EXPERIMENTAL DESIGN AND OPTIMIZATION OF FREQUENCY AND VOLTAGE CONTROL SYSTEM IN A MICRO HYDRO POWER GENERATING UNIT USING FUZZY LOGIC

A Thesis

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By

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Declaration

I Asinge Weko Jack, do hereby declare that this thesis entitled: "**Experimental Design and Optimization of Frequency and Voltage Control System in a Micro Hydro Power Generating Unit Using Fuzzy Logic**" has never been submitted as a requirement for the award of any degree in any academic institution worldwide. All citations are duly acknowledged by means of reference.

Signature and date……………………………………………………………………………….

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Certification

This is to certify that this research work entitled **"Experimental Design and Optimization of Frequency and Voltage Control System in a Micro Hydro Power Generating Unit Using Fuzzy Logic"** presented by Asinge Weko Jack a Master student with registration number: 1163-03216-06057 was carried out under our supervision and guidance.

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Acknowledgement

I wish to express my gratitude to my Supervisors: Dr. UKAGWU Kelechi John and Mr. MUSA Nasaaga for their support, guidance, encouragement and contribution towards the success of this project. I also acknowledge the assistance and support of the head of Electrical Engineering department Ms. Kalyankolo Zaina during the project. Finally, I extend my gratitude to all faculty members and colleagues who have given me helpful advice and suggestions during this research process. May God bless you all!

Dedication

I dedicate this work to the almighty Lord, to my parents (***Barageranya Banywesize Jean*** and ***Mujijima Bikaya Ahadi***) and friends.

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List of Abbreviations

AGC: Automatic Generation Control

ALFC: Automatic Load Frequency Control

AVR: Automatic Voltage Control

FLC: Fuzzy Logic Controller

LFC: Load Frequency Control

LQG: Linear Quadratic Gaussian

MHPPs: Micro Hydro Power Plants

PID: Proportional Integral and Derivative

PSS: Power System Stabilizers

pu: per unit

ABSTRACT

Hydro power plants have been a major source of energy over the years and there have been series of improvement from micro units to large scale units. Irrespective of the great milestones achieved in generation of electrical energy through hydro power plant, there have also been challenges confronting these means of power generation amidst which include voltage and frequency instabilities. This research work used fuzzy logic control algorithm in order to contribute to Micro Hydro Power Plants stability and dynamic performance improvement. Its effectiveness was shown through a comparative analysis to Conventional Controllers simulated in Matlab/Simulink 2018a. Both controllers were subjected to dynamic performance tests in order to evaluate their respective transient, performance stability and robustness responses in a designed Micro Hydro Power Plant. Results revealed that Fuzzy Logic Controller reduces the response time from 8.23s to 3.32s (improvement of 4.91s averaged over all conducted tests) and provides smaller overshoot with a reduction from 49.65% to 35.54% (improvement of 14.11% averaged over all conducted tests). These results show that Fuzzy Logic Controller has significantly improved the stability and the dynamic performance of the considered Micro Hydro Power Plant.

CHAPTER ONE

INTRODUCTION

1.0 Introduction

Designed plants and systems are required to achieve a set of defined performance specifications. They should behave in a desired manner. Controllers are used to achieve this objective. Controllers are devices that generate a signal based on a certain algorithm and controls the output of the plant[1]. In a closed-loop structure, the controller uses the error between sensed plant response and the desired set point in order to generate a proper control signal [2]. Particularly, hydro power plants use frequency or voltage controllers in order to produce a quality power. The Automatic Generation Control (AGC) and Automatic Load Control schemes are used for frequency control while the Automatic Voltage Regulator (AVR) is used for voltage regulation [3].

There are numerous types of frequency or voltage controller depending on their structure and the desired performance level. The Proportional Integral Derivative (PID) type is the most popular among them. It regulates the plant output depending on the proportional, integral and derivative terms [4]. PID controllers have shown better performance and made a great contribution in ameliorating power system dynamics [5]. However, due to their linear nature, PID controllers are not suitable for non-linear, complex and stochastic power systems [5]. Development of technology has led to the implementation of improved controllers based on modern and more sophisticated approaches. Fuzzy logic controllers are among techniques that are being developed.

In opposition to the binary logic, Fuzzy logic is a multi-valued logic that relates to sets with no sharp boundaries where objects' membership is evaluated in term of degree [5]–[7]. It is an extension of the binary logic to accommodate different degrees within the interval [0 1]. Any element can possess a certain degree of membership represented by the infinite number of value between 0 and 1, where 0 and 1 implies no membership and full membership, respectively. Fuzzy logic application appears to be most suitable for complex and non-linear systems with an unspecific control objective and unavailable exact mathematical model [5], [7], [8]. In recent years, researchers and designers have started to use fuzzy logic as a powerful tool in various applications.

Fuzzy logic was theoretically proposed by Professor Lotfi Zadeh (1965) in his paper "fuzzy sets''[9]. Researchers used this technique to resolve problems that seemed to be difficult. In 1975, Mandani implemented fuzzy logic in application to process control. He used fuzzy logic for the control of a steam motor[9]. The first industrial implementation of fuzzy logic was realized by the Danish company Smidth in 1978[10] *and* [11]. Fuzzy logic practically flourished in Japan where it was applied in several control systems. From 1990 onwards, many industrial applications in USA and Germany uses fuzzy logic control. Fuzzy logic control has also gained great interest in application for frequency and voltage controls in power systems [6], [8], [12], [13].

In this research work, fuzzy logic control algorithm has been employed for frequency and voltage control in Micro Hydro Power Plants (MHPPs).

1.1 Problem Statement

The existing power system is currently facing major issues. Consumers of the electrical energy are always complaining about the power quality. Efforts for power system improvement have to be undertaken in order to curb the epileptic power system. Regulating the voltage and frequency of the generating unit has contributed to the power quality enhancement[14]. A standard and conventional method is to apply Proportional, Integral and Derivative (PID) algorithm in AGC and AVR. However, this technique may demonstrate poor results in application to MHPPs which are complex, nonlinear, stochastic and difficult to model systems [4], [8], [12]. Efforts to improve this algorithm by using heuristic tuning methods were demonstrated in [15] and [16].

