does not contain the ability to maintain these challenges to increase its generation efficiency and due to this problem, it mainly fails to be synchronized with the grid.

The aim of the research is to conduct power stability study of Musarara mini-hydropower plant, and the problem associated there and then design a controller that helps to improve the stability of the system. The PID controller for AVR system and load frequency control (LFC) system are proposed to improve the power stability of the generator. The AVR and LFC systems are modelled and simulated in MATLAB Simulink with the synchronous generator to verify the stability improvements. The results obtained after simulation show that the AVR with PID controller and LFC with PID controller give quick responses with minimum overshoots where the voltage is maintained at the terminal voltage of 1 per unit with the help of designed AVR with tuned PID controller. The tuned PID shows the reduced overshoot than the untuned PID controller i.e., it has been reduced from 26.3% to 4.42%, and the setting time has been reduced from 5.14 seconds to 3.33 seconds. With the LFC, the frequency returns to the original value of 50 Hz after the system is being subjected to the load changes because the tuned PID shows the reduced overshoot than the untuned PID controller i.e., it has been reduced from 25.9% to 2.17% and the rise time has been increased from1.74 seconds to 0.422 seconds.

Keywords: *Synchronous generator, mini-hydro plant, power stability improvement, automatic voltage regulator, load frequency control and PID controller.*

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List of abbreviations

REG: Rwanda energy group

AVR: Automatic voltage regulator

LFC: Load frequency control

FLC: Fuzzy logic controller

PSS: Power system stabilizer

CMS: Content management system

MATLAB: Matrix Laboratory

A.C: Alternating current

IPPs: Independent Power Producers

PPA: Power purchase agreement

KW: Kilo Watts

MHPP: Mini-hydropower plant

DC: Direct current

CAVR: Conventional automatic voltage regulator

SMIB: Synchronous machine infinite bus

LINPACK: Linear system package

EISPACK: Eigen system package

HVDC: High voltage direct current

SVC: Static Var Compensator

TCSC: Thyristor controlled series capacitor

FACTS: Flexible alternating current transmission systems

ANN: Artificial neural networks

CHAPTER 1. INTRODUCTION

1.1 Background

Rwanda has high abundant natural energy resources, including hydropower, solar power, thermal power, and methane gas. Today, Rwanda has the total installed capacity of 235.6MW from different power plants where hydropower contributes 50.6% of total installed capacity, thermal sources contribute 43.4%, and solar sources contributes 5% of the total installed capacity. This was accomplished by allowing private energy investors known as Independent Power Producers (IPPs) to participate in raising the installed capacity of the country[1].

The growth of the total installed power plants was shown by Rwanda Energy Group (REG) in Figure 1.

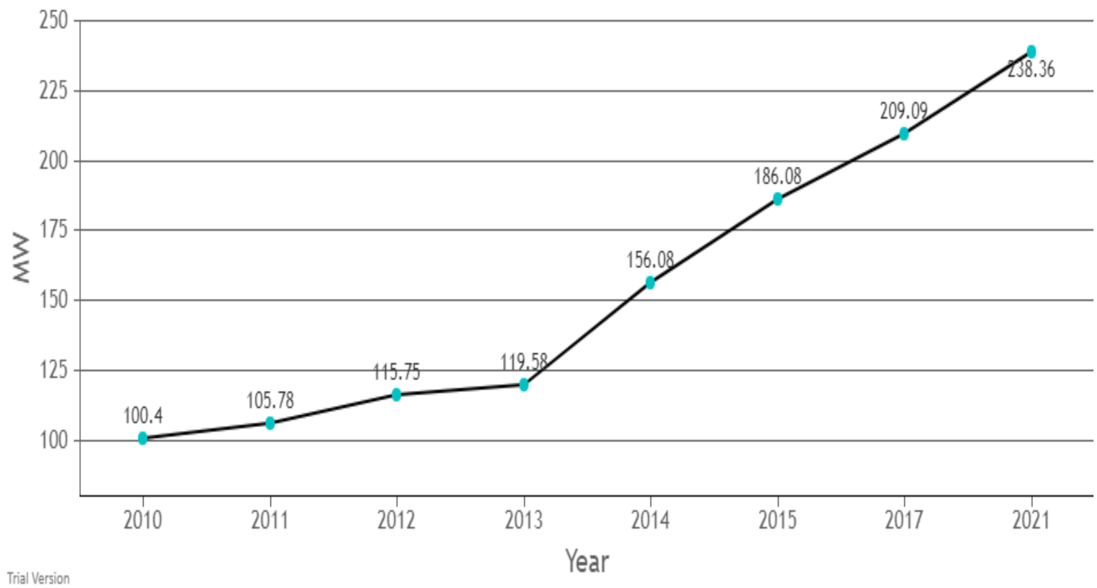

Figure 1:Evolution of Installed capacity of Rwanda in MW [1]

Rwanda has enough water resources, including natural lakes, rivers, groundwater, marshlands, and runoff. This opportunity to have a huge amount of water in various parts of the country encourages investors to invest in mini-hydropower projects, to contribute to the program of raising the installed capacity by selling their energy produced to the national grid through power purchase agreement (PPA). This is accomplished by involving REG and IPPs in power purchase agreements (PPAs) that are tailored to their specific needs. A mini hydro is type of localized power generation that generates independent power that can be connected to the grid to increase any country's installed capacity by meeting the demand of electricity or feed a small nearest community. Mini-hydropower plants are made up of small synchronous generator that are connected to the grid in parallel. These units should have an adjusted voltage and frequency to maintain the synchronism[2].

Load changes have a great impact on such generators due to their small KVA ratings. It results in deviation of the frequency to move beyond its limit, and voltage of the system fluctuates because terminal voltage regulator fails to keep the voltage set point constant. This may cause the generator to lose synchronization[3]. And if the generator loses synchronization, it will automatically fail to connect to the grid, causing a disruption in the transmission line.

The case study of this research is Musarara mini-hydropower plant which is a part of Amahoro Energy Ltd in Gakenke District. This site utilizes a 500 KW Ossberger synchronous generator and can produce 450KW. This generator has power stability problem due to its unstable voltage and frequency deviation. Until now, this problem is not yet handled, and it becomes major limitation to effectively operate the plant.

Amahoro Energy Ltd is looking to expand its current site in the future and develop other hydroelectric projects in the region to increase output to the national grid. The photos show different components of Musarara mini-hydropower plant.

Figure 2: Penstock of Musarara mini-hydropower plant with 60m of head.

Figure 3: Musarara MHPP generator production display unit.

This study tries to control the voltage and the frequency at Musarara MHPP according to the power demand of 450 KW of the plant and the load change by designing an AVR with tuned PID controller which has quick response and reduced overshoot and settling time to stabilize the voltage and LFC with tuned PID controller to control the frequency deviation. This results in improvement of the plant power stability.

1.2. Problem statement

In Rwanda, the large part of electricity comes from hydropower and many hydropower plants in Rwanda are mini hydro connected or feeding to the grid. They mostly contain small synchronous generator connected to the utility. Due to small rating of those generators, they are highly influenced by load variations and the system voltage and frequency deviations as a result.

The case-study of this research is Musarara MHPP, in which the generator voltage deviates beyond the tolerance values, as the generator is unable to control its voltage with the variation of the load and the frequency is deviating from the nominal value leading the generator to lose from synchronism. As a result, there is loss of synchronization between grid and generator which decrease the generation efficiency of the power plant.

1.3. Objectives

1.3.1. Main Objective

This research focuses at identifying the performance and stability problems of the mini-hydropower plant and on identifying and evaluating potential solutions to the problems accordingly.

1.3.2. Specific objectives

The specific objectives include:

- Data collection and their analysis to evaluate the performance of the generator.
- Identify appropriate techniques for enhancing the stability limit of mini-hydro synchronous generator.
- Identify the right solution to the problem based on collected data from the power plant.

- Model and simulate the system using MATLAB/Simulink software to provide the improvement by integrating the identified technology.
- Draw conclusions and recommendations for future implementation.

1.4. Limitation of the Study

The research does include only assessment of the problem and identifying solution to the problem. As there are no electronic devices to be implemented now at the plant, the research was conducted by use of modelling and simulation software.

1.5. Study scope

The scope of study includes gathering performance data of the power plant, design of the model AVR with PID controller, and load frequency control with tuned PID controller.

1.6. Hypothesis and Significance of the Study

1.6.1. Hypothesis

This research aims at analyzing the power stability problems arising in Musarara mini-hydropower plant and showing potential solution to problem by modelling and simulation of AVR and LFC with PID controlled using the software called MATLAB/ Simulink.

1.6.2. Study significance

This research aims at improving the voltage and frequency stability of synchronous machine and help to overcome the problem of power reliability to the Rwandan community.

1.7. Thesis Outline

The outline of this project consists of six chapters.

- The first chapter is Introduction, which provides a brief overview of the study's background and motivation, problem statement, objectives, limitations, expected outcomes, and project outline.
- The second chapter is the theoretical background and literature review, which includes related work done by other researchers on this topic, as well as theoretical concepts and fundamental definitions used in this research project.

- The third chapter describes the research methodology and tools used in the project's implementation
- The fourth chapter covers modeling and simulation of the system utilized as a solution to the stated problem.
- The fifth chapter presents a discussion and results analysis of the project research findings in relation to the project objectives.
- The sixth chapter discusses the research findings' conclusion and recommendations.

1.8. Description of Study Area

The case study of this research is Musarara mini-hydropower plant which is a part of Amahoro Energy Ltd located in Gakenke District, in Rusasa Sector, in Northern Province. Musarara mini-hydropower plant is a plant generating a maximum power of 450 kW. This site utilizes a 500KVA, Ossberger synchronous generator. Currently, the plant is not generating that maximum power of 450KW due to stability problems and unstable water flow.

Figure 4: Musarara MHPP

CHAPTER 2. LITRATURE REVIEW

2.1. Introduction

This research is based on improving power stability of a mini-hydro power plant in Musarara MHPP by designing an AVR with PSS-based fuzzy logic controller. This chapter presents the theoretical background and researches done on similar topics.

2.2. Theoretical Background on Mini-hydropower Plants

2.2.1. Hydroelectric Power

With energy becoming the current catch phase in business, industry, and society, energy alternatives are growing daily. Hydroelectricity is one option for meeting rising energy demand and a dependable renewable resource. Simply put, affordable and dependable electricity is critical to any nation's economic growth and security[4]. Today's world is reliant on consistent, low-cost, and abundant energy. There is no such thing as creating or destroying in nature, however, its shape can change. For thousands of years, people have used water to their advantage. They used to use water for electrical power generation many years ago. People's lifestyles have improved because of water use for electricity generation. During power generation, water falling in form of kinetic energy is converted to another form which provides electricity [2]. As water is the key input to get electrical energy, this is known as hydroelectric power or hydropower.

2.2.2. Hydropower Plants Classification

Hydropower plants are more classified:

1.Referring to the amount water flowing, there run-off river power plants. Run-off river power plants may be classified as run-off river power plants without pondage and reservoir power.

2. There are three types of power plants based on water head availability: low head, medium head, and high head.

3. There are three types of loads supplied: Base load, peak load, as well as pumped storage plants for peak load.

4. Hydroelectric power plants are classified according to their installed capacity; we have large, medium, small, mini, and micro hydropower plants. These are briefly explained in table 1[2]:

Table 1: Classification of hydropower plants according to their generation capacity

Large hydro	Producing higher than 100 Megawatts (MW) and usually connected to large grid.
Medium hydro	Between 15MW and 100MW and usually connected a grid.
Small hydro	Between1MW and 15MW and usually connected to a grid.
Mini hydro	Between 100KW and 1MW and either stand alone or connected to a grid.
Micro hydro	Between 5KW and 100KW and usually are standalone feeding the small number of consumers in rural remote areas.
Pico hydroelectric	They produce below 5KW.

Referring to the Fourth classification, Mini hydro is mainly being discussed in this research. In general, mini hydro, micro hydro and Pico hydro are classified as small hydro plants. Many hydropower plants are "run-of-river". Small hydropower can be constructed in the place where they cannot damage the population around as most of small hydropower plants are run-of-river schemes or are integrated into existing water infrastructure [2]. Because water availability and low investment costs, small-scale hydropower is more reliable to produce electricity, and it requires low cost of installation in rural areas.

2.2.3. Hydropower as Part of a Mini-Grid

With an abundance of available resources, small hydro schemes play the most important role among all mini grids. Consideration factors for the development of mini-hydro systems are as follows [4]:

- Can be added to an existing network
- Can be standalone or grid connected
- Provide provision for future connection to national grids

- It is flexible to load change
- Can be interconnected with other generators on the same network

Advantages of mini hydropower

- Abundant of water resource
- Low impact to environment
- Mature proven technology
- Long equipment life span
- Reliability
- Low maintenance cost
- Requires a smaller number of operators
- It can be hybrid with other energy sources

2.2.4. Basic Parts of Hydropower Plants and Energy Generation

Water must flow to generate kinetic (moving). This energy is converted to mechanical (machine) energy when flowing water runs turbine blades. Turbine begins to rotate the generator rotor shaft, to convert mechanical energy into electrical energy. Some power plants take the inputs from rivers, streams, and canals, but to increase the reliability of water supply, dams are needed [4]. The reservoir plays the same role as battery by storing water and releasing it when needed to generate power. The dam creates a "head," or the height from which water flows. A pipe which conducts water from the reservoir to the turbine is called penstock. When water is flowing with high pressure, it will help to easily push the turbine swords, this allows directly to turns the rotor which is immediately connected to the generator shaft to convert the rotational energy into electrical energy.

This principle was discovered by Michael Faraday in 1831 when he realized the electricity could be produced by rotating coils placed in the magnetic field. When water completes its work of rotating the turbine, it directly released to the river and being used in other services like irrigation, cleaning and so on [5], [6].

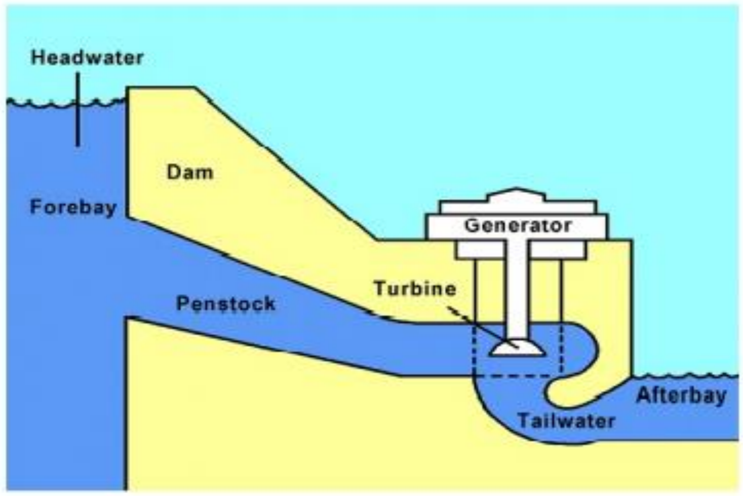

Figure 5: Single block diagram of hydropower plant [6]

2.2.5. Hydroelectric Power Computation

The volume of water discharged, and the head help determine the actual electrical power. It means that the power produced depends on the amount of water supplied. The type of turbine to be used is determined by the power plant's head and discharge, as well as the generator's required rotational speed.

Pressure (water pressure) is generated by the head, and the higher the head, the higher the pressure required to drive turbines. This force is measured in pounds per square inch (pounds per square inch). More power translates to more head or faster flowing water[5]. To find the power via a specific place, the formula utilized:

$\boldsymbol{P = m \times g \times H_{net} \times \eta}$ Eq 2. 1

Where P is the produced power in Watts (W), m is the mass flow rate in kg/s, g is the gravitational constant (9.81m/s2), and $\boldsymbol{H_{net}}$is the net head. This is the gross head measured at the site after losses of heads are considered into account.

To keep things simple, suppose that the net head losses are 10%, so $\boldsymbol{H_{net}} = H_{gross}$ is the sum of the efficiencies for all component parts of hydropower plant, which are usually the turbine, the drive system and the generator [7]. In most cases of small hydropower plant, the efficiency of turbine would be 85%, the drive efficiency would be 95% and the efficiency of generator would be 93%, resulting in a massive system efficiency of 0.85x0.95x0.93=0.751, or 75.1%.

2.3. Modelling of Small Hydropower Plants

2.3.1. Governor Modelling

A governor is a device that keeps the prime mover's rotor speed within acceptable limit regardless of load changes. The speed is controlled by varying the water supplied to the prime mover. Many governors work based the action of centrifugal force and are composed of a pair of masses rotating around a spindle driven by the prime mover and kept from flying outward by a controlling force, usually applied by springs.

The controlling force is overcome as the speed increases, and the masses move outward; the movement of the masses is transmitted to valves that supply the prime mover with its working fluid or fuel. The revolving masses are balls connected by link arms to a vertical spindle, and the controlling force is the weight of the balls. An increase in load has the opposite effect[7]. Modern governors control fuel flow to internal combustion engines, as well as steam, water or flow rate to various types of turbines

The governor's purpose is to control the fuel to the engine cylinders in order to manage the unit's speed, maintaining the speed constant among all load conditions imposed on the generator being driven by the engine as well as the frequency [5], [4].

The governor's equation is displayed in different manners with the same purpose, but they show various operating conditions and control modes. The main objective of the governor is: to set the guide vane's opening according to different boundary conditions. Figure 6 shows the complete control block diagram of the proportional-integral-derivative (PID) governor system.