A particle swarm PID parameters tuning optimization for voltage control was proposed in [15]. The fitness function regarding to power system dynamic performance and the disadvantages of using Ziegler-Nichols methods in automatic voltage control were respectively, evaluated and studied. Further studies considered nonlinear constraints [16]–[18] and proposed the use of fractional order PID in single and interconnected power generation system. In [18], Delassi used the robust fractional order PID controller in the AGC of multi-area power system by introducing nonlinear constraints and making an attempt of tuning the controller's optimal parameters through the differential evolution evolutionary algorithm.

Though the previous propositions appeared to slightly improve the system's performance, conventional PID controllers are still not providing sufficient stability in the stochastic and nonlinear power system. They lack simplicity, robustness, and flexibility when applied to complex power systems. Moreover, they are based on analytical model that may be complex and unavailable in some cases. In recent years, further studies revealed that human experience may contribute to controller design for power system stability improvement [9]. A fuzzy logic approach was therefore proposed in this work.

Fuzzy logic approach is based on the practical knowledge rather than on the analytical model. It is a multi-valued control in opposition to binary control approach. This research used fuzzy logic control algorithm in application to voltage and frequency control in MHPPs and tried to show its effectiveness over conventional controllers.

1.2 General Objective

This study aims to design and optimize a frequency and voltage control system in application to MHPPs using a fuzzy logic control algorithm.

1.3 Specific Objectives

1. To design, simulate and optimize a fuzzy logic controller with application to MHPPs.
2. To evaluate the dynamic performance of the micro hydropower plant controlled with the designed fuzzy logic controller.
3. To evaluate the degree of improvement in term of reliability and stability of the fuzzy logic controlled micro hydropower plant through a detailed comparison with conventional controllers.

1.4 Research Questions

At the end of this study, the following questions should be answered:

1. Why are the conventional controllers not effective for frequency and voltage control in a MHPP?
2. What are controller designs that are capable of enhancing the overall stability and reliability of the MHPP while acting in its frequency and voltage controls techniques?
3. At what extent the reliability and stability of a MHPP can be improved by ameliorating its voltage and frequency controller?

1.5 Conceptual Framework

Figure 1.1. presents the conceptual framework of this research. The main goal is to regulate voltage and frequency through the usage of controllers with different approaches: the conventional approach and the fuzzy logic approach. Due to problems associated with conventional controller, a fuzzy logic controller is proposed, designed and tested in the Micro Hydro Power Plant with the desired performance specifications. The dynamic behavior of the designed Fuzzy Logic Controller is compared to Conventional controller (PID controller) and the extent to which Fuzzy Logic Controller can improve the power system dynamic is elaborated through the calculation of the average improvement in response time and overshoot for all parameters under consideration.

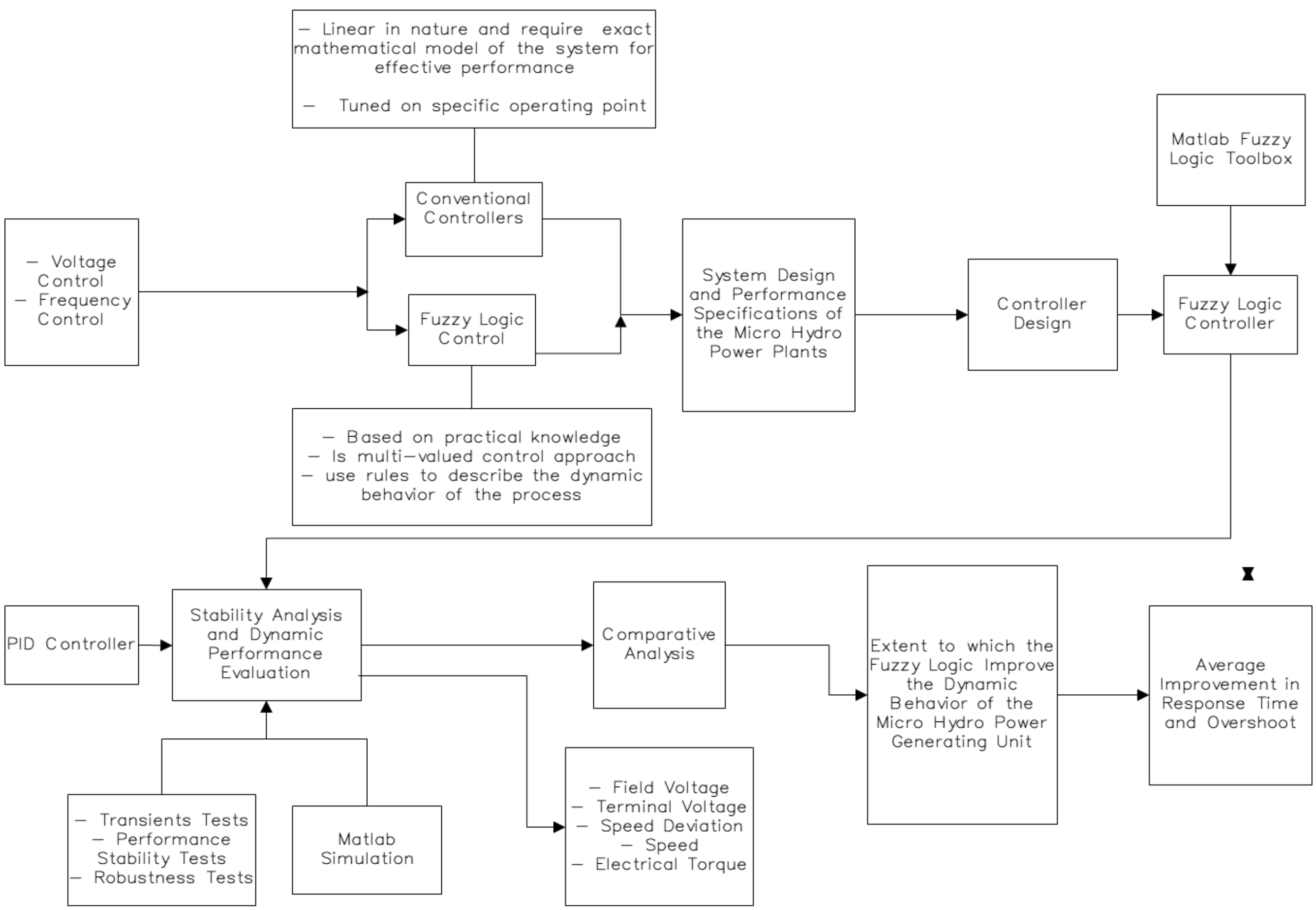


Figure 1.1. Conceptual Framework

1.6 Significance of the Study

Micro hydro power plants are facing a significant problem regarding frequency and voltage regulation due to lack of proper control algorithm. On one side, engineers and researchers are seeking for solutions and on the other side; consumers need power of good quality. This research work has contributed to respond to the need by providing a means for frequency and voltage regulation for the improvement system's quality of supply. For an academic purpose, this research serves as a reference manual for future research in the area of voltage and frequency control.

1.7 Scope and Limitations of the Study

This research work focuses on the design and optimization of a control system for frequency and voltage parameters control using fuzzy logic to improve power system stability. This study is done for a single area micro hydro power generating unit limited to 100kW at 400V. Future researches may extend it to multi-areas power systems with considerations on loads sharing problems

CHAPTER TWO

LITERATURE REVIEW

2.0. Introduction

This chapter provided a theoretical approach and discussed relevant scholarly books, conference reports, journal articles and actualized materials on frequency and voltage control and stability in MHPPs. Important theories, concepts and methods in this area were reviewed and synthetized and a literature gap was derived.

2.1. Theoretical Approach

2.1.1. Hydro Power Generating Unit

Hydro power plants generate electrical energy through converting the potential energy stored in water [19]. They use hydraulic turbine to develop mechanical torque that is converted into electrical energy through the alternator [20]. The main components of a hydro power generating unit are illustrated in Figure 2.1 as described in [21].

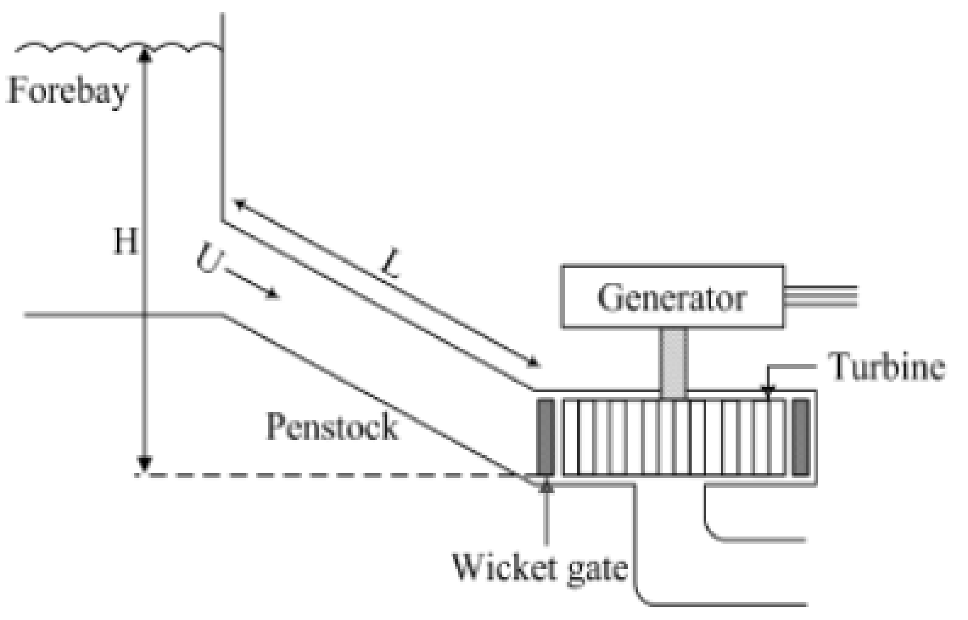


Figure 2.1. Components of a Hydro Power generating unit [21]

A hydro power plant mainly consists of a turbine, a generator, a penstock and wicket gates. Water is picked from the dam (located at a high head) and flows through the penstock before reaching the turbine. The flow of water to the turbine is controlled by wicket gate. The water runs the turbine-generator set and the rotating generator produces the electrical energy. End-users or loads are connected to the power generating plant by means of transmission lines via transformers [22].

Hydro power plants are classified into two main group depending on the generated power: small scale and large hydro power plants [19]. The capacity of the hydro power plant determines the type of voltage and frequency control to be applied.

- Small scale hydro power plants generate below 10MW
- Large scale hydro power plant generate more than 10MW

Small scale hydro power plant are preferred for their simplicity in controllability and their modest size that helps to reduce pressure and environmental impact [22]. Further studies classify small scale hydro power plants into the followings:

- Pico Hydro Power Plants: P < 5 kW
- Micro Hydro Power Plants: P < 100 kW
- Mini Hydro Power Plants: P < 1.000 kW
- Small Hydro Power Plants: P < 10.000 kW

2.1.2. Frequency and Voltage Control in MHPPs

The automatic generation control (AGC) is used for frequency control while the Automatic Voltage Regulator (AVR) is used for voltage regulation [3]. A clear description of the AGC was presented in [22]. In fact, the turbine uses the governor in order to increase or decrease the mechanical power by continuously monitoring the rotor speed deviation (difference between the electrical and mechanical power). The increase or decrease in rotor speed deviation let the governor (controller) to close or open wicket gate in order to maintain the power balance. Figure 2.2 presents the AGC and the AVR where ΔP_G is the difference in power outputs.