All variables of turbine are expressed in per unit values [5].

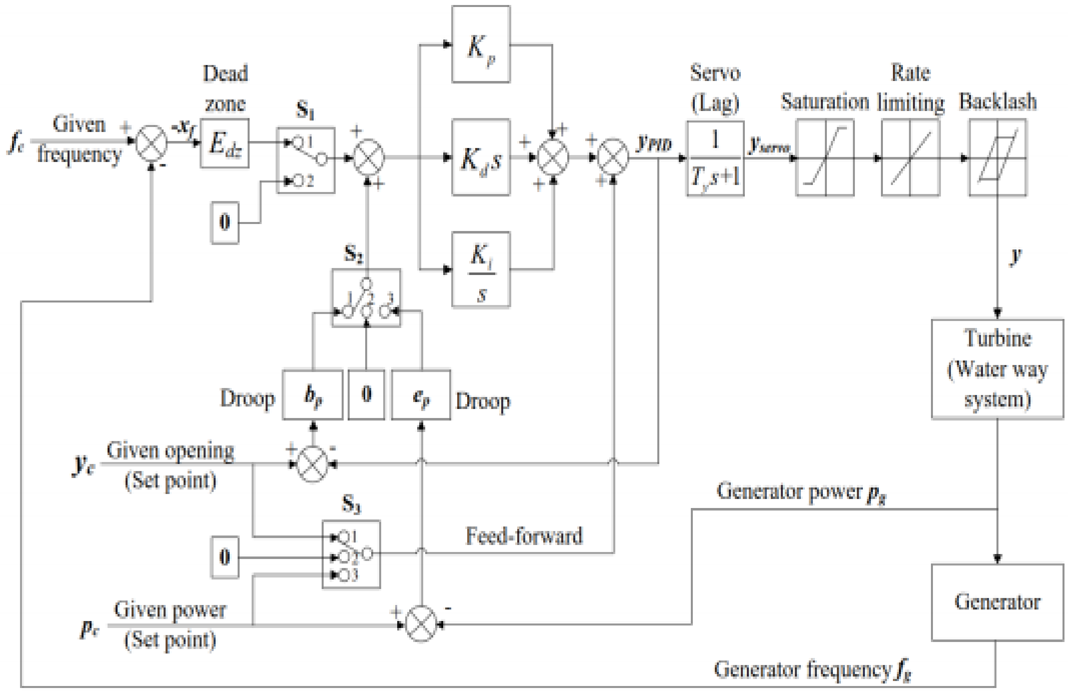

Figure 6: Diagram of governor model [7]

2.3.2. Turbine or Prime-Mover Modelling

The prime mover, that also has another name of turbine, provides rotational power to supplied to the generator through the generator shaft. The turbine that uses coal, nuclear, gas as well as combined cycle units is a steam turbine a steam valve restricts the mechanical power. The main mover in hydroelectric machines water gate controls the mechanical power of a hydro-turbine. We can denote the turbine -generated power as Pm because It is the mechanical energy transferred to the generator [4], [7], [8]. We will denote the mechanical power control as ΔPV. The general model of the turbine is indicated in Figure 7.

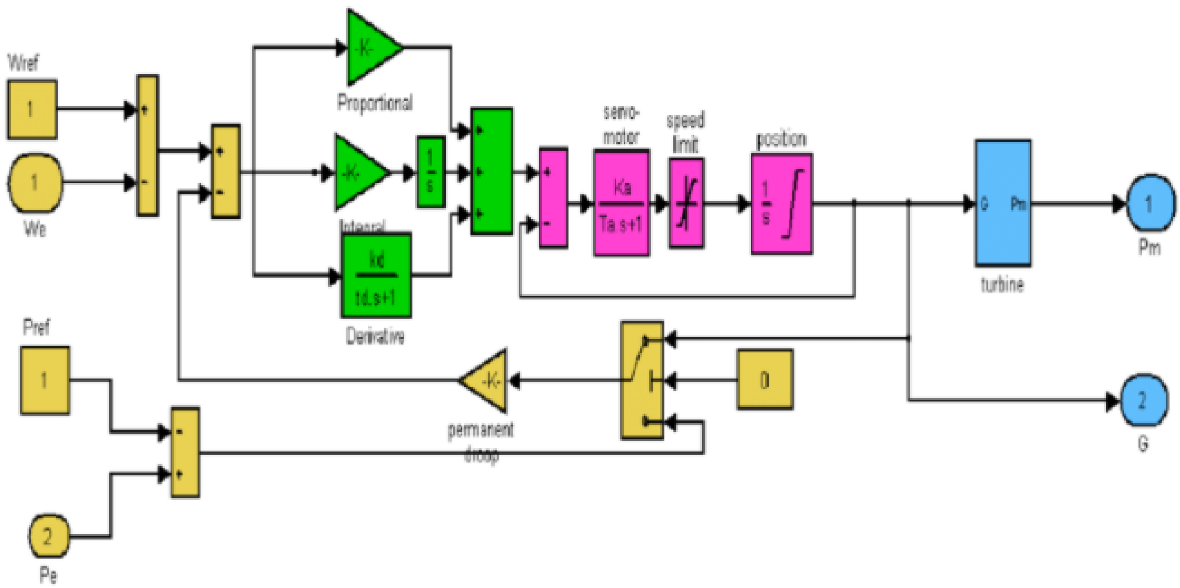

Figure 7: General model of turbine [7]

2.3.3. Generator Modelling

The equation showing the relationship between mechanical power and electrical power is called "swing equation" and it is considered as correlation in power system analysis. This equation depicts the relationship between synchronous machine acceleration and deviation between input power (mechanical) and output power (electric power).

$$\frac{2H}{w_{0e}}\frac{d^2\delta_e}{dt^2} = P_m - P_e \qquad Eq\ 2.2$$

Or, since $\omega = \frac{d\delta}{dt}$, we can write the above equation as:

$$\frac{2H}{w_{0e}}\frac{d\omega_e}{dt} = P_m - P_e \qquad Eq\ 2.3$$

Where δ_e is the machine electrical torque.

Pm is the mechanical input power in per unit

Pe is the electrical output power in per unit

H is the inertia constant given in M joules/Megawatts sec, is shown as follows:

$$H = \frac{1}{2}\frac{I\omega^2{}_{0m}}{S_b} \qquad Eq\ 2.4$$

S_b is the MVA rating of the machine; I it was the moment of inertia of all machine masses in kg-m 2x 10^6;

ω_{0m} is the synchronous rotor speed in mechanical revolutions per second

ω_{0e} is the synchronous rotor speed in mechanical pulses per second [4].

Put in per unit

$$\frac{2H}{w_{0e}}\frac{d\omega_e}{dt} = P_m - P_e \qquad Eq\ 2.5$$

$$\frac{w_{0e}2H}{w_{0e}}\frac{d\frac{\omega_e}{\omega_o}}{dt} = P_m - P_e \qquad Eq\ 2.6$$

$$2H\frac{d\omega}{dt} = P_m - P_e \qquad Eq\ 2.7$$

Where $\omega = \frac{\omega_e}{\omega_o}$

Below is attached a full block model of the hydro plant.

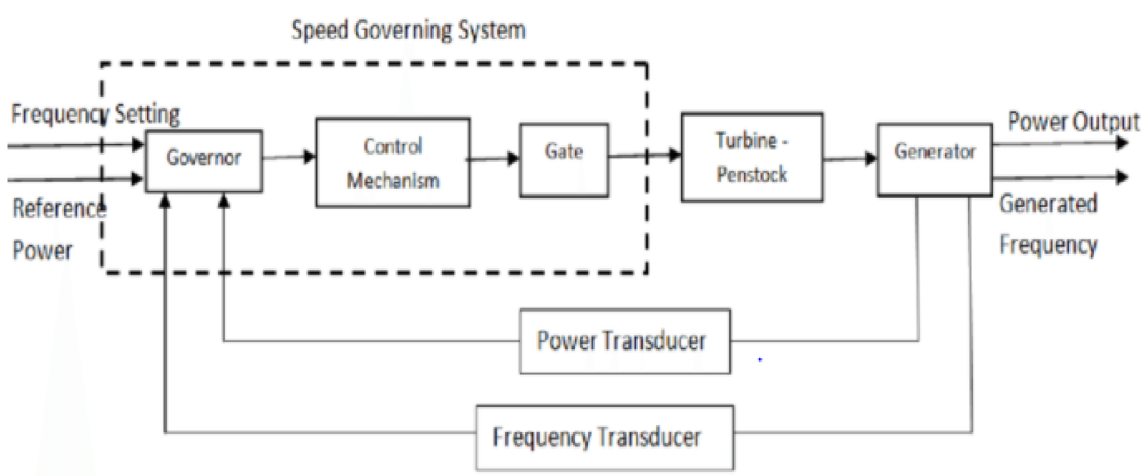

Figure 8:Full block model of the hydro plant [7]

2.4. Power System Stability

In the control of power system, there major variables to be controlled are:

- Voltage
- Frequency

The ability of a power system to keep an allowable situation of equilibrium under normal working conditions and to keep an allowable situation of equilibrium after being subjected to a disturbance is referred to as power stability[9].

Power system instabilities can manifest in a variety of ways, depending on the system's configuration and working conditions.

In general, stability problem comes from the failure of maintaining synchronism. Because the power system relies on synchronous machines to generate electricity, all synchronous machines must remain in synchronism mode for the system to function properly. Voltage and frequency deviations have an effect on this stability [9].

In this study, we focus on the following two major stability categories:

- Voltage stability
- Frequency variation

Voltage stability

When the voltages remain constant at all buses after subjection of any disturbance from initial working condition, we call this in power system as" voltage stability". Voltage instability can cause loads, generators, and other power devices to fail or disconnect. With a large variation in load, the voltage stability level of a mini grid decreases as line length increases.

During load variations, the far-end voltage may swing from high to very high values for very long line lengths. The voltage rises during light loads and falls during heavy loads. As a result, a change in load influences wide voltage fluctuations, causing the system to become unstable. As a result, finding the right solution to the problem is critical in order to provide consumers with reliable power [9].

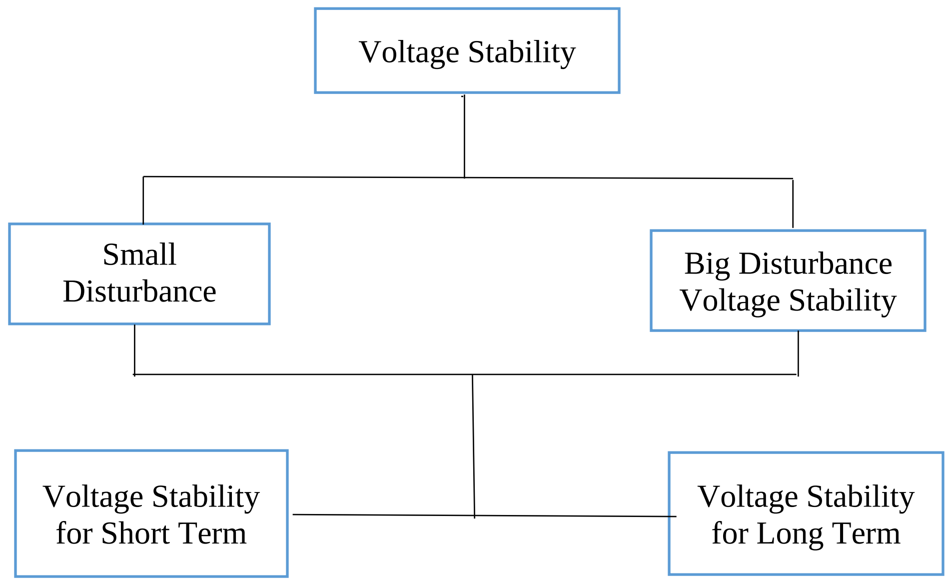

Figure 9: Categories of voltage stability[9]

Frequency stability

Frequency deviation represents the variation of output frequency due to voltage and load variation. An increase of load on the generator leads to a decrease of the turbine speed and frequency of the synchronous machine. The deviation of the frequency impacts the operation of the load supplied by the grid. Thus, the proper way of controlling the frequency is very essential the security of the grid [9].

2.4.1. Power System Stability Problems

Power system stability is classified into two types: steady-state stability and transient stability.

When a power system maintains synchronism after a short period of disturbance, such as a small power perturbation, this is referred to as "steady-state stability."

A power system is said to be transiently stable it the various generating stations return to equilibrium after a periodic system disturbance. The most troublesome system disturbances are those caused by line faults [3], [9], [10].

Factors that may affect power system stability are:

1. **System Impedance:** which must cover the total reactance of all generators.

   This can influence phase angle stability and delay the synchronization.

2. **Duration of the fault** is the major point of maintaining the stability. Duration may depend on the circuit-breaker tripping speed and the relaying method used.
3. **Generator loadings:** if the generator is highly loaded, this can lead to the transient fault which can be difficult to retain the stability in quick way.
4. **System loading** which will determine the phase angles among the various internal voltages of the connected units.

2.4.2. Cause of instability in power system

Voltage deviations in today's power system can be influenced by a number of additional factors, including network transmission capability, generator reactive power and voltage control limits, voltage sensitivity of the load , reactive compensation device characteristics, and voltage control action[10].

2.4.3. Methods of Power Stability Improvement

In hydro power plants, power stability is a key factor to achieve better generation and transmission efficiency and it is improved by enhancing the voltage stability and controlling the frequency of the generator. Also, power stability is enhanced by reducing oscillations, reducing overshoots of the signals and sample time. This can be achieved by AVR with PSS, AVR with different controllers like PID controller and fuzzy logic controller, AVR with Genetic Algorithm, AVR with Artificial Neural Networks (ANN) and other algorithms and frequency control like LFC and so on.

2.4.3.1. Enhancement of voltage stability with automatic voltage regulator

Voltage control in hydropower plant is generally enhanced by controlling generator reactive power and the main way of controlling the terminal voltage is to control the excitation by using automatic voltage regulator (AVR). The objective of using AVR is to maintain the synchronous generator voltage at a specific level. To maintain the voltage magnitude at the required level, the excitation system controls the amount of reactive power generated or consumed [11]–[13].

Through the excitation system, the direct current is supplied to the generator rotor field windings with the help of slip rings to produce the magnetic field, adjusts the voltage of generator, controls reactive power flow, and help in enhancing power system stability and in the case of perturbations, the exciter must respond quickly to maintain the required voltage at the generator terminals. Below is attached the block diagram of excitation control system of the generator.

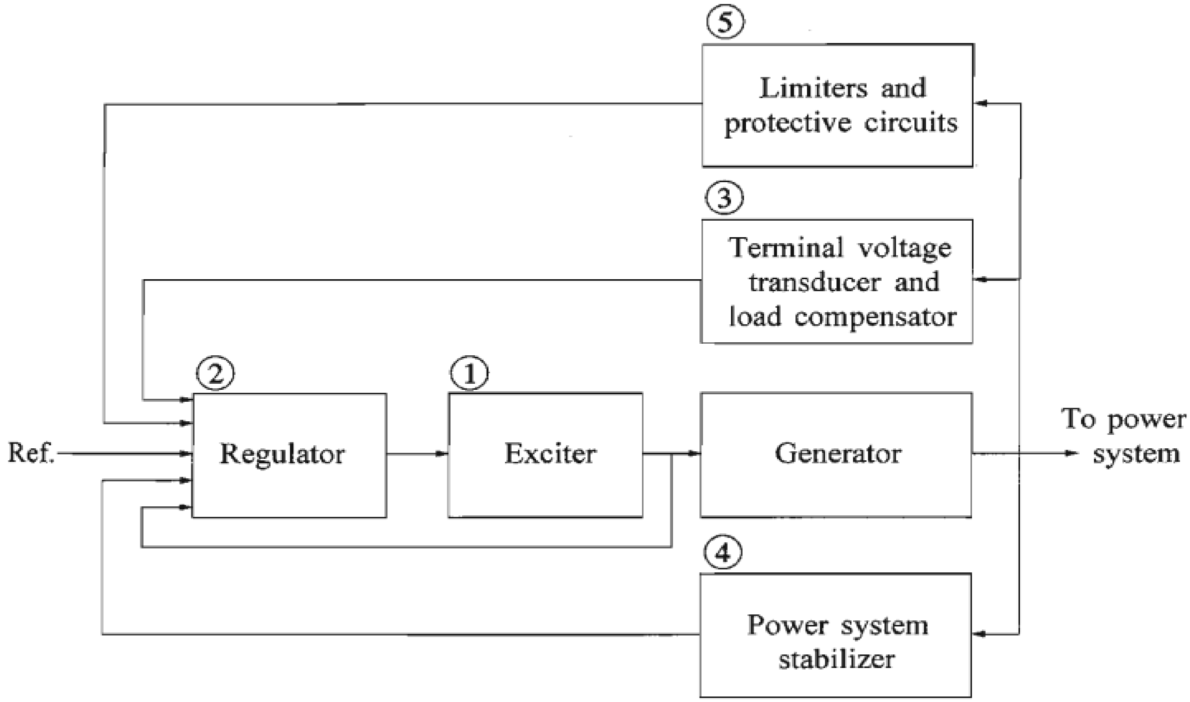

Figure 10: the block diagram of excitation control system of the generator [14], [15].

1.The function of exciter is to supply the direct current to the rotor field windings of the generator to produce magnetic field which is required in increasing the induced e.m.f

2.The function of regulator is to process and amplify input control signals to a certain level and regulates the exciter control.