In the AVR diagram, the generator terminal output voltage is sensed, transformed, rectified and compared to a voltage reference. The voltage error obtained is used to increase or decrease the excitation voltage which will in turn increase or decrease the terminal voltage output accordingly [3], [22], [23].

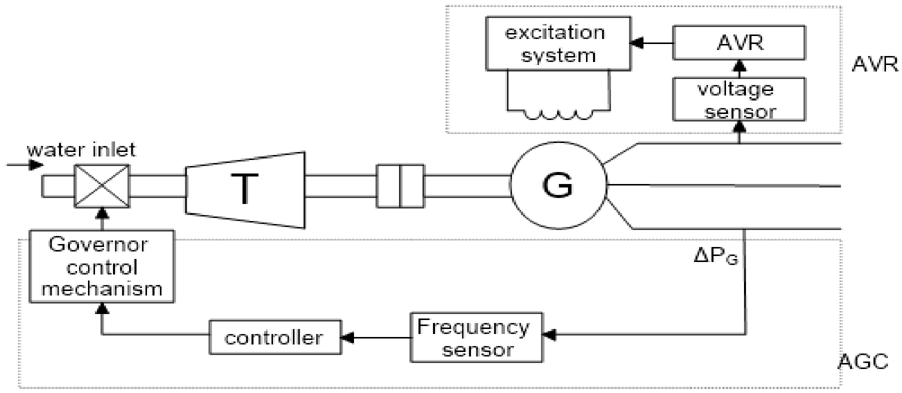


Figure 2.2. AGC and AVR in a MHPP [22]

2.1.3. Theory on MHPPs Stability

The main goal of installing a controller in a power plant is to achieve a certain degree of dynamic performance [14]. These performances are set in term of stability, availability, reliability and flexibility. In this section, a theoretical approach on power system stability was performed.

Researchers are defining stability as the ability of a power system to recover its original or normal state following the occurrence of disturbances [5], [24]. Indeed, power systems are naturally nonlinear and complex. Their operating conditions and parameters are continuously changing. Loads variation, short circuit, small faults, switching actions, generator output and input are factors contributing to the nonlinearity and complexity of the power system [22]. A power system should be able to retrieve its original or normal state following small or large disturbances. An unstable power system may collapse and experience shutdown or black-out which reduce the overall system reliability and availability.

Based on the type of the disturbance, its time span and nature; stability can be classified as frequency, voltage and rotor angle stabilities [25]. Rotor angle stability is defined as the ability of a generator to remain in synchronism following a disturbance in the interconnected system. [16], [26]. Steady voltage and frequency are, respectively, studied in voltage and frequency stability. This research is limited to voltage and frequency stability. Stability issues in interconnected system are not studied.

2.1.3.1. Frequency Stability

In a stable power system, the balance between the power supply and the power demanded has to be continuously maintained. Frequency deviations occur when there are mismatches between generation and load demands. Small deviations may be easily corrected while large frequency deviations may lead to equipment damage or interruptions and blackouts. The ever changing load connected to the power system would require a well-designed frequency controller in order to always adjust to deviations [14].

Frequency control is termed as ALFC (Automatic Load Frequency Control). There are three levels of frequency control in a power system [24].

- *The primary frequency control.* It is termed as AGC (Automatic Generation Control) or turbine-governor regulation [8]. It participates in eliminating the mismatch between the generation and the load. It also contributes to rotor speed regulation.
- *The secondary frequency control.* It is termed as LFC (Load Frequency Control) and is used when the primary frequency control fails to satisfactory eliminate frequency deviations. In interconnected power systems, the LFC mostly contribute in adjusting the tie-lie power within participating units. It ensures loads sharing and eliminate overload in the interconnected power system.
- *The tertiary frequency control* acts in generators commitment and dispatch. It manages congestion in the transmission network and restores frequency at its desired value when secondary control was not successful.

This research work only discussed the primary frequency control, termed as AGC.

2.1.3.2. Voltage Stability

The ability of a power system to maintain a constant voltage at its all buses following the occurrence of disturbances is termed as power system voltage stability [24]. Instability in voltage may be caused by switching loads, loss of transmission line, short-circuits faults and so on [14]. Voltage instability in the power system may result in loss of load and transmission line tripping, generator collapse and blackouts.

There are two main types of voltage stabilities: large disturbances voltage stabilities and small disturbances voltage stabilities. The time span of each type may vary from few microseconds to several hours. Large disturbances voltage stability is the capability of a power system to retrieve steady voltage after severe disturbances such as loss of transmission lines, loss of generations and occurrence of faults in the system. However, small disturbances voltage stability is the ability of the power system to retrieve its nominal voltage after a small disturbance, such as step load change, is occasioned in the system [24].

2.1.4. Theory on PID Algorithm

The controller involved in AVR and AGC can be implemented using different types of algorithms depending on the application. It may be implemented using conventional PID methods, robust methods, adaptive methods, nonlinear methods or optimization and intelligence methods [26].
A standard and conventional way of designing a controller is to use a PID algorithm. It consists of three parameters (Proportional, Integral and Derivative) that are adjusted and selected in order to meet the desired output. A block diagram of the PID controller is shown on figure 2.3 and equation (2.1) gives its mathematical model [3];

$$u(t) = K_p \left[e(t) + \tau_d \frac{de(t)}{dt} + \frac{1}{\tau_i} \int_0^t e(\tau) d\tau \right] \tag{2.1}$$

$$e(t) = u(t) - u(t-1) \tag{2.2}$$

and the transfer function of equation (2.1) is given by equation (2.3)

$$C(s) = K_p \left(1 + \tau_d s + \frac{1}{\tau_i s} \right) \tag{2.3}$$

where: u(t) is the desired output, e(t) is the error between the set point and the actual output, τ_d is the derivative time, τ_i is the integral time and Kp is the proportional gain.