3.Terminal voltage transducer and load compensator detects generator terminal voltage, rectifies, and filters it to dc quality, and compares it with the reference voltage which represents the desired terminal voltage.

4.Power system stabilizer produces an additional input signal to minimize the output oscillations. The most used control signals are rotor speed deviation, accelerating power, and frequency deviation.

5. Limiters and protective circuits allow the protection of the system components [15].

2.4.3.2. Modeling of AVR

The quantity of the terminal voltage decreases as the reactive power load of the generator increases. A one-phase potential transformer is used to measure the magnitude of the voltage. The rectified voltage is compared to an alternating current set point signal. The error signal obtained from the amplifier regulates the excitation field to increase the terminal voltage of the exciter. As a result, the generator field current rises, raising the e.m.f of the generator. To get an equilibrium, the reactive power should be decreased, causing the terminal voltage to increase to the desired level[14], [16]–[20].

Modelling of amplifier

There are different types of amplifiers used in excitation system which are magnetic amplifier, rotating amplifier, and modern electronic amplifier. It is modelled by the gain K_A and the time constant T_A which gives the following transfer function:

$$\frac{V_R(s)}{V_E} = \frac{K_A}{1+sT_A} \qquad \textbf{Eq 2. 8}$$

The standard values of amplifier gain are in the range between 10 and 400 and the amplifier time constant is very small in the range between 0.02 and 0.1 second and which is sometimes neglected [11], [12], [14], [16], [18], [20].

Modelling of exciter

Excitation systems come in a variety of configurations. Modern excitation systems use an alternating current power source through solid-state rectifier, such as an SCR. The output of the exciter voltage is a non-linear function of the field voltage due to saturation effects in the magnetic circuit. As a result, there is no clear relationship between the terminal voltage and the field voltage of the exciter.

The modern exciter is modelled with the help of its transfer function which is represented by the time-constant T_E and gain K_E as follows:

$$\frac{V_F(s)}{V_R(s)_0} = \frac{K_E}{1+sT_E} \qquad \textbf{Eq 2. 9}$$

The constant of time of modern exciter are small and neglected [12], [14], [16, [18], [20].

Modelling of generator

The e.m.f of the synchronous machine is determined by the magnetization curve of the machine and its terminal voltage is affected by the generator load. The generator is modelled by using its transfer function with the gain K_G and a time constant T_G as follows:

$$\frac{V_T(s)}{V_F(s)} = \frac{K_G}{1+sT_G} \qquad \textbf{\textit{Eq 2. 10}}$$

These constants are load dependent, K_G may vary between 0.7 and 1 and T_G between 1.0 and 2.0 seconds from full load to no-load [11], [12], [14], [16], [18], [20].

Modelling of sensor

A potential transformer senses the voltage, and a bridge rectifier rectifies it in one form or another. The sensor is modelled as follows:

$$\frac{V_S(s)}{V_T(s)} = \frac{K_R}{1+sT_R} \qquad \textbf{\textit{Eq 2. 11}}$$

T_R is too small and is in a range between 0.01 and 0.06 second[11], [12], [14], [16], [18], [20]. From the above generator models, the AVR block diagram is represented as follows:

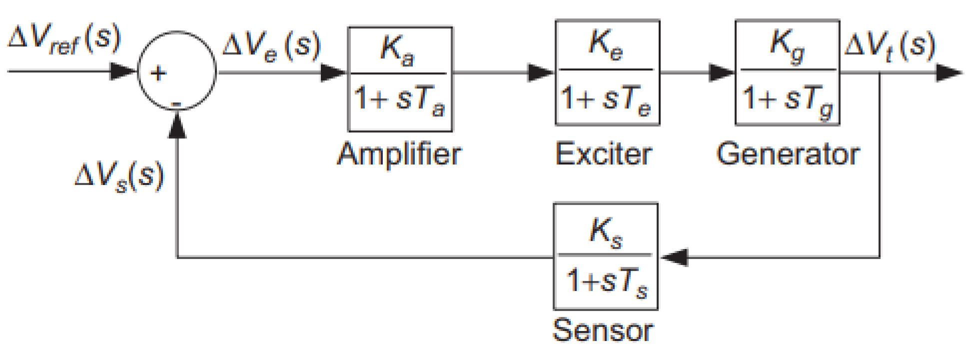

Figure 11: A simplified automatic voltage regulator block diagram[11], [12], [14], [16]

The open- loop transfer function of the block diagram shown in figure 11 is

$$K_G(s)H(s) = \frac{K_A\, K_E K_G\, K_R}{(1+sT_A)(1+sT_E)(1+sT_G)(1+sT_R)} \qquad \textbf{\textit{Eq 2. 12}}$$

And the closed-loop transfer function describing the relation between the generator terminal voltage $V_T(s)$ and the reference voltage $V_{ref}(s)$ is

$$\frac{V_T(s)}{V_{ref}(s)} = \frac{K_A\, K_E K_G\, K_R(1+sT_R)}{(1+sT_A)(1+sT_E)(1+sT_G)(1+sT_R)+K_A\, K_E K_G\, K_R} \qquad \textit{Eq 2. 13}$$

Or $V_T(s) = T(s)V_{ref}(s)$

Let the step reference voltage be $V_{ref}(s) = \frac{1}{s}$,using the final value theorem, the steady state response is:

$$V_{Tss} = \lim_{s\to 0} sV_T(s) = \frac{K_A}{(1+K_A)} \qquad \textit{Eq 2. 14}$$

2.4.4. Enhancement of Transient Stability of Synchronous Generator with Fuzzy Logic Controller (LFC)

To improve voltage stability, the LFC was evaluated using the single machine infinite bus power system (SMIB) system. To improve the machine's transient stability, the SMIB model was created in MATLAB/Simulink software. The automatic voltage regulator is a critical synchronous machine auxiliary component (AVR). The AVR's function is to adjust the terminal voltage of the synchronous generator whenever the terminal voltage changes from a continuous change in loading or presence of fault [11]–[14], [16], [18], [20].

The AVR compares the terminal voltage or the error signal to a reference voltage.

The current excitation system contains components such as automatic voltage regulators (AVR), Power System Stabilizers (PSS), and filters that aids in system stabilization and terminal constant voltage maintenance[21].

To do so, it is given a reference voltage to which it must compared with, which is typically a step voltage. PID controllers continue to be the preferred controllers for designing the AVR used to get the best performance PID parameters the AVR system. Foe the AVR to function properly, the PID controller parameters must be properly selected. Traditionally, the Ziegler-Nicholas method is used to evaluate the PID controller parameters[12],[20].

1. Fuzzy Logic

Fuzzy logic-based control algorithms can be implemented in stages. The following reasons have motivated the use of such control techniques:

• LFC is more reliable over other control algorithms

• Implementation is simplified.

Fuzzy Logic was initiated in 1965 by Lotfi A. Zadeh, professor for computer science at the University of California in Berkeley [15].

FL is a multivalued logic that help defining the intermediate values between conventional logics such as true/false, yes/no, high/low, and so on. To apply a more human-like way of thinking in computer programming, concepts such as rather tall or very fast can be mathematically moldered and processed by computers. A fuzzy system, which has its roots in Greek philosophy, is another way of setting membership and logic concepts. To reduce the model's complexity in problem solving, fuzzy logic requires careful attention; it employs linguistic terms that deal with the causal relationship between input and output constraints[15].

The control system development by referring to fuzzy logic involves the following process:

- Control variables selection
- Definition of membership function
- Formulation of rules
- Strategy of Defuzzification

Furthermore, unlike a linear control technique, the fuzzy logic controller design can provide both small and large signal dynamic performance at the same time. As a result, the fuzzy logic controller can improve the synchronous generator's robustness. In this case, the fuzzy logic approach's development is limited to the controller's design and structure. The terminal voltage error and its variations were the input constraints, and the output was the voltage exciter increment.

Voltage error e (k) and error change de are the definitions of FLC inputs (k). The fuzzy controller provided the use of the input and output normalized universes [15].

The table 2 shows the comparison done on how different technics have been used and how they improve the stability by reducing overshoots and setting times.

Table 2: Comparison of PID and FLC on improvement of stability by reducing overshoots and setting times [15].

	Without Controller	With PID Controller	With Fuzzy Logic Controller
Peak Overshoot	1.632	1.289	0.446
Peak Overshoot Time	18ms	24ms	29ms
Settling Time	Undefined	70md	54ms

From many analyses done, the fuzzy logic controller has many benefits than PID controller, but the major limitation of setting rules makes it more complicated, it means it requires an expert person to set the rules to achieve to the quick response.

2. Power System Stabilizers

The PSS part describes the design of power system stabilizer and the combination of PSS with AVR, examination of various input signals, and the excellent tuning methodologies. The purpose of a PSS is to increase the angular stability limits of a power system by reducing synchronous machine rotor oscillations via generator excitation. This damping is achieved by applying an electrical torque to the rotor that is synchronous with the speed variation.

This supplementary control has more benefits during power outages and large loads[15], [21]. However, power system instabilities can occur in a variety of ways due to the damping effect of the PSS on the rotor. These damping effects decreases as the PSSs are tuned.

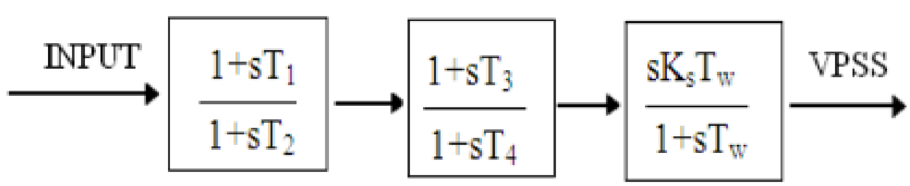

Figure 12: Lag-lead power system stabilizer [21]

The figure 12 shows the structure of a "lead-lag" PSS. The output signal is voltage signal, represented as V_{PSS} . The transfer function of PSS is shown as follows:

$$V_{PSS}\,(s) = \frac{sK_sT_w}{1+sT_w}\cdot\frac{(1+sT_1)}{(1+sT_2)}\cdot\frac{(1+sT_3)}{(1+sT_4)}\cdot Input(s)\ ...$$

This controller structure has a washout block, $\frac{sT_w}{1+sT_w}$, used to minimize the over-response of the damping during serious events. Since the PSS has to produce a component of electrical torque in phase with the speed deviation, phase lead blocks circuits are utilized to minimize for the lag (hence, “lead-lag’) between the PSS output and the control action, the electrical torque [12][15], [21].

The number of lead-lag blocks needed is given by the system and the tuning of PSS. The gain Ks of the PSS is an interesting factor as the damping given by the PSS increases proportionally to raise the gain to the critical gain value, after which the damping being to decrease.

Because of the reliability of the machine based on its parameters, all PSS have to be found separately for each type of Generator[21].

3. Design Considerations

The main purpose of power system stabilizer is to reduce undesired oscillations which may affect the power system transient stability. As those oscillations are reduced by adjusting the generator field voltage, the reactive power output fluctuates[21]. Then, the PSS gain is carefully selected to obtain an acceptable gain margin of Volt/VAR oscillation. The time constant of the “Wash-Out Filter” can be adjusted to allow frequency shaping of the input signal to reduce this swing. Again, a control enhancement may be required during loading/unloading or generation loss when large variations in frequency and speed act through the PSS and drive the system towards instability.

Modified limit logic will allow these limits to be minimized while maintaining PSS dampening action for all other system events[21].

Another aspect of power system stabilizer behavior that requires consideration is possible interaction with other controls that may be part of the excitation system or an external system, such as HVDC, SVC, TCSC, and FACTs. In addition to low frequency oscillations, the input to PSS contains high frequency turbine generator oscillations, which should be considered when designing the PSS. As a result, the emphasis should be on studying the potential of PSS torsional interaction and verifying the conclusion before commissioning PSS [15].

2.4.5. Enhancement of transient stability of synchronous generator by using PID controller

The Proportional Integral Derivative (PID) controller is a very useful feedback controller that is used in the industrial control process. It has been successfully used for over 50 years. The PID algorithm, as the name implies, contains three principal modes of operations: proportional, integral, and derivative modes. A proportional controller mode has the advantage of minimizing rise time, but it never eliminates steady state error.

In proportional mode, if the proportional gain is extra high, the system may become unstable while low gains give small output responsa to a large input error. In integral controller mode, there is a benefit of eliminating the steady-state error, but it can fail to give the successful transient response. In a derivative controller mode, there is a benefit of increasing the system stability and reducing the overshoot as wee as improving the transient response. If the derivative gain is too large, it can cause a process to become unstable. To have a successful system, these three controller modes are combined and designed to minimize the error to zero, reduce the overshoot, improve the transient response. The design of this controller requires the three main parameters, proportional gain (k_p), integral gain (k_i) and derivative gain (k_d). The gains of the controller are tuned by the trial-and-error method based on the experience and plant behavior. The block diagram of PID controller for a closed loop system is shown in Fig. 13. The transfer function of PID controller Laplace domain is represented by:

$$TF_{PID} = k_p + \frac{k_i}{s} + k_d s$$

The outcome of PID controller, that is calculated in the time domain from the feedback error as follows:

$$u(t) = k_p e(t) + k_i \int_0^t e(t)dt + k_d \frac{de(t)}{dt}$$

To design the PID controller properly, we need an intelligent expert to select the best tuning method of PID parameters to reduce the steady state error and increase the transient response.

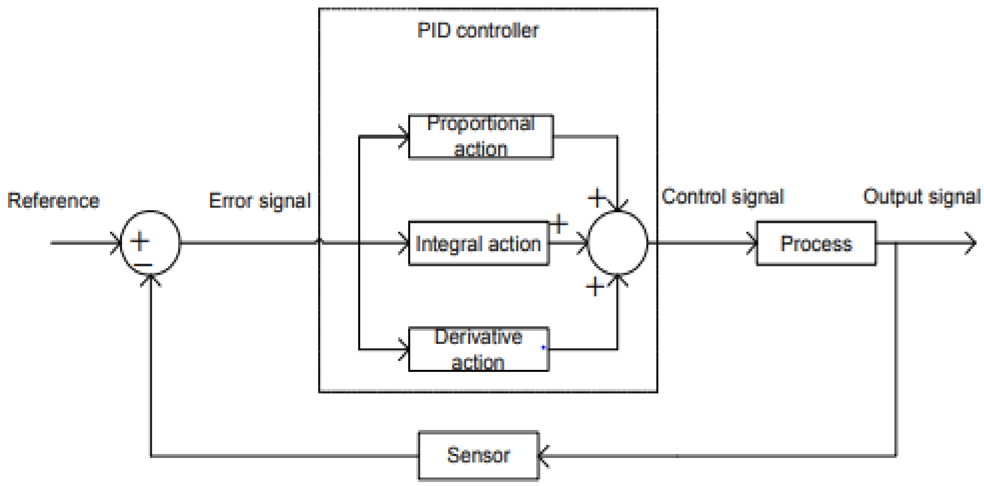

Figure 13:Closed loop system of a PID controller

2.4.5. Generator Frequency Control

2.4.5.1. Isochronous and Droop Frequency Control Modes

The frequency of an alternating current generator is solely determined by the rotational speed of the generator shaft. This means that the mathematical drive must be equipped with a speed controller in order to keep the angular velocity within close limits despite torque fluctuations caused by changes in the electrical load[8], [9].

There are various modes of controlling the frequency of a synchronous generator either a standalone, a grid connected or in an interconnected system of generators. Those technics are isochronous control mode and droop control mode. They have the difference between each other according to their uses and system connection.

Because droop mode influences variations in frequency, it allows interconnected generators to work in collaboration by dividing loads in equal proportion to their power. It is more benefit when is used in grids with many interconnected. In droop mode, a generator's output and frequency are inversely proportional each other because when frequency decreases, output increases.

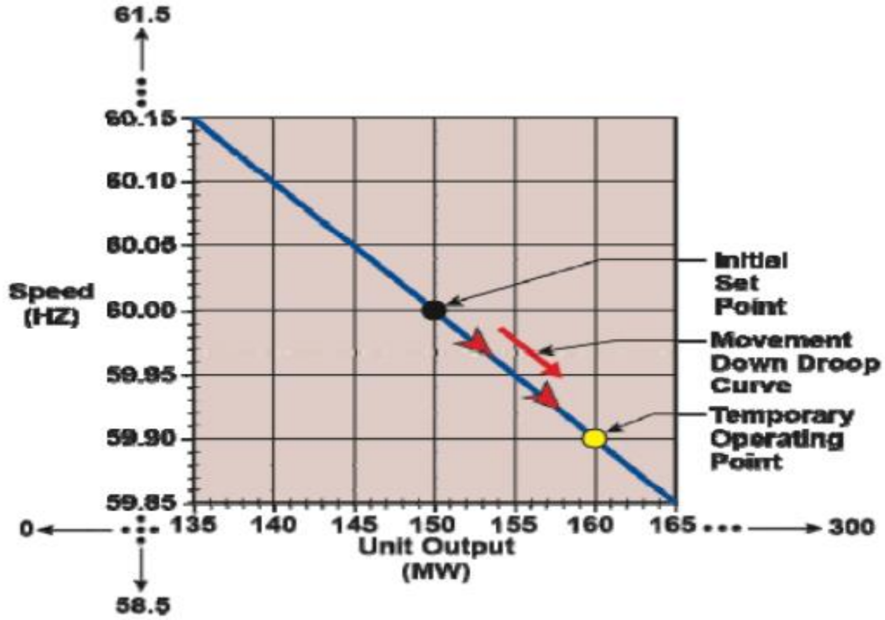

Figure 14: Governor control-droop speed mode[9]

When a generator in droop control mode gets a large load, problems may occur. If the load is tripped, the frequency will settle at a value greater than its nominal value.