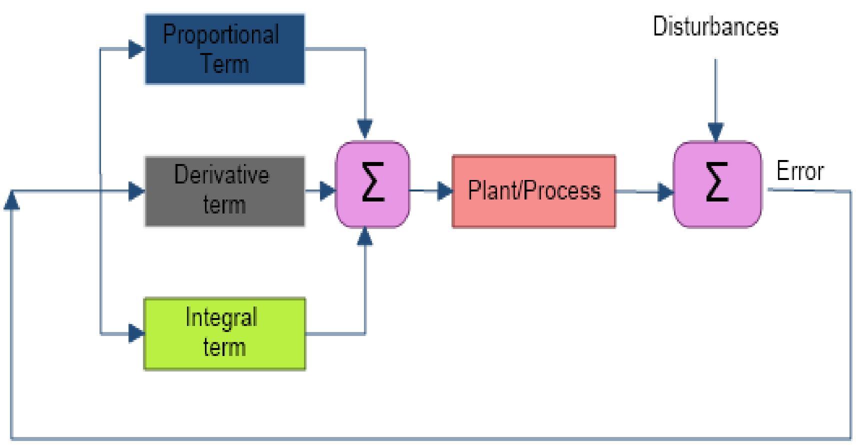


Figure 2.3. Block diagram of a PID controller [3]

The obtained error between measured values and set point is corrected using the three parameters. The proportional term makes a correction proportional to the current error. It multiplies the error by a constant parameter called proportional gain constant. A high proportional gain constant causes an unstable power system while a small gain leads to low sensitive controller [8]. The integral parameter corrects the accumulated error over a specified time domain. Both the magnitude and the duration of the error are corrected with the integral parameter. It eliminates the steady state error that was previously caused by a proportional controller. The integral parameter measures the speed at which the set point reaches the process variable. A controller with high value of the integral parameter may lead to instability. The derivate improves system stability and settling time by predicting the system behavior. It evaluates the rate of change of the error for a specified time period.

2.1.5. Theory on Fuzzy Logic

Classical logic theory is based on binary output where an element is considered to be only false or true. However, fuzzy logic is viewed as a generalization of the classical crisp logic theory. It has been extended to handle the concept of partial truth. An element is considered not only to be false or true but there is a degree of truth and false: membership. Classes of objects are of no sharp boundaries. The membership function is extended and comprised all real number between 0 and

1. Briefly, fuzzy logic introduces vagueness by eliminating the sharp boundary dividing members from nonmember in a set [5].

2.1.5.1. Fuzzy Logic Architecture and Design

Fuzzy logic theory has led to the implementation of fuzzy logic controllers which consist of four main components: fuzzification and defuzzification modules, a knowledge base and an inference engine. Figure 2.4 shows the architecture of a fuzzy logic controller.

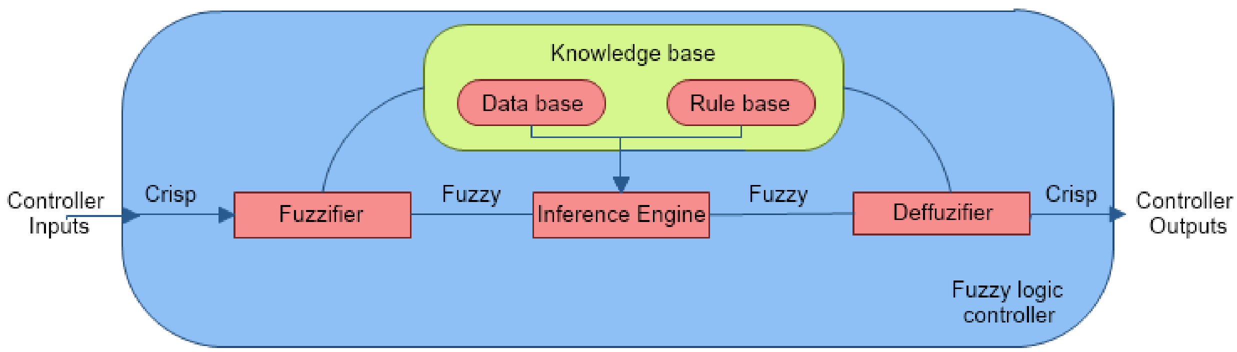


Figure 2.4. Architecture of a fuzzy logic controller [5]

In this architecture:

- Crisps values measured from the process are transformed into linguistic value through *fuzzification* module with the help of membership functions.
- *Knowledge base* stores definitions of each membership function and provides necessary rules to the inference engine.
- Rules are executed through the *inference engine* which simulates operator's experience and makes control actions.
- Linguistic variables outputs from the inference engine are converted back into numerical value through *defuzzification module*.

A procedure for fuzzy logic controller design is proposed [5], [27], [28] and in general, the design process consists of five important steps which are described below.

Selection of Control Variables

A control system evaluates input variables in order to provide output. A first step in controller design is to clearly know system requirements. These requirements include control variables (inputs and outputs) definition. In common, dynamic fuzzy logic controller design uses the error, the change of error or the integer of error as input variables in order to obtain a desired output.

Definition of Membership Functions

Fuzzy logic is based on linguistic variable rather than on numerical value. Measured numerical values are processed and converted into linguistic variable using well defined membership functions. They allow assigning to each numerical value a certain degree of belonging to the universe of discourse. Practically, a membership function for a fuzzy set B on the universe of discourse X is defined as $\mu_B\colon X \to [0,1]$, each elements of X is mapped to a value between 0 and 1 called the degree of membership of the element in X to the fuzzy set B.

Numerous shapes of membership functions have been identified from the literature: Singleton, flat-shaped, rectangular, triangular, Trapezoidal, Gaussian and so on. Application and performance specifications determine number and shape of suitable membership functions. Triangular and trapezoidal shaped membership functions are the commonly used.

Rules Creation and Inference

Rules infer output variables based on input variables. Fuzzy rules set relations between fuzzy sets and are of *IF…THEN* form. They consist of three components: a premise, an implication and a consequent. For example, the rule *IF A is X THEN B is Y*, has: "*A is X*" for premise or antecedent, "*B is Y*" for consequent and "*IF premise THEN consequent"* for implication. Where *A* and *B* are linguistic variables respectively defined by *X* and *Y* fuzzy sets in the given input/output space (universe of discourse). Fuzzy rules are represented in form of matrix for process with multi-inputs/outputs and the dimension of the matrix is determined by the number of defined fuzzy sets

Fuzzy rules interpretation involves three steps: premise evaluation, implication action and aggregation action. A rule may possess conjunctive premise or disjunctive premise. Premise evaluation consists of checking the condition on the antecedent in order to deliver a single number. Implication applies the result to the consequent and aggregation combines results of all rules in one single fuzzy number. The process flow is shown on Figure 2.5. *A and B* are antecedents which are combined and inferred in order to deliver the total output *C* for the considered rules.

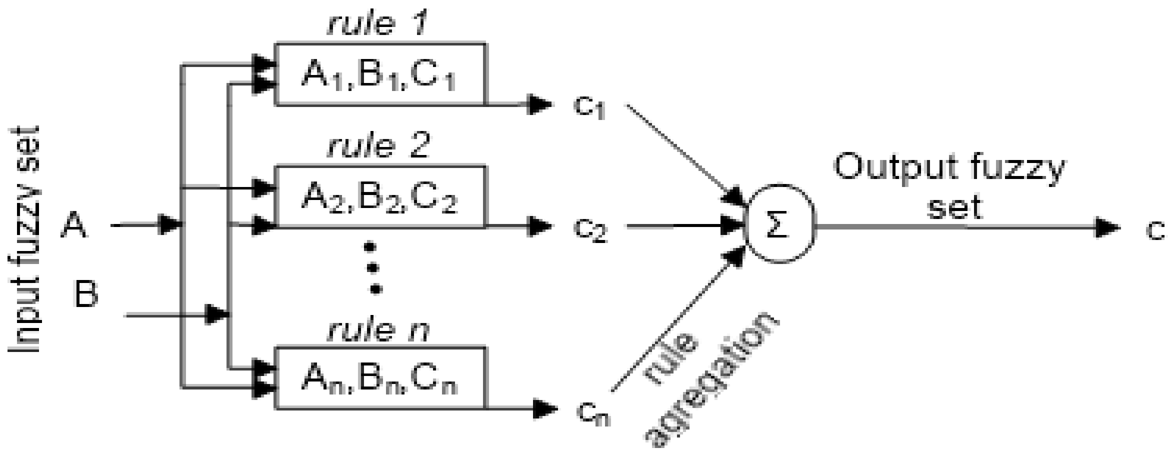


Figure 2.5. Fuzzy logic rules inference and interpretation [5]

Inference Engine

Fuzzy inference is the process of mapping inputs into output by using fuzzy logic. Control decisions are taken during this step. Fuzzy inference process involves membership definition, fuzzy logic premise evaluation, implication and aggregation and fuzzy logic rules creation.

Commonly used fuzzy inference engines developed in the literature include: Mandani-type fuzzy logic engine and Takagi-Sugeno fuzzy inference system [5], [7], [9], [29]. These techniques are discussed in the following fuzzy modeling section.

Defuzzification Process

The inference engine provides a fuzzy set or its membership function as a result. The controller is unable to use this information for operation. A crisp value should be obtained from the obtained fuzzy set. Defuzzification is the process to convert fuzzy set back to crisp values which are readable by the controller.

Researchers have proposed many defuzzification techniques [5], [7], [29], [30]. They include: center of gravity or center of area, max-membership method, weighted average method, middle of maxima method, center of sum and so on. The most commonly used defuzzification technique is the center of gravity.

2.1.5.2. Fuzzy Logic Modeling

The comprehensive dictionary of electrical engineering defines fuzzy logic modeling as the linguistic description of rules based on the plant's dynamic behavior and its control objective [31]. Rules may be obtained from engineer, designer or operator's experience and knowledge on the process, understanding of the dynamics behavior of the process or by using rule generation methods (self-learning fuzzy logic controllers). Mostly used modeling techniques include, but not restricted to, Mandani and Takagi-Sugeno modeling techniques.

It is generally accepted that the first real fuzzy logic implementation was based on Mandani modeling. It Maps inputs data to inputs membership functions, uses input membership functions to formulate rules and make decision. From these rules, fuzzy output membership functions are generated and converted back into a single numerical value readable by the controller. Mandani fuzzy modeling has been widely used by engineers and researchers due to its simplicity and easy of practical implementation. However, such inference systems have been shown heuristic and are model free [32]. Furthermore, they are based on fixed memberships functions and rules are predefined by the operator based on its understanding of the dynamic behavior of the process. Therefore, Mandani fuzzy models are seemingly not able to tackle system stability issues.

Takagi-Sugeno modeling was introduced in order to model nonlinear and more complex power systems where parameters are ever changing and the model is not specific. Takagi-Sugeno modeling is well known as a powerful universal tool for function approximation. Comparatively to Mandani-type, the Takagi-Sugeno modeling is more computationally efficient and provides a theoretical foundation to represent complex nonlinear systems more accurately. Based on its function approximation capability, a number of stability analysis and controller technique approaches have been developed. Takagi-Sugeno modeling is therefore given the capability of working well with optimization and adaptive control technique. Thus, when combined with adaptive controls, Takagi-Sugeno modeling seems to exhibit satisfactory well dynamics by improving the overall power system stability.

2.2. Literature on Topic

Fuzzy logic was applied to MHPPs in [33] by combining roles of the Electronic Load Controller (ELC) and servomotor in one controller that was able to maintain a steady state voltage and frequency regardless to changes occurring in the power system. The research was oriented to water management and two inputs for fuzzy logic were used: the gate position and the electrical power dissipated on a ballast load. The MHPP and components were modelled using transfer functions which don't perfectly mimic the dynamic behavior of the system. However, this research work used nonlinear equation to model the MHPP's components and the rotor speed deviation (difference between the electrical and mechanical power) and its change were used as inputs to the fuzzy logic controller.