Isochronous mode is typically used when a generator is either self-contained or the largest unit on a grid. In this mode, the energy admitted to the prime mover is tightly regulated in response to load changes, which would cause frequency changes in droop control mode[9].

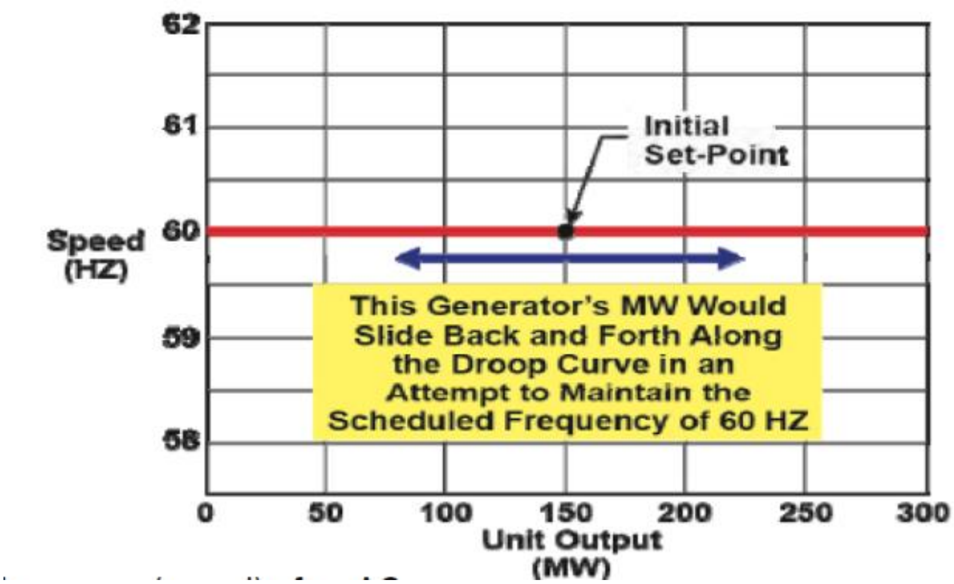

Figure 15: Governor Control-Isochronous mode[9]

The load decreases, the frequency increases in droop mode vise versa, but because the energy directed to the prime mover is rapidly reduced in isochronous mode, the frequency remains constant. The generator maintains a constant speed regardless of load in isochronous mode. When multiple generators in isochronous mode are operating on the same grid (or in parallel) and the load changes, problems arise.

If all the units are in isochronous mode, they will begin competing to see who will respond first. In the case of parallel generators, one will carry the entire load while the other will not. Droop control mode is preferred when multiple generators are operating synchronously on the same grid. Governors regulate generator shaft speed, adjust generation for small changes in load, and operate by adjusting the prime mover's input.

2.4.5.2. Load Frequency Control Mode

When a large demand is suddenly placed on a rotating electromechanical generator, the generator's rotational speed decreases. This causes the voltage and frequency produced to reduce. Conversely, when those large change in load are removed, this can cause the generator to speed up until the control systems can adjust [8], [23], [24].

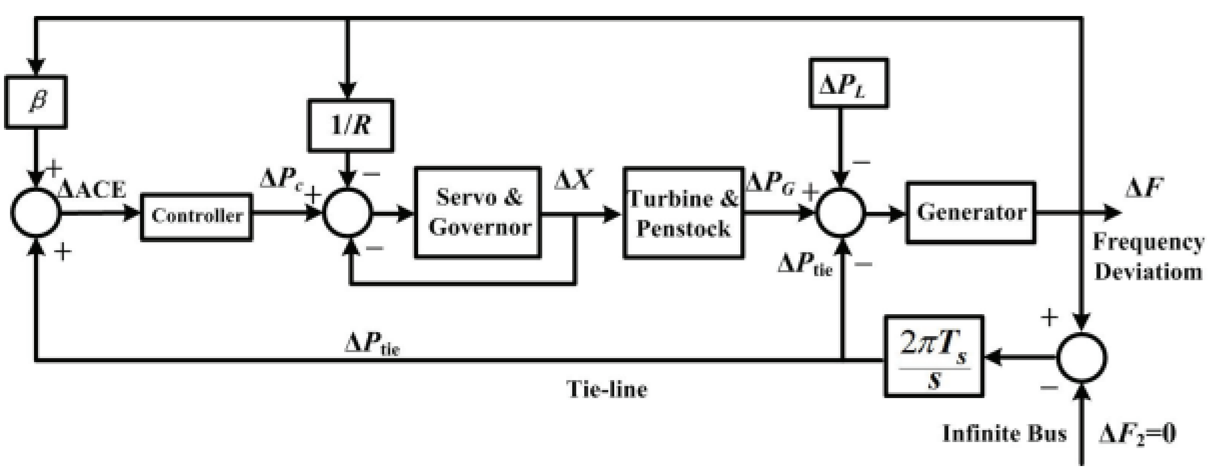

Figure 16: Block diagram of load frequency control of a small hydro plant connected to infinite bus [25]

In the grid-connected mode, the control area is not only fed by the micro hydro power unit, but also is supported by the source from an infinite bus by tie line. Thus, the control object under this mode contains two parts. One is to eliminate the frequency deviation in the control area. PID controller and the SMC controller can eliminate the frequency deviation and the area control error, simultaneity keep the net power of the timeline zeroth. Both can realize the control object of the grid-connected mode [25].

2.5. MATLAB Software Tool

MATLAB is a matrix laboratory. This software was designed to allow easy access to matrix software. This is a high-intelligent language for technical computing. It contains computation, visualization, and programming environment. It is also modern programming language environment, with sophisticated data structures, built-in editing and debugging tools, and support for object-oriented programming. Due to its features, it can be a serious tool to be used to conduct research. This thesis work used MATLAB Simulink to represent the status of Musarara MHPP and to aid in improving its power stability through voltage and frequency control.

The software components of this thesis are tasked with performing many mathematical functions, as well as the input-output actions that are required to accomplish them.

When compiling the list of algorithms, we kept in mind the idea of modularity in that all systems should have the ability to perform an individual unit test for functionality without requiring the use of other source code [26].

CHAPTER: RESEARCH METHODOLOGY

3.1. Introduction

To attain the general and specific objectives of this study, the following methods and techniques will be followed.

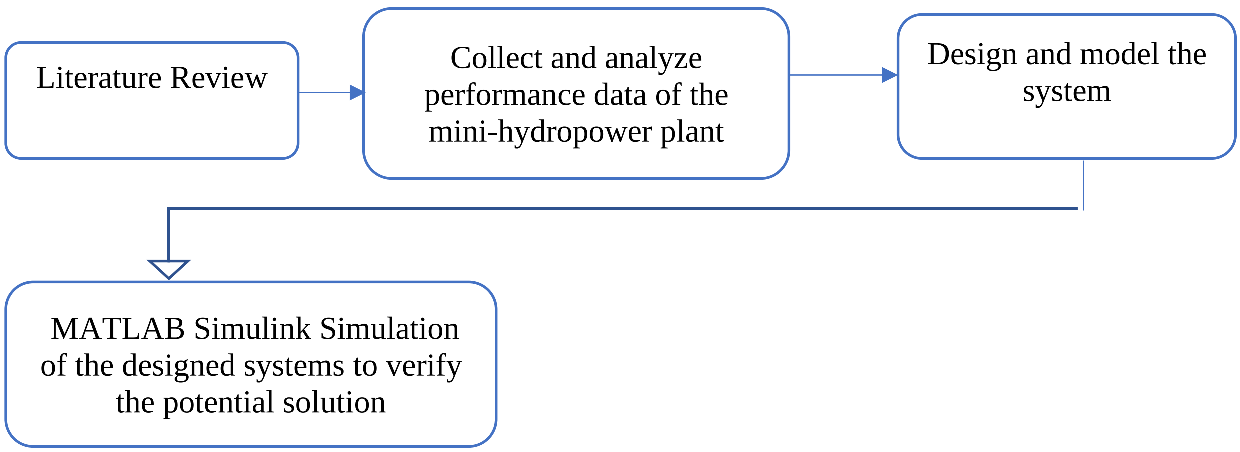

Figure 17: Steps for research methodology

After having some basic concept of power stability of mini-hydro plants which is helpful for better understanding, this section is going to show used methods and different followed steps to achieve results. This method is composed by data collection and analysis of data, design, and simulation by using MATLAB/Simulink and Power World Simulator software, analysis and discussion on results obtained.

3.2. Data collection

The data for the thesis are gathered from various day/night shift operations records at Musarara MHPP and from REG/EUCL at Camp Belge Substation.

Those data are:

- Different generation records of Musarara MHPP
- Different tripping records or Shutdown of Musarara MHPP
- Operating parameters of Gisenyi feeder and its tripping status for different times.

Based on the data collected, there is an opportunity of improving Musarara MHPP's power stability are investigated.

Conclusions and recommendations based on the data analysis have been forwarded for future implementation in all mini-hydropower plants.

Describe what data are collected and how they are collected. Also give interpretations of the data.

Different data records of Camp Belge Substation from June to August in the year of 2021

The data have been taken in two months, and four days have been picked in general to represent the two months, it means that two days have been taken to represent one month as shown in figures 18, 19, 20 and 21 respectively. The y-axis represents the line current (A), voltage (V), active power (MW), reactive power (MVAR), power factor ($\cos\phi$), and frequency (Hz) where the x-axis represents the time in hours from 0:00 to 23:00 Kigali time.

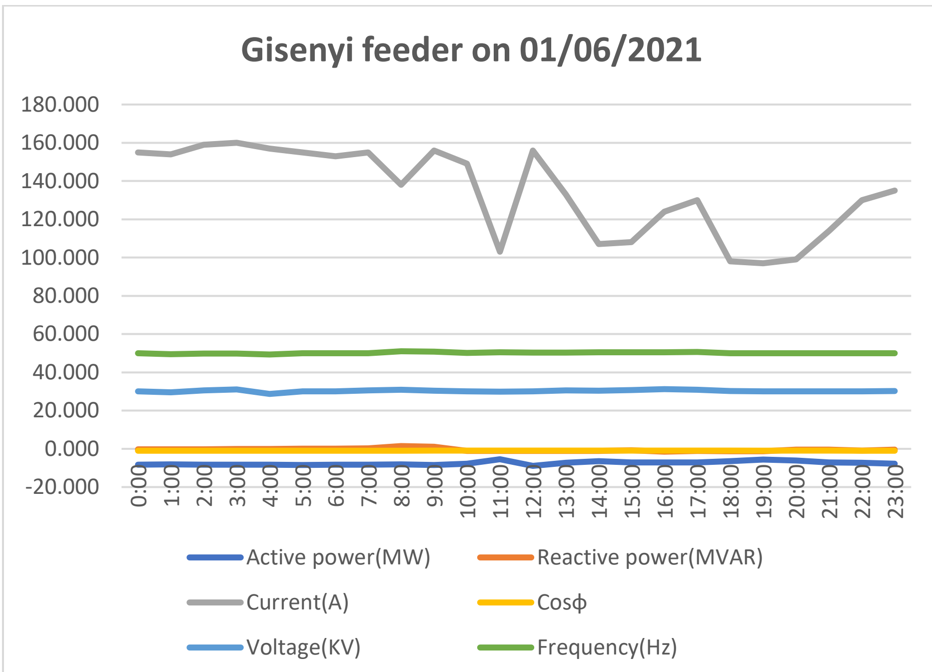

Figure 18: Gisenyi feeder status on 01/06/2021

From figure 18, the line current is more varying due to many perturbations and faults occur in the line, the maximum frequency and minimum frequency are 51Hz and 49.31Hz respectively, this means that there is no over frequency or underfrequency because the frequency drop is between -5% and 5% which is 47.5Hz and 50.25Hz respectively and both active power, reactive power and power factor are varying suddenly due to line voltage variation but there is no undervoltage and overvoltage presented which means that the feeder is safe. The voltage regulation must be calculated by referring to the actual minimum voltage and maximum voltage of the feeder.

The line voltage recorded from 0:00 to 23:00 are:

$30V,\ 29.5V,\ 30.5V,\ 31V,\ 28.7V,\ 30V,\ 30V,\ 30.5V,\ 30.9V,\ 30.4V,\ 30.1V,\ 29.9V,\ 30V,\ 30.6V,\ 30.4V,\ 30.7V,\ 31.2V,\ 30.9V,\ 30.2V,\ 30V,\ 30V,\ 30V,\ 30.1V$ respectively.

The minimum voltage is $28.7V$

The maximum voltage is $31.2V$

Then the voltage regulation at minimum voltage of $28.7V$ is $V\ regulation = \frac{V0-Vi}{Vi} \times 100\% = \frac{28.7-30}{30} \times 100\% = -4.33\%$ and the voltage regulation at maximum voltage which is $31.2V$is $V\ regulation = \frac{V0-Vi}{Vi} \times 100\% = \frac{31.2-30}{30} \times 100\% = 4\%$

Where Vi is the rated line voltage of Gisenyi feeder and Vo is the actual line voltage of Gisenyi feeder. From the calculated voltage regulations, there is no overvoltage or undervoltage because the voltage regulations are between -5% and 5% of the rated line voltage of 30V, it means it is 28.5V and 31.5V respectively.

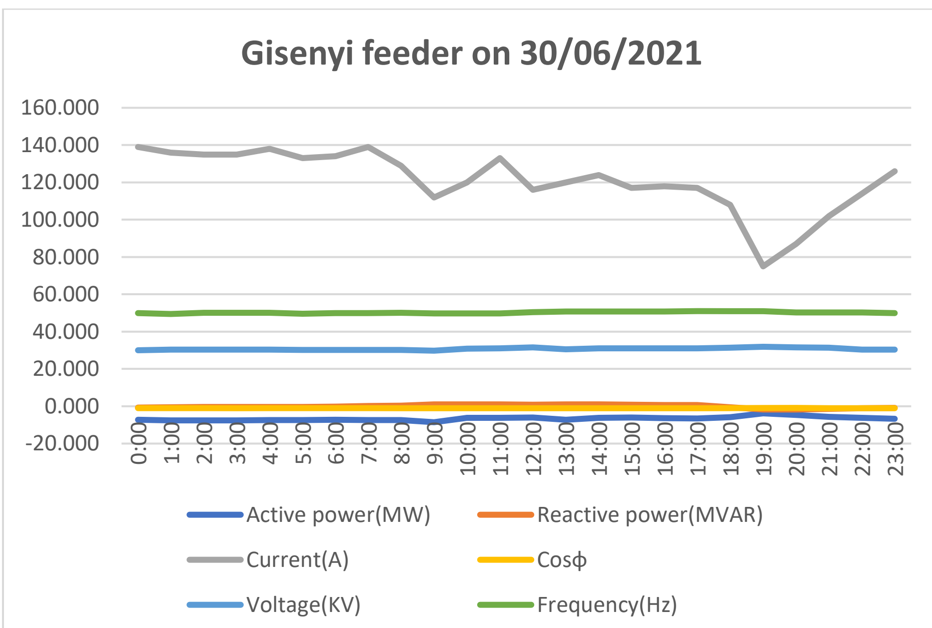

Figure 19: Gisenyi feeder status on 30/06/2021

From figure 19, the line current is more varying due to many perturbations and faults occur in the line, the maximum frequency and minimum frequency are 51Hz and 49.48Hz respectively, this means that there is no over frequency or underfrequency because the frequency drop is between -5% and 5% which is 47.5Hz and 50.25Hz respectively and both active power, reactive power and power factor are varying suddenly due to line voltage variation. The line voltage recorded from 0:00 to 23:00 are:

$30.1V, 30.4V,\ 30.4V,\ 30.4V,\ 30.4V,\ 30.17V,\ 30.17V,\ 30.17V,\ 30.17V,\ 29.8V,\ 30.9V,$ $31V,\ 31.5V,\ 30.6V,\ 31.01V,\ 31.01V,\ 31.01V,\ 30.98V,\ 31.45V,\ 31.9V,\ 31.56V,$ $31.32V, 30.35V,\ 30.35V$ respectively.

The minimum voltage is $29.8V$

The maximum voltage is $31.9V$

Then the voltage regulation at minimum voltage of $29.8V$ is $V\ regulation = \frac{V0-Vi}{Vi} \times 100\% = \frac{29.8-30}{30} \times 100\% = -0.66\%$ and the voltage regulation at maximum voltage which is $31.9V$is $V\ regulation = \frac{V0-Vi}{Vi} \times 100\% = \frac{31.9-30}{30} \times 100\% = 6.3\%$

Where Vi is the rated line voltage of Gisenyi feeder and Vo is the actual line voltage of Gisenyi feeder. From the calculated voltage regulations, there is an overvoltage at 19:00 with voltage of 31.9V and at 20:00 with voltage of 31.56V and there is no undervoltage because the voltage regulations are between -5% and 5% of the rated line voltage of 30V, it means it is 28.5V and 31.5V respectively.

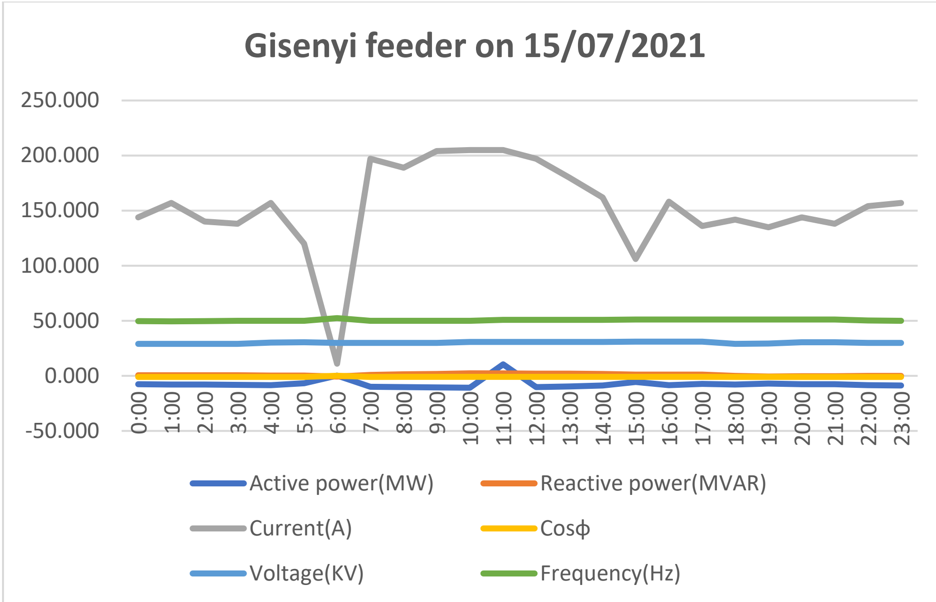

Figure 20: Gisenyi feeder status on 15/07/2021

From figure 20, the line current is more varying due to many perturbations and faults occur in the line and at 6:00 was highly decreased due to earth fault presented, the maximum frequency and minimum frequency are 52.5Hz and 49.48Hz respectively, this means that there is no over frequency or underfrequency because the frequency drop is between -5% and 5% which is 47.5Hz and 50.25Hz respectively and both active power, reactive power and power factor are varying suddenly due to line voltage variation but there is no undervoltage and overvoltage presented which means that the feeder is safe. The line voltage recorded from 0:00 to 23:00 are:

$29.11V,\ 29.11V,\ 29.11V,\ 29.11V,\ 30.1V,\ 30.4V,\ 29.9V,\ 29.9V,\ 29.9V,\ 29.9V,\ 30.8V,\ 30.8V,\ 30.67V,\ 30.67V,\ 31.05V,\ 31.05V,\ 31.05V,\ 29.03V,\ 29.2V,\ 30.4V,\ 30.4V,\ 30.02V,\ 30.15V,\ 30.02V$ respectively.

The minimum voltage is $29.03V$

The maximum voltage is $31.15V$

Then the voltage regulation at minimum voltage of $29.03V$ is $V\ regulation = \frac{V0-Vi}{Vi} \times 100\% = \frac{29.03-30}{30} \times 100\% = -3.23\%$ and the voltage regulation at maximum voltage which is $31.15V$is $V\ regulation = \frac{V0-Vi}{Vi} \times 100\% = \frac{31.15-30}{30} \times 100\% = 3.83\%$

Where Vi is the rated line voltage of Gisenyi feeder and Vo is the actual line voltage of Gisenyi feeder. From the calculated voltage regulations, there is no overvoltage or undervoltage because the voltage regulations are between -5% and 5% of the rated line voltage of 30V, it means it is 28.5V and 31.5V respectively.

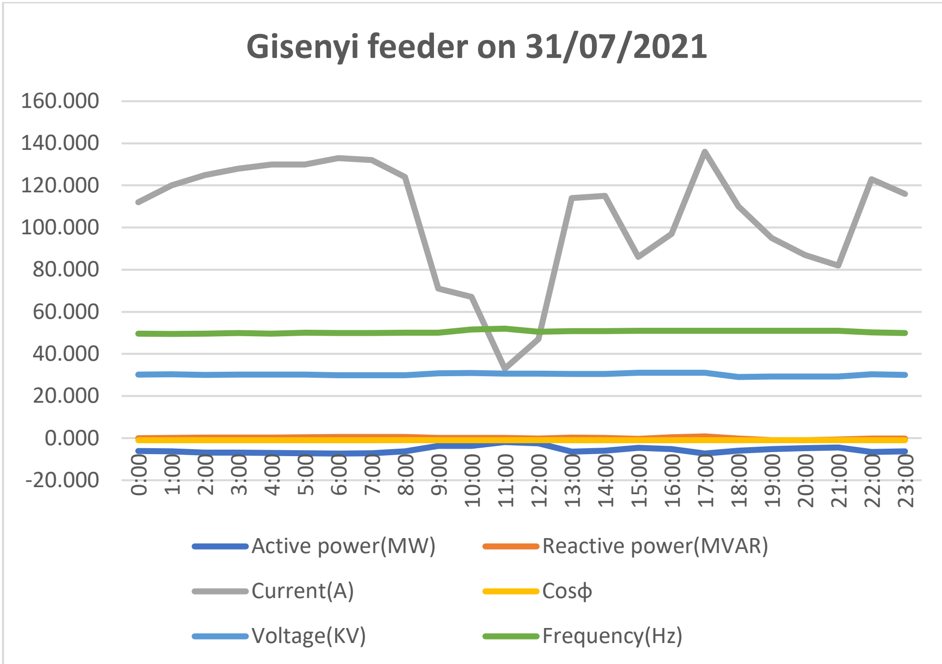

Figure 21: Data analysis of Gisenyi feeder

From figure 21, the line current is more varying due to many perturbations and faults occur in the line and at 11:00 was highly decreased due to earth fault presented, the maximum frequency and minimum frequency are 51.99Hz and 49.48Hz respectively, this means that there is no over frequency or underfrequency because the frequency drop is between -5% and 5% which is 47.5Hz and 50.25Hz respectively and both active power, reactive power and power factor are varying suddenly due to line voltage variation but there is no undervoltage and overvoltage presented which means that the feeder is safe. The line voltage recorded from 0:00 to 23:00 are:

$30.1V$, $30.32V$, $30.03V$, $30.11V$, $30.11V$, $30.11V$, $29.9V$, $29.9V$, $29.9V$, $30.76V$, $30.9V$, $30.59V$, $30.67V$, $30.44V$, $31.44V$, $31.05V$, $31.05V$, $31.05V$, $29.03V$, $29.2V$, $29.2V$, $29.2V$, $30.33V$, $30.02V$ respectively.

The minimum voltage is $29.2V$

The maximum voltage is $31.44V$

Then the voltage regulation at minimum voltage of $29.2V$ is $V\ regulation = \frac{V0-Vi}{Vi} \times 100\% = \frac{29.2-30}{30} \times 100\% = -2.66\%$ and the voltage regulation at maximum voltage which is $31.44V$is $V\ regulation = \frac{V0-Vi}{Vi} \times 100\% = \frac{31.44-30}{30} \times 100\% = 4.8\%$

Where Vi is the rated line voltage of Gisenyi feeder and Vo is the actual line voltage of Gisenyi feeder. From the calculated voltage regulations, there is no overvoltage or undervoltage because the voltage regulations are between -5% and 5% of the rated line voltage of 30V, it means it is 28.5V and 31.5V respectively.

From the information collected from Camp Belge substation, the variations of voltage and frequency occur in the feeder are caused by different status of power plants injecting in Gisenyi feeder and different perturbations occur in the feeder.

Different generation records of Musarara MHPP from June to August in the year of 2021

The data collected in Musarara MHPP are based on output voltage, reactive power, output current, active power, apparent power, frequency, and power factor as shown in the charts drawn using Microsoft Excel. The legend shows all variables presented on the graph.

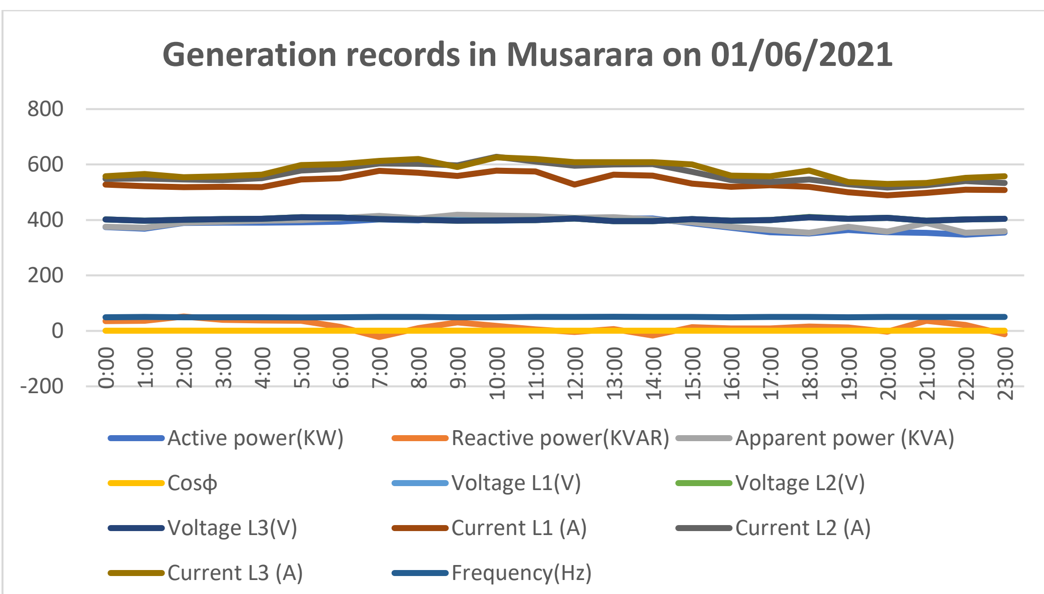

Figure 22: Musarara generation record on 01/06/2021

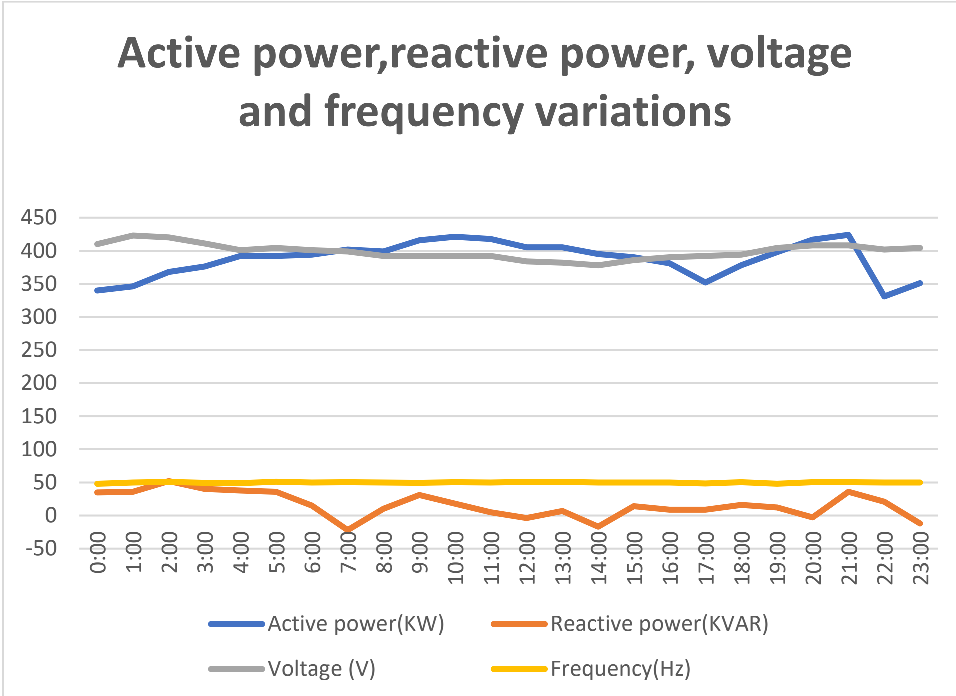

Figure 23: Active power, reactive power, voltage, and frequency variation on 01/06/2021

From the figure23, the maximum frequency and minimum frequency are 51.05Hz and 48Hz respectively, this means that there is no over frequency or underfrequency because the frequency drop is between -5% and 5% which is 47.5Hz and 50.25Hz respectively and the output voltage is varying according to the load variation and amount of water input. In figure 22, the current is slightly varying and there is no undercurrent or overcurrent presented. The line voltage recorded from 0:00 to 23:00 are:

$410V,\ 423V,\ 420V,\ 411V,\ 401V,\ 404V,\ 401V,\ 399V,\ 392V,\ 392V,\ 392V,\ 392V,$ $384V,\ 382V,\ 378V,\ 386V,\ 390V,\ 392V,\ 394V,\ 404V,\ 408V,\ 408V,\ 402V,\ 404V$ respectively.

The minimum voltage is $378V$

The maximum voltage is $423V$

Then the voltage regulation at minimum voltage of $382V$ is $V\ regulation = \frac{V0-Vi}{Vi} \times 100\% = \frac{378-400}{400} \times 100\% = -5.5\%$ and the voltage regulation at maximum voltage which is $423V$ is $V\ regulation = \frac{V0-Vi}{Vi} \times 100\% = \frac{423-400}{400} \times 100\% = 5.75\%$

Where Vi is the rated voltage of the generator and Vo is the actual voltage of the generator. From the calculated voltage regulations, there is overvoltage at 10:00 and there is undervoltage at 14:00 because the voltage regulations are between -5% and 5% of the rated line voltage of 400V, it means it is 380V and 420V respectively.

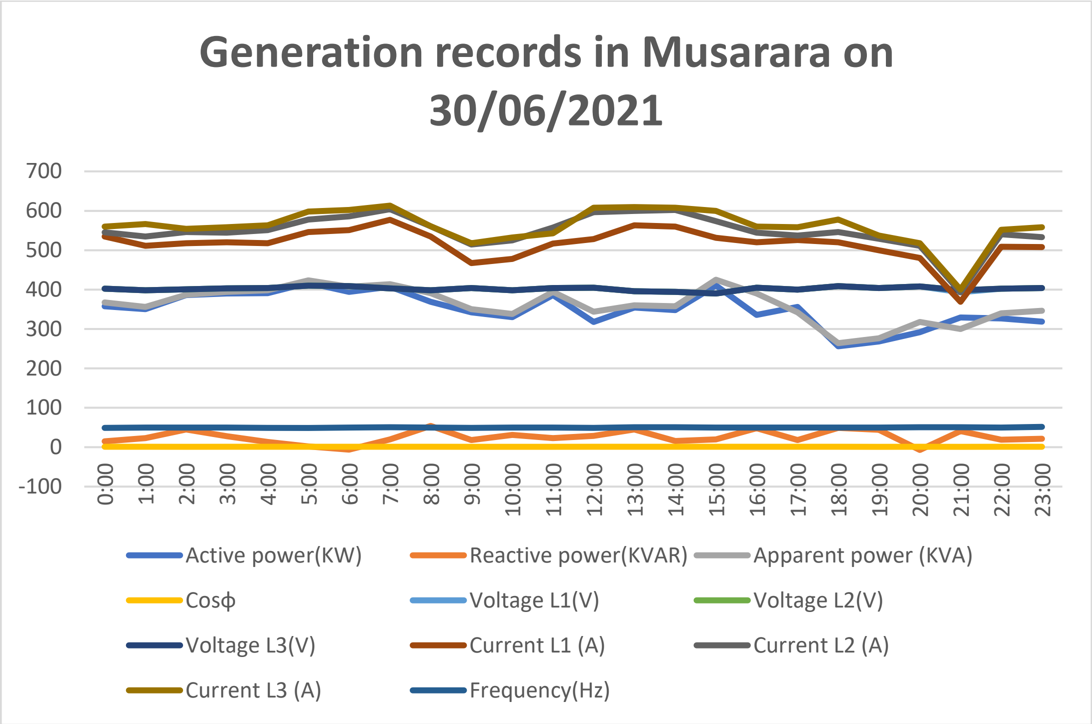

Figure 24: Musarara generation record on 30/06/2021

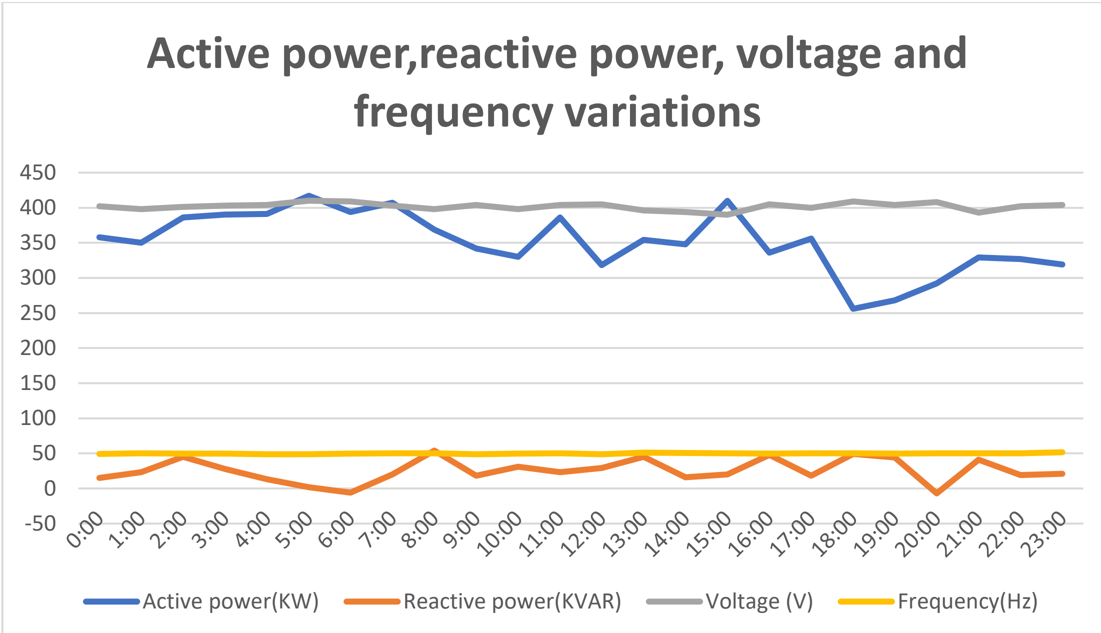

Figure 25: Active power, reactive power, voltage, and frequency variation on 30/06/2021

From the figure25, the maximum frequency and minimum frequency are 51.6Hz and 48.78Hz respectively, this means that there is no over frequency or underfrequency because the frequency drop is between -5% and 5% which is 47.5Hz and 50.25Hz respectively and the small output voltage variation and frequency variation has been caused by change input which is water supply. In figure 24, the current is slightly varying and there is no undercurrent or overcurrent presented. The line voltage recorded from 0:00 to 23:00 are:

$402V$, $398V$, $401V$, $403V$, $404V$, $410V$, $409V$, $403V$, $398V$, $404V$, $398V$, $404V$, $405V$, $396V$, $394V$, $390V$, $405V$, $400V$, $409V$, $404V$, $408V$, $393V$, $402V$, $404V$ respectively.