A fuzzy logic controller was designed in [3] for synchronous generator terminal voltage control. All components (excitation, amplifier and generator) were modeled with simple first order transfer function. The model may not be practically realizable and can only be used for a first approximation of the system behavior. This research used a complex model of turbine, generator and excitation system that reflects the near reality as modeled in Matlab/Simulink.

2.3. Literature on Method

Different types of algorithms are used to implement the AVR and AGC in MHPPs. It may be implemented using conventional PID methods, robust methods, adaptive methods, nonlinear methods or optimization and intelligence methods as reviewed in [26]. Each these methods possess its merits and demerits in regard to the application.

A PID controller is designed depending on the system dynamic behavior. A power system, for example, is of specific dynamic behavior. The controller should be adjusted and its parameters selected in order to meet the desired dynamic performance. This is known as PID controller tuning. Efforts for PID parameters tuning and optimization have been shown in the area of power system control. In accordance to the process and performance specification, a certain PID tuning type can be chosen: manual, Ziegler-Nichols, Cohen-Coon, Software tuning and modern heuristic approaches.

A particle swarm PID parameters tuning optimization for voltage control was proposed in [15]. Particle swarm technique iteratively improves a candidate solution in order to optimize a process regarding to a certain performance specification [34]. A predefined new fitness function regarding to power system dynamic performance in term of automatic voltage control was also evaluated. Moreover, disadvantages of using Ziegler-Nichols methods in automatic voltage control were founded. Though its common application in different processes; Ziegler-Nichols method was shown not suitable for Automatic Voltage regulation [16]. It shows high overshoot, uses trial and error techniques hence it is time consuming and may leads to overvoltage. The usage of particle swarm PID optimization approach; results in interesting performance improvement. However, when the power system is subjected to multiple disturbances and uncertainties, PID controller may show low robust ability as compared to controllers based on robust methods.

Robust control method uses different techniques to improve the dynamic performance of the power system in term of:

- Optimal control against disturbances;
- Robust control of uncertain loads and nonlinear systems;
- Disturbances rejection and closed loop shaping.

Number of investigations have been carried out in this field [16]–[18], [35]. Delassi used the robust fractional order PID controller in the AGC of multi-area power system in [18]. Here, nonlinear constraints are introduced and the controller's optimal parameters were tuned through the differential evolution evolutionary algorithm. Results showed a high improvement in term of performance index and dynamic performance in comparison to other optimization techniques. Furthermore, the investigated controller demonstrated effectiveness through robustness analysis against sudden load change and large parameter variation. Vijay sharpened this study by responding to high requirement specification such as loop shaping [35]. The controller used H_∞ control problem with bounding conditions. It resulted in a more robust and optimal controller that would maintain the system stability for a certain fixed range of parameters variations.

Power system suffers from its stochastic characteristic. Parameters keep changing for every period of time. This introduces more uncertainty and nonlinearity. More sophisticated control methods should be implemented in response to this question. In recent years, researchers have proposed adaptive control methods [24]. They are used to design controllers that learn the system's parameters at any instant as could be observed through the use of adaptive methods.

Small oscillations in frequency and voltage may lead to overall power system collapse. Therefore, controllers should be able to sense online changes and provide suitable output. Adaptive controllers are designed for this objective. They self-learn the system parameter to adapt for variations and initiate output that maintains the power system stability. Adaptive control techniques involve: model reference adaptive control, self-tuning controllers, sliding mode adaptive control and robust adaptive control.

Adaptive technique to control voltage and frequency of wind power system was applied in [24]. A conventional PI controller was firstly designed and problems associated with uncertainty were solved using the self-tuning controller method. The PI controller parameters were self-tuned in order to cope to the changing load parameters in the power system. However, in [36] Hussein applied adaptive control technique to design a stabilizer for a multi-machine power system. This study demonstrated the effectiveness of adaptive control method in damping local and inter-area oscillations occurring due to switching loads and power system disturbances.

The range of which satisfactory well dynamic performance is achieved depends upon the system and its problem specification. Some applications may tolerate relatively poor performance while others only accept high requirements. Power systems are complex, nonlinear and have high requirements in term of dynamics.

In addition to adaptive control, nonlinear control methods are used. They attempt to solve problems associated with complexity, nonlinearity and to further respond to the high requirement characteristic of the power system. Examples of how to solve power system nonlinearity are found in [37] and [38]. In [38] Vedam used two nonlinear formulation methods; the discrete-time predictive control and the feedback-linearizing formulations. It was concluded that the designed controller could potentially improve the power system dynamic performance. However, further researches based on intelligence control methods try to study the subject using modern techniques.

Progress in electronics and computer science has allowed developing control methods based on artificial intelligence. Methods such as expert system, genetic algorithm, artificial neural network, differential evolution, fuzzy logic and simulated annealing are considered with great attention.

Artificial intelligence uses these intelligent techniques to mimic human's behavior and intelligence. Controllers based on artificial intelligence are capable of learning the system and react proportionally. Examples using expert control system and artificial neural network techniques are found in the literature.

Artificial neural intelligence for real time parameters self-tuning of a conventional power system controller was used in [39]. An attempt to change loading conditions in the system and evaluate its robustness and stability was carried out. Artificial neural intelligence was shown to provide better results. Other application to voltage control are found in [40] where expert system was used in order to minimize loss, voltage deviation and number of transformer tap changing. Although it was not used to regulate generator voltage output, this study emphasized the fact that expert system in combination with Supervisory Control and Data Acquisition (SCADA) system may be useful for operator's decision making in power system voltage control. However, expert system seems to be inefficient. It lacks flexibility and crisp representation of human experience is very difficult to implement.

Therefore, simple and flexible artificial intelligence techniques have been developed. Fuzzy logic controller is easy to implement and currently attracting a number of researchers.