The minimum voltage is $390V$

The maximum voltage is $410V$

Then the voltage regulation at minimum voltage of $390V$ is $V\ regulation = \frac{V0-Vi}{Vi} \times 100\% = \frac{390-400}{400} \times 100\% = -2.5\%$ and the voltage regulation at maximum voltage which is $410V$is $V\ regulation = \frac{V0-Vi}{Vi} \times 100\% = \frac{410-400}{400} \times 100\% = 2.5\%$

Where Vi is the generator's rated voltage and Vo is the generator's actual voltage.

From the calculated voltage regulations, there is no overvoltage and there is no undervoltage because the voltage regulations are between -5% and 5% of the rated line voltage of 400V, it means it is 380V and 420V respectively.

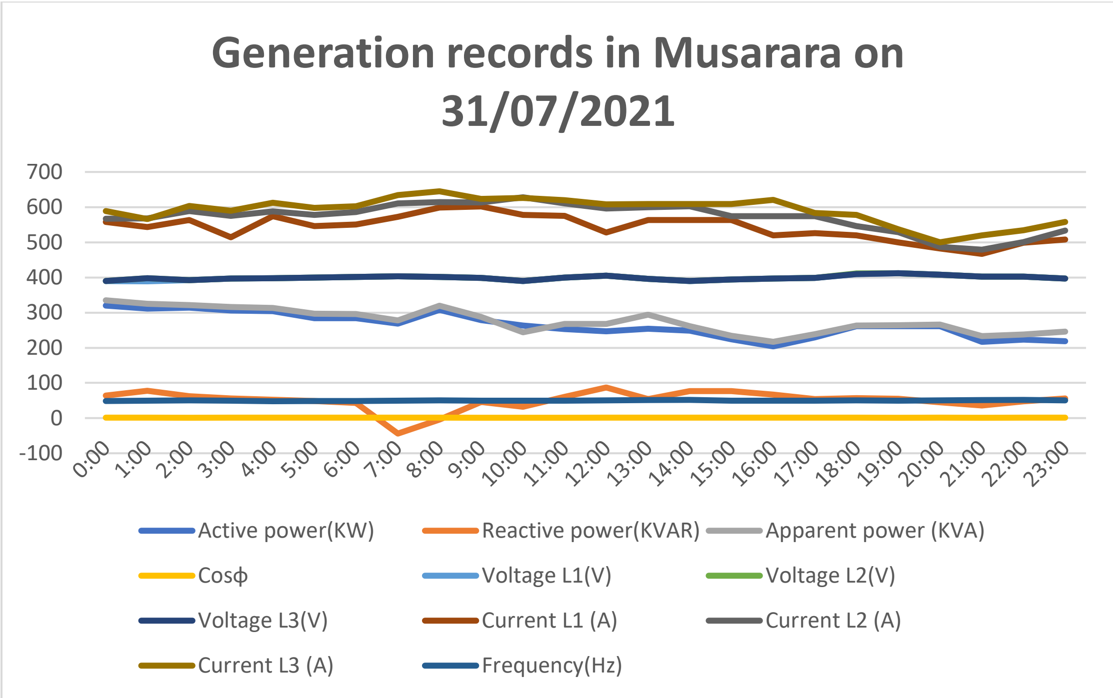

Figure 26: Musarara generation record on 31/07/2021

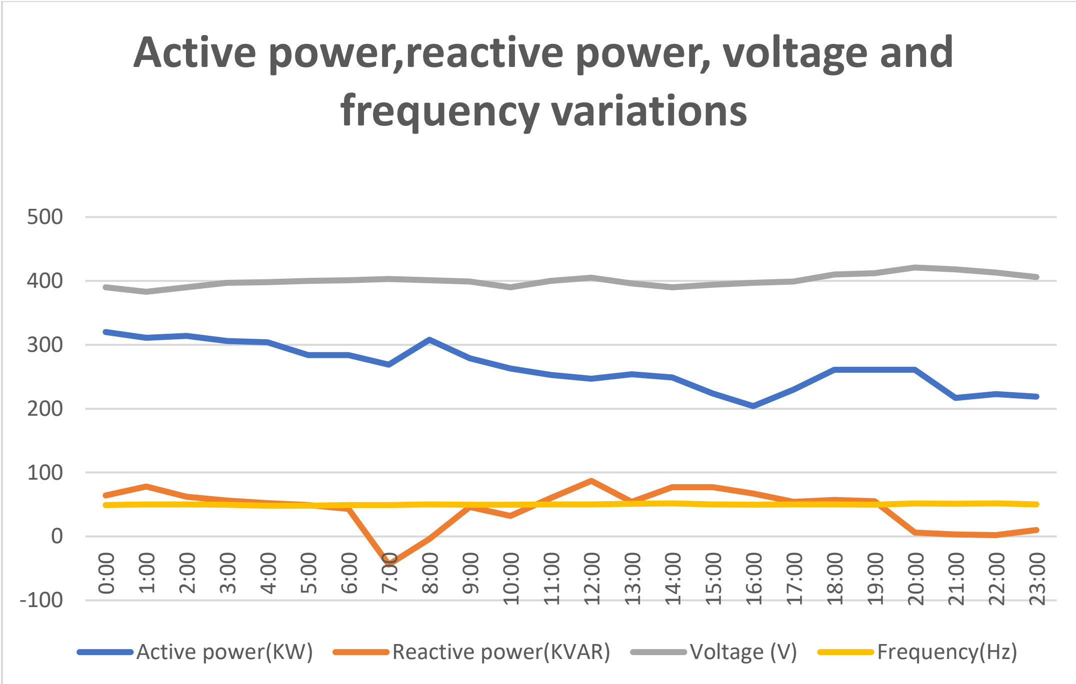

Figure 27: Active power, reactive power, voltage, and frequency variation on 31/07/2021

From figure 27, the maximum frequency and minimum frequency are 51.76Hz and 48.02Hz respectively, this means that there is no over frequency or underfrequency because the frequency drop is between -5% and 5% which is 47.5Hz and 50.25Hz respectively and the small output voltage variation and frequency variation has been caused by change input which is water supply. In figure 26, the current is slightly varying and there is no undercurrent or overcurrent presented. The line voltage recorded from 0:00 to 23:00 are:

$390V,\ 383V,\ 390V,\ 397V,\ 398V,\ 400V,\ 401V,\ 403V,\ 399V,\ 400V,\ 398V,\ 404V,$
$405V,\ 396V,\ 394V,\ 390V,\ 405V,\ 400V,\ 409V,\ 404V,\ 408V,\ 393V,\ 402V,\ 404V$
respectively.

The minimum voltage is $383V$

The maximum voltage is $409V$

Then the voltage regulation at minimum voltage of $383V$ is $V\ regulation = \frac{V0-Vi}{Vi} \times 100\% = \frac{383-400}{400} \times 100\% = -4.25\%$ and the voltage regulation at maximum voltage which is $409V$is $V\ regulation = \frac{V0-Vi}{Vi} \times 100\% = \frac{409-400}{400} \times 100\% = 2.25\%$

Where Vi is the rated voltage of the generator and Vo is the actual voltage of the generator. From the calculated voltage regulations, there is no overvoltage and there is no undervoltage because the voltage regulations are between -5% and 5% of the rated line voltage of 400V, which means it is 380V and 420V respectively.

Referring to the data taken and analyzed, the plant is generating the power which is not constantly stable due to voltage variation related to reactive power variations, frequency variation and some other issues related to power stability. According to the data of tripping faults collected in the power plant, the generator has been shut down due to frequency and voltage deviations, another main cause of remove on grid is several times of earth faults and overcurrent faults occur in Gisenyi feeder which cause the feeder relay to trip then the connected power plants become shutdown. Then different techniques or methods must be applied to maintain the power stability of the power plant by stabilizing the voltage and the frequency according to the load change.

After getting the status of Musarara MHPP, the voltage and the frequency are not stable as well as the output power, then the voltage must be stabilized by designing an AVR with PID controller and the frequency must be stabilized by designing the load frequency controller (LFC) according to the load change.

CHAPTER 4. SYSTEM DESIGN, MODELLING, AND SIMULATION

4.1. Mathematical modeling and design of AVR

4.1.1. AVR without controller

The aim of designing the AVR is to maintain the output voltage of a synchronous generator at a certain level. Figure 28 shows the schematic diagram of an AVR system.

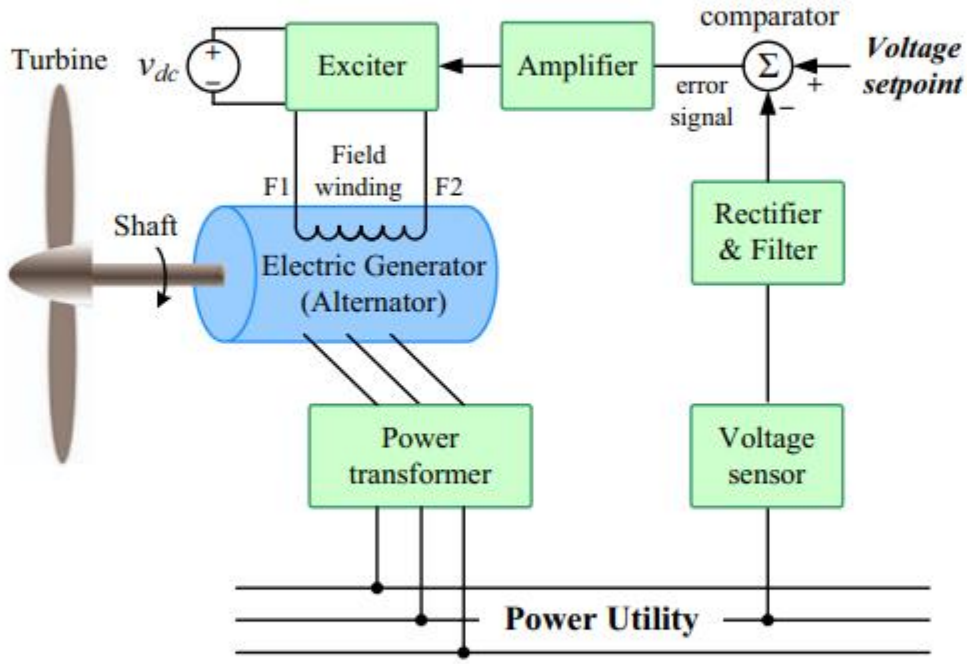

Figure 28: Schematic diagram of an AVR system [14]

An AVR is made up of four key parts such as: amplifier, exciter, generator, and sensor.

The error signal is simplified and then fed to the exciter, which adjusts the generator field winding voltage/current to compensate for any deviation in generator terminal influenced by new working conditions in a fast and stable manner.

To search for the AVR dynamic performance using a mathematical formula, a transfer function for each part of the AVR is assumed, with the main time constants used and saturated or other limitations avoided.

Modelling of amplifier

The model of the amplifier is obtained from a gain K_A and a time constant T_A, as below.

$$G_{Amplitude}(s) = \frac{K_A}{1 + T_A s}$$

where K_A always vary in the range between 10 and 40 while T_A ranges between 0.02 s and 0.1s

Exciter model

As the case of amplifier, transfer function model of an exciter may be shown by a gain K_E and a time constant T_E and is given by:

$$G_{Exciter}(s) = \frac{K_E}{1 + T_E s}$$

The operating values of gain K_E are in the range between 1 and 10 and T_E is between 0.4 and 1.0 s.

Modelling of generator

As shown in the equation, the generator is mathematically represented by a gain K_G and a time constant T_G.

$$G_{Generator}(s) = \frac{K_G}{1 + T_G s}$$

Here in, K_G and $T_G$are the constants which depend on generator loading conditions. K_G has the range between 0.7 and 1.0 and T_G ranges between 1.0 s and 2.0 s

Modelling of sensor

The AVR sensor contributes to the measurement, rectification, and smoothing of the system voltage. The sensor is mathematically represented by a gain K_S, and a time constant T_S, as shown in the following equation:

$$G_{Sensor}(s) = \frac{K_S}{1 + T_S s}$$

where T_S is too small and ranges between 0.001 and 0.06 s and K_S is about 1.0

According to the settings of Musarara MHPP, the setting values of its generator AVR card are the following:$K_A = 10; T_A = 0.1;\ K_E = 1.0;\ T_E = 0.4;\ K_G = 1.0;\ T_G = 1.0;\ K_S = 1.0;\ T_S = 0.05.$

The entire AVR transfer function block diagram is shown below, using the model's above parameter values:

$$G_{AVR}(S) = \frac{\Delta V_t(s)}{\Delta V_{ref}(s)} = \frac{0.1s + 10}{0.0004s^4 + 0.0454s^3 + 0.555s^2 + 1.51s + 11}$$

The control circuit of the above transfer function was designed in MATLAB Simulink as shown in the figure 29:

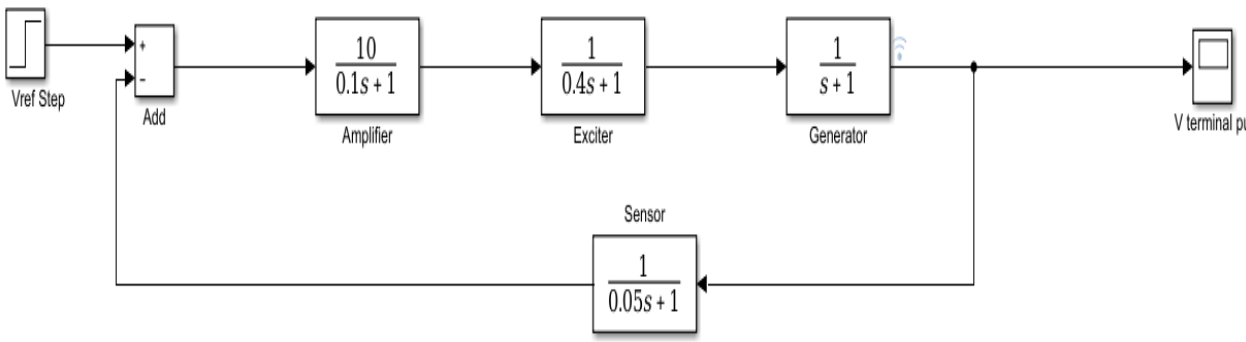

Figure 29: Musarara MHPP AVR transfer function without controller

As shown in figure 29, all parts of the AVR are modelled and connected together by using MATLAB/Simulink to control the generator terminal voltage. The result from the model simulation is shown in figure 30.

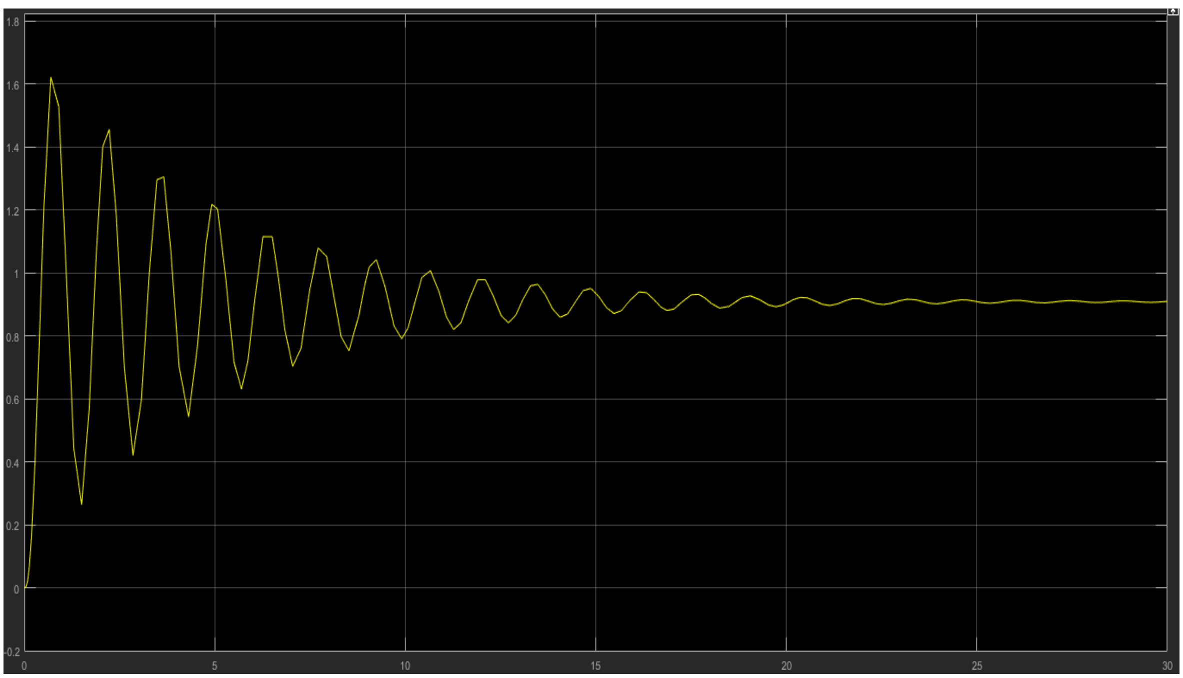

Figure 30: Output terminal voltage in per unit for AVR without controller

It can be observed that the terminal voltage is around 0.9per unit. It means that the terminal voltage is not 1 per unit as required. Furthermore, terminal voltage has oscillatory response, it is not constant. A controller, such as a PID, must be installed in the concerned system to improve the transient response of this AVR system and minimize the steady-state error.

4.1.2 Design of AVR with PID controller

The PID controller (proportional integral derivative controller) improves oscillations response by eliminating steady-state error. Figure 31 depicts Musarara MHPP AVR block diagram with PID controller. After inserting the PID into the system, it was designed in MATLAB/Simulink and simulated to obtain a new terminal voltage in per unit. According to the Musarara synchronous generator, the amplifier gain is 10 with a time constant of 0.1 sec and the exciter, generator, and sensor gains are 1 with their time constants of 0.4 sec, 1.0 sec, and 0.05 sec respectively. The AVR was designed to operate at the generator's maximum and minimum voltage, where the terminal base voltage is 400V.

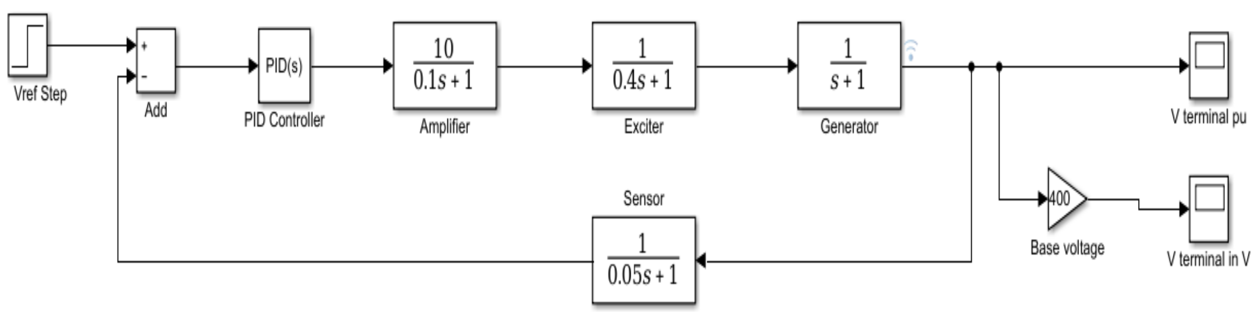

Figure 31: Block model of Musarara synchronous generator AVR design

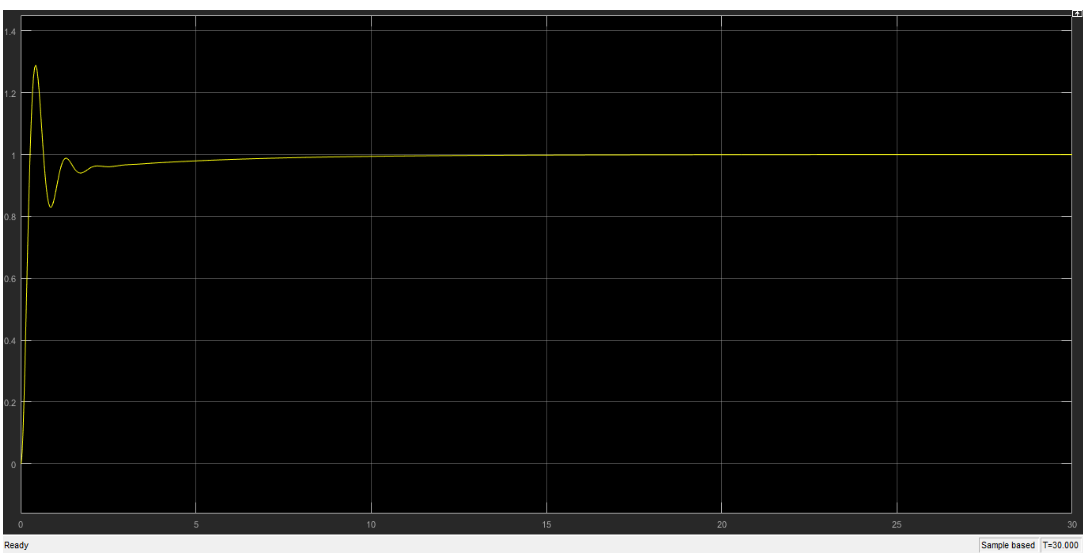

Figure 32: Terminal voltage in per unit

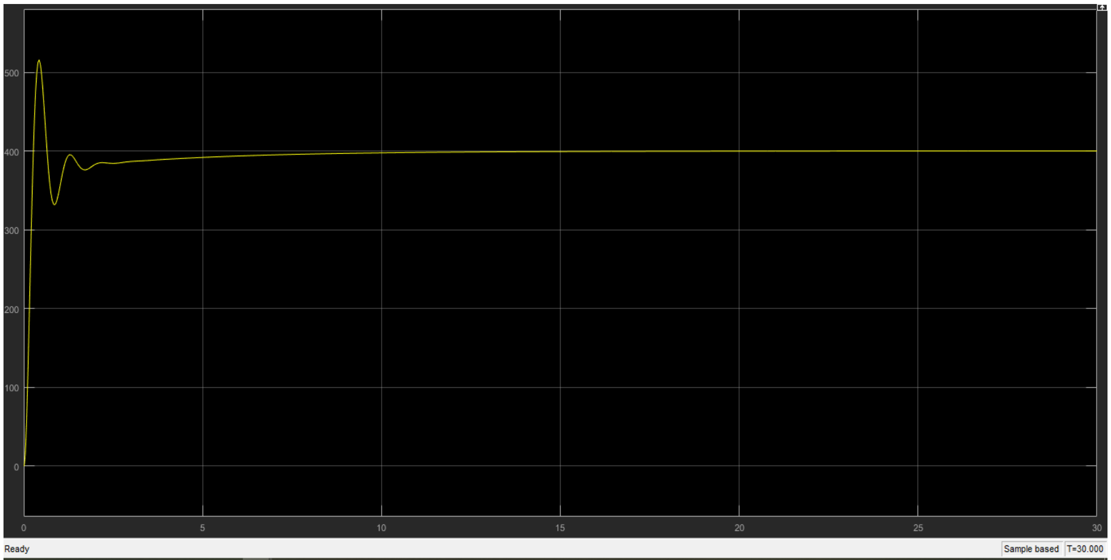

Figure 33: Terminal voltage in Volts.

After simulation of the model shown in figure 31, the comparison of before and after inserting the PID controller in the system, it is observed that the terminal voltage is not recovered to 1 per unit as shown in figure 32 and to 400V as shown in figure 33 which is the required voltage. Also, it is observed that the terminal voltage has oscillatory response having high overshoot. Then to restore the voltage at 1 per unit or at 400V base and to reduce the overshoot of the signal, we need to tune the PID controller in MATLAB Simulink software.

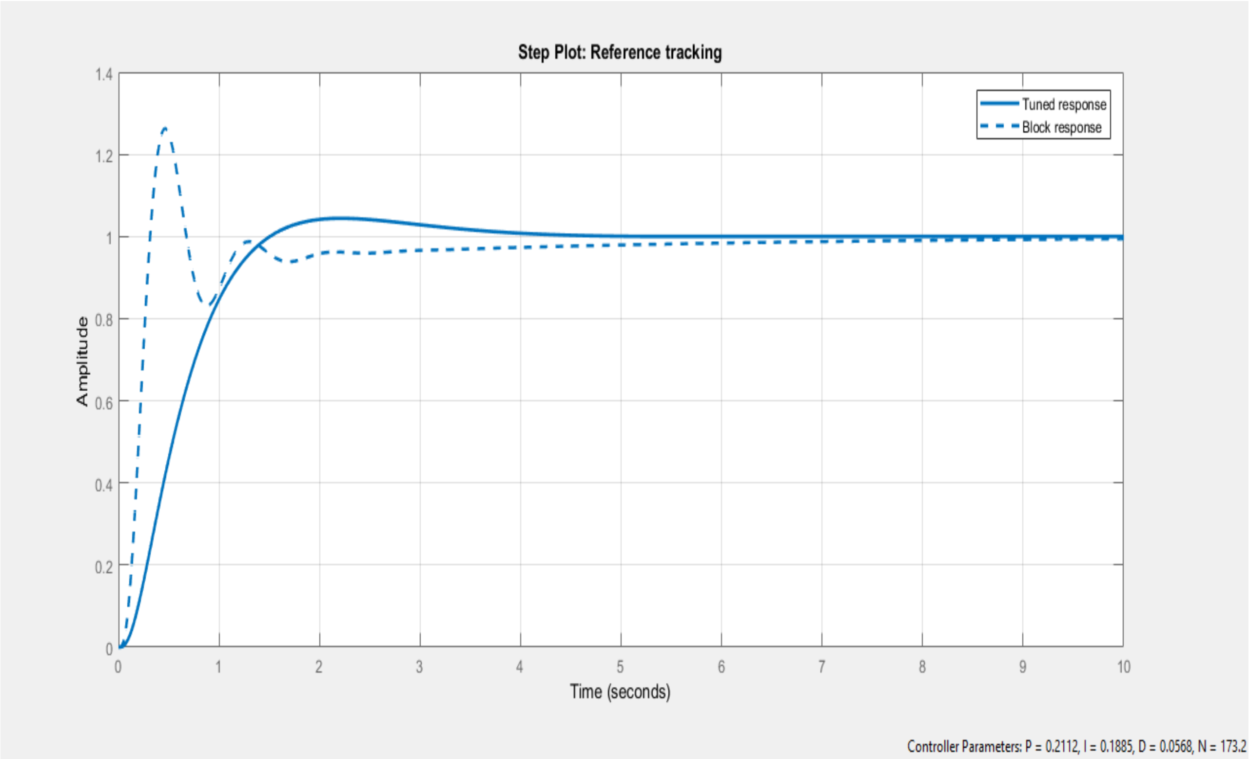

Figure 34: Musarara MHPP AVR with Tuned-PID controller

As shown in figure 34, the two signals are totally different, the dashed one shows the PID controller without tuning and the undashed one shows the tuned PID controller. After tuning, the overshoot has been reduced and the voltage has been restored to 1 per unit. The controller parameters (proportional, integral, and derivative) showing the difference between untuned and tuned PID controller are shown in figure 35. As it is shown the values of proportional, integral, and derivative are different for tuned PID and untuned PID controller.

Controller Parameters

	Tuned	Block
P	0.21121	1
I	0.18851	0.25
D	0.056796	0.3
N	173.2203	100

Performance and Robustness

	Tuned	Block
Rise time	0.928 seconds	0.189 seconds
Settling time	3.33 seconds	5.14 seconds
Overshoot	4.42 %	26.3 %
Peak	1.04	1.26
Gain margin	24.8 dB @ 12.9 rad/s	9.92 dB @ 12.7 rad/s
Phase margin	69 deg @ 1.52 rad/s	39.5 deg @ 6.33 rad/s
Closed-loop stability	Stable	Stable

Figure 35: Parameters of tuned and untuned PID controller

According to the information given in the figure 34, the tuned PID shows the reduced overshoot than the untuned PID controller i.e. it has been reduced from 26.3% to 4.42%, and the setting time has been reduced from 5.14seconds to 3.33 seconds as shown in figure 35 which make the signal to be restored at 1 per unit.

4.2. Frequency Control

The frequency was controlled using the load frequency control metho. The primary function of a load frequency controller is to adjust the frequency of the system when there is a variation in load. In this thesis, LFC is used to control the frequency of Musarara power plant in response to lad changes and perturbations. Figure 36 depicts the load frequency control model based on perturbations occur in Musarara MHPP.

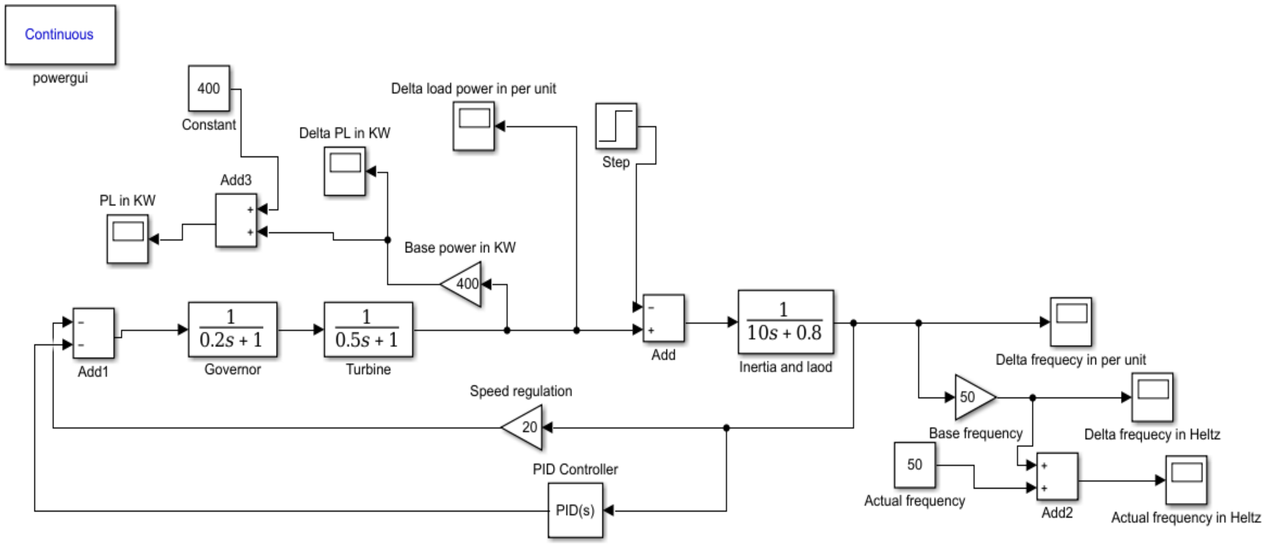

Figure 36: Musarara MHPP load frequency control with PID controller

This model has been simulated according to the load change to see if the frequency has been returned to its original value after being subjected to a sudden load perturbation. The simulation has been done for three times on the load changes of 0.2 per unit, 0.15 per unit and 0.1 per unit. The figures below show the change in frequency of 0 per unit and of 0 Hz, the original frequency of 50 Hz, the load change which is 60KW equals to 0.15 per unit as the base value is 400KW and the new power or load after perturbation correction with load frequency control which is 460KW respectively.

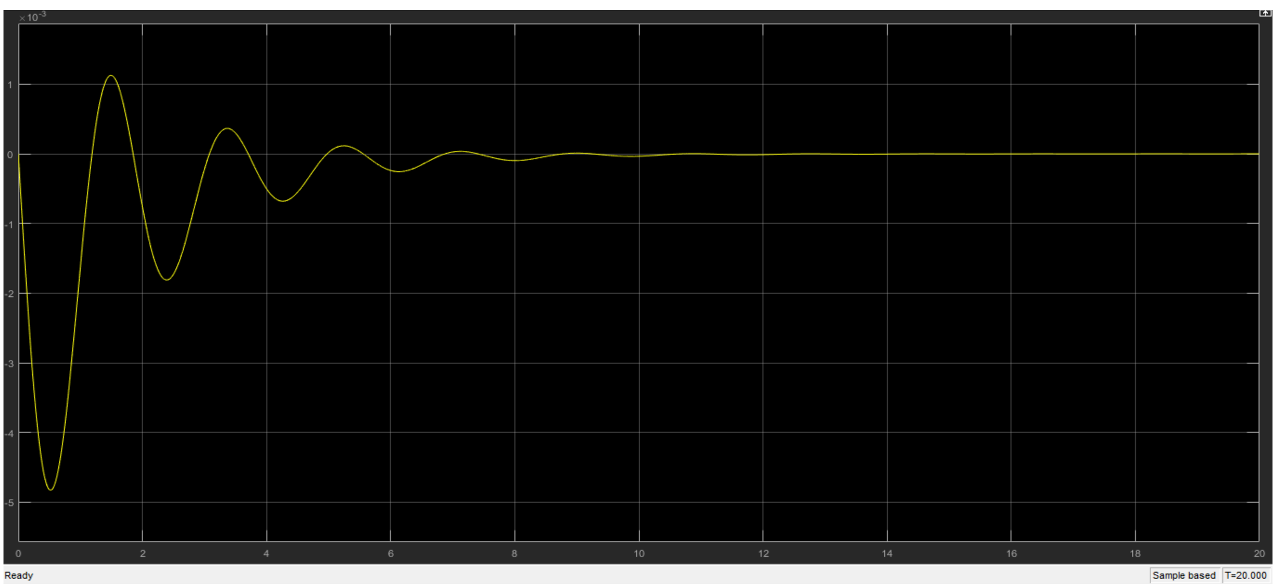

Figure 37: Change in frequency in per unit

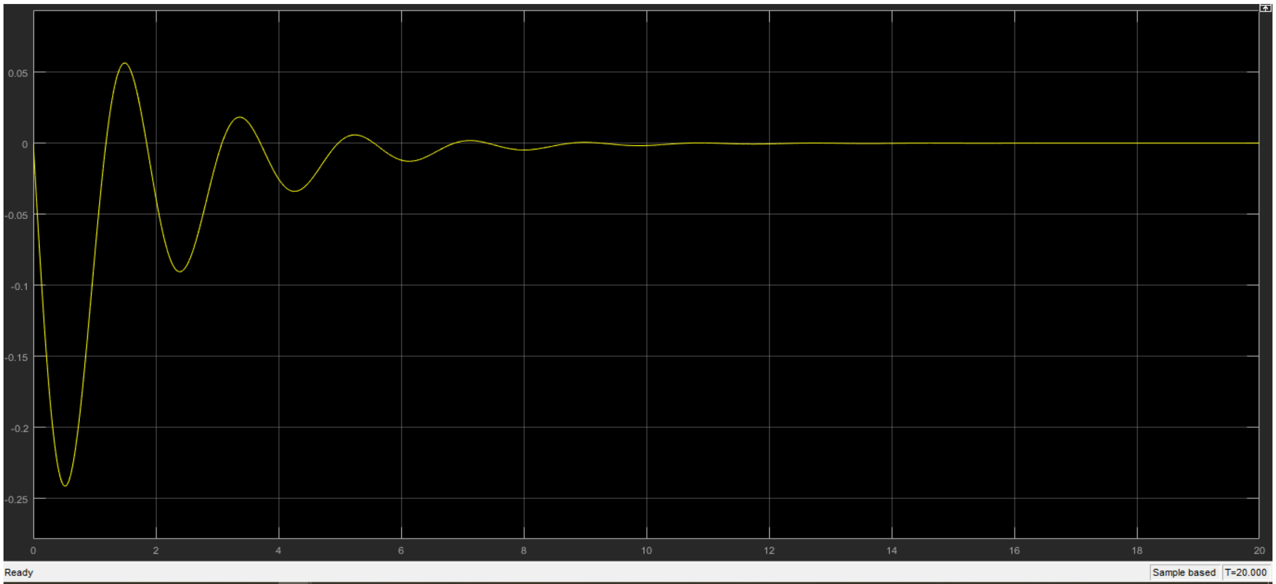

Figure 38: Change in frequency in Hz

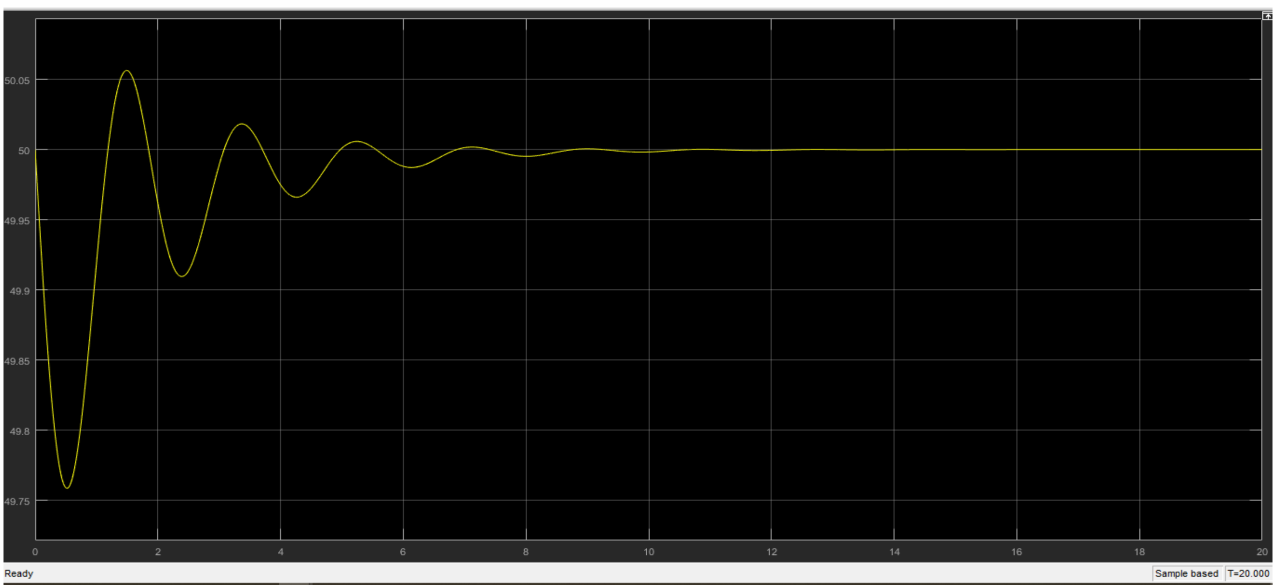

Figure 39: 50HZ frequency after correction of load perturbation

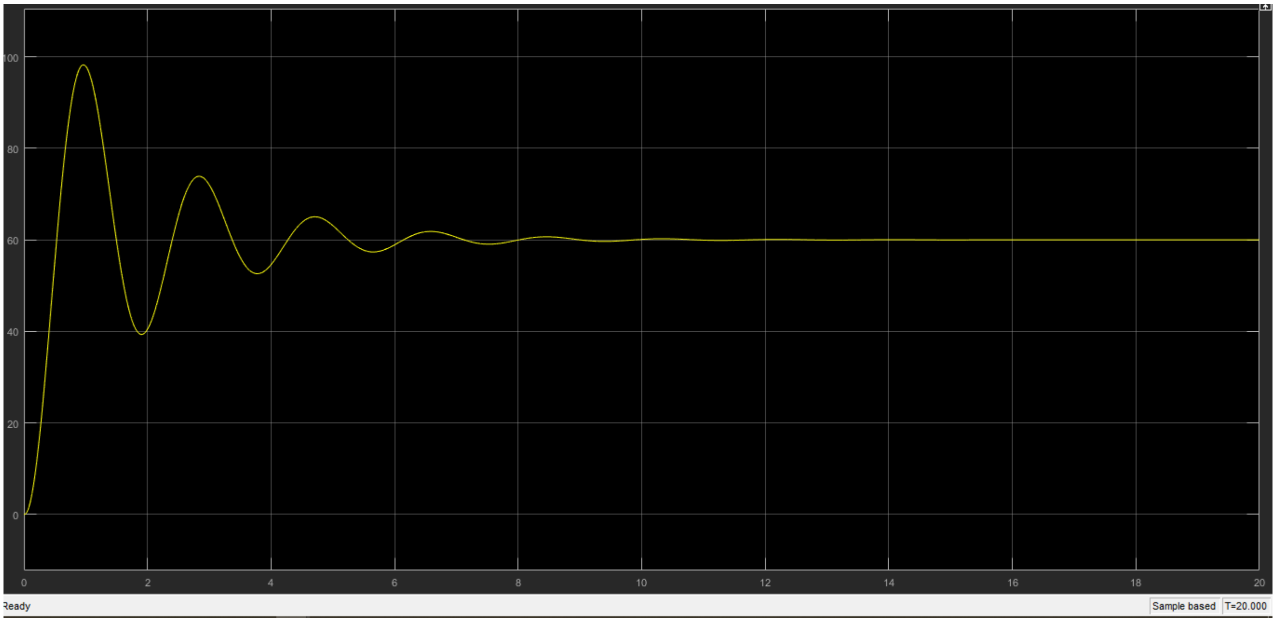

Figure 40: Change in load power in KW

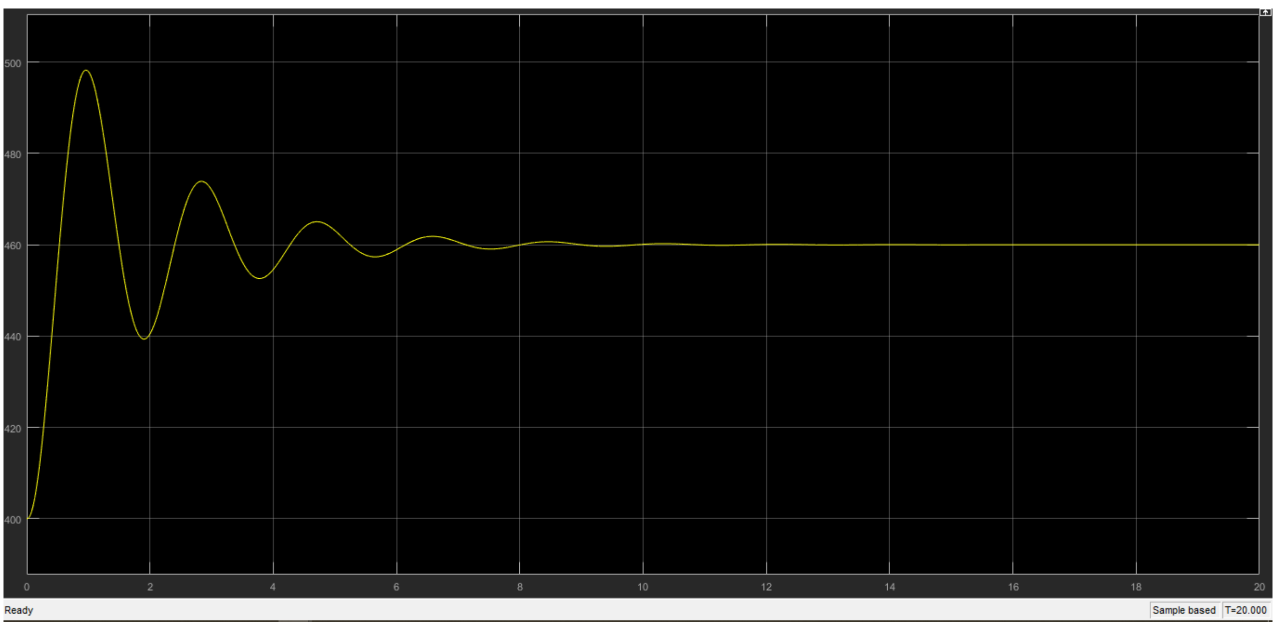

Figure 41: New load power after correction of load perturbation

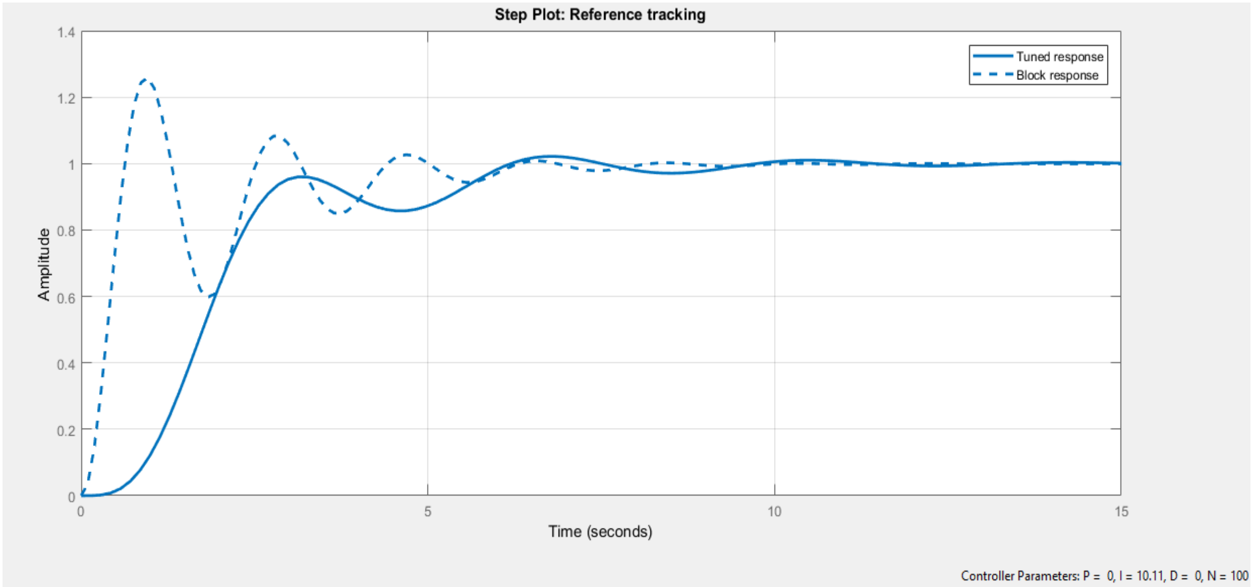

Figure 42: Tuned PID controller of LFC

Controller Parameters

	Tuned	Block
P	0	50
I	10.1065	30
D	0	10
N	100	100

Performance and Robustness

	Tuned	Block
Rise time	1.74 seconds	0.422 seconds
Settling time	9.08 seconds	7.59 seconds
Overshoot	2.17 %	25.9 %
Peak	1.02	1.26
Gain margin	6.91 dB @ 1.71 rad/s	26.5 dB @ 14.6 rad/s
Phase margin	74.4 deg @ 0.514 rad/s	23.9 deg @ 3.3 rad/s
Closed-loop stability	Stable	Stable

Figure 43: Control parameters of tuned and untuned PID controllers

According to the information given in the figure 34, the tuned PID shows the reduced overshoot than the untuned PID controller i.e.; it has been reduced from 25.9% to 2.17% and the rise time has been increased from1.74 seconds to 0.422 seconds which make the signal to be restored at 1 per unit.

CHAPTER 5: RESULTS AND DISCUSSION

After designing the load frequency control for controlling the frequency and setting it to the original value of 50 HZ after the subjection of load change and designing AVR with the help of PID controller tuned in MATLAB Simulink software, simulation can be done easily. The simulations done are based on voltage and frequency controls by using AVR and LFC respectively. From the simulation of AVR without controller based on Musarara MHPP as shown on the model in figure 29, the result in figure 30 shows that the signal is more oscillating with high overshoot and the terminal voltage is not set at its original value of 1 per unit. After that the system has been improved by employing PID controller as shown in figure 31 and figure 32 where the signal of the terminal voltage is at 0.9per unit with high overshoot and setting time. Then to reduce the overshoot, setting time and set the terminal voltage at 1 per unit, the PID controller has been tuned in MATLAB Simulink as shown in figure34 and figure 35 where the overshoot has been reduced as well as the setting time and the terminal voltage is totally restored to 1 per unit which its original value equal to the reference voltage which means that the error between the reference voltage and the actual voltage due to load change and perturbation has been compensated to be zero error. From the simulation of LFC with its model shown in figure 36, the system was designed to control the frequency according to the change in load, when there is change in load, the frequency changes, then the system was designed to adjust the frequency to its original value after load change or any other perturbation in the plant. The LFC works on the principle where when there is change in load, governor control the water gate to reduce or increase the power. Figures 37 and 38 shows the changes in frequency in per unit and in Hz after load change occur and the figure 39 shows the 50 HZ frequency which is the original frequency after correction of load change, figure 40 shows the change in load and figure 41 shows the new load power correction of perturbation. All signals have high overshoots and setting time which have been corrected by tuning the PID controller of the LFC as shown in figure 42 and the results are shown in figure 43. The designed systems show that there is improvement on voltage stability and frequency stability of the power plant, but they should be successful with expert and attentive user.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

The AVR and LFC with PID controller designs have been used to reduce power system oscillations and improve system stability by controlling the synchronous generator voltage and system frequency, respectively. We conclude from the simulation results, which were obtained by comparing the output signals for various cases in the Simulink models, that the system operated AVR and LFC with PID controller achieve the desired value of voltage and frequency of the machine as the tuned PID shows the reduced overshoot than the untuned PID controller i.e., it has been reduced from 26.3% to 4.42%, and the setting time has been reduced from 5.14 seconds to 3.33 seconds. With the LFC, the frequency returns to the original value of 50 Hz after the system is being subjected to the load changes because the tuned PID shows the reduced overshoot than the untuned PID controller i.e., it has been reduced from 25.9% to 2.17% and the rise time has been increased from1.74 seconds to 0.422 seconds. These results shows that the system is more responding than the conventional system without controllers.

This means that the designed systems achieve the better settling time by quicker than other systems without controller. Referring to the results obtained after simulation and referring to the analog settings of mini- hydropower plants especially in Musarara MHPP, the new method would improve the power stability of the plants when they are subjected to sudden small load. This is what my research has covered.

This topic has many researches which can be done on it, like improvement of voltage stability of Musarara MHPP by using FACTs devices, improvement of transient stability of Musarara MHPP by using Fuzzy logic controller, improvement of transient stability of Musarara MHPP by using Genetic Algorithm and so on. Also, one can do research on how to adopt pumped-storage hydropower plant in Rwanda because of less quantity of water available in many power plants in Rwanda, this should increase the generation efficiencies of the power plants as well as increasing the transmission efficiencies to raise the national installed capacity.

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