A number of investigations on fuzzy logic application to power system control have been carried out. Anower in [8] proposed and developed a fuzzy frequency controller for the improvement of dynamic performance of a single area power system. The proposed controller was found to show well dynamics in comparison to conventional controllers. Narayan deepened this study in [41] by extending the area of control. He used fuzzy logic controller for robust control of frequency and tie-line power flow in a multi-area power system. Comparison based on robustness between conventional and fuzzy controllers was studied and the optimal fuzzy logic controller was designed in Matlab/Simulink.

Efforts of applying fuzzy logic for voltage or generator excitation control have been shown in [3], [42]–[44]. Most of these works focus on the improvement of power system stability. They use comparative methods in order to show the effectiveness of the proposed controller. In [43] Nema combined a block of IEEE excitation control and the fuzzy logic controller with simulation in Simulink/Matlab. A great improvement was demonstrated in the power system stability and oscillation damping. However, Okozi compared the dynamic performance obtained by using PID controller and self-tuning fuzzy PID controller in [3]. The best result was obtained through the Self-Tuning Fuzzy PID controller.

2.4. Literature Gap

Instabilities are common problem in power system frequency and voltage control. Installing a power system controller seems to be an optimal solution in damping oscillations and improve power system dynamics. Most of power system controllers use the conventional control approach based on a linear mathematical model and fixed power system parameters. However, power systems are of dynamic nature and their parameters change over time. Furthermore, the power system is complex, nonlinear and its mathematical model is sometimes unavailable. Conventional approaches based on fixed-parameters appear unable to provide satisfactory dynamics for such complex systems.

Recent researches introduced new techniques in power system control [5], [13], [29], [32], [38], [40]. Robust methods [35], adaptive control [36], expert system, optimization [40], nonlinear and intelligence methods have been developed [37]. Each technique possesses its own feature and capability. Robust methods suit for systems with low dynamic performance specifications. They become unreliable and difficult to implement for system with high degree of uncertainty and nonlinearity. Studies involving intelligence techniques are more promising and have been considered with great attention. Expert and adaptive controls are being used in order to learn the system's parameters and improve its dynamics in regard to changes occurred. They provide a mean to solve problems related to the lack of system's model and high degree of complexity, nonlinearity and uncertainty. Complexity and computation burden become an issue when dealing with adaptive and expert control systems.

Another method of intelligent technique is the fuzzy logic. Indeed, fuzzy logic control is a new area of research in hydroelectric power system aiming to design controllers with low computation burden and low complexity for a considerable dynamic improvement. Recent development in research in this area have shown promising results. The literature reports a number of investigations oriented to study fuzzy logic in combination with conventional PID controllers or direct fuzzy logic according to certain specified dynamic performance. In this research, a new set of dynamic performance is defined and fuzzy logic in application to MHPPs is developed. A particular application to voltage and frequency control in MHHP is being investigated.

Table 2.1. Summary of the reviewed literature

AUTHORS	**TITLE**	**OBSERVATION AND RESEARCH GAPS**
ABERBOUR Juba *at al, (*2015).	Particle Swarm Optimization Based PID Parameters Tuning for the Automatic Voltage Regulator System	Effectively tuned the PID controller. Tuning techniques were based on the existence of an exact analytical models of the power plant. Which may not be available for complex systems.
Delassi *at al. (2018)*	Load frequency control problem in interconnected power systems using robust fractional PID controller	Added nonlinearity and uncertainty to model the power system and tested for robustness. Proposed controls algorithms were only suitable for systems with low dynamic performance requirements.
Issam Salhi (2009)	Fuzzy controller for frequency regulation and water energy save on Micro hydro electrical power plants	The research was oriented to water saving and transfer functions were used to mimic the dynamic of the MHPP. This study used nonlinear equation to model the MHPP and is oriented to both voltage and frequency controls but did not capture the linear approach in term of comparative analysis.
Okozi Okechuku (2009)	A fuzzy logic based automatic voltage regulator for alternator terminal voltage and reactive power control	The research was done for only voltage control and used only the alternator without using the turbine. In addition, all components were modelled using first order transfer function which may not reflect the near reality but this work is oriented to both voltage and frequency control and the MHPP is modelled with nonlinear equations in Matlab/Simulink.

Pimpa *at al.(2002)*	Voltage Control in Power System Using Expert System Based On SCADA System	Used techniques to learn system's parameters in order to solve problems related to the stochastic nature of the power plant These models may be complex to implement and are with computation burden. This research used a simple fuzzy logic controller that is based on the operator experience expressed though rules.
El-Hawary (1998)	Electric Power Application of fuzzy systems	The comparative analysis was based on a predefined conventional controller which was not tuned. In this work, the FLC was compared to a well-tuned PID controller.
Anower *at al (2006).*	Fuzzy frequency controller for an AGC for the improvement of power system dynamics	The study was only done for the automatic frequency control. This research work combines voltage and frequency studies.
Rakesh K. Nirmalkar and S.M. Deshmukh (2016)	Simulation of Optimized PID with Power System Stabilizer Using Matlab	Conducted an analysis of dynamic response of a power system with Conventional Controllers. In addition, a comparative analysis of PID controller to different other type of Power System Stabilizers was carried out. However, authors didn't consider the incorporation of Fuzzy Logic Controllers in the system. In this work, a comparative analysis of Fuzzy Logic Controller to all other conventional controllers is carried out.

In this research, these various problems and gaps are addressed by the design of an imbedded fuzzy logic controller which has improved the frequency and regulated the voltage in the Micro Hydro Power Plant.

CHAPTER THREE

METHODOLOGY

3.0 Introduction

This chapter presents performance specifications and gives details on MHPP and controller design considerations and procedures. A clear understanding and definition of the MHPP functioning and parameters design was performed priori to controller design.

In this research, a gradual design process is envisaged. A simple controller based on conventional approaches is first simulated in the considered MHPP with defined parameters. An improvement in the controller dynamic performance has been incorporated by improving the controller design algorithm. Therefore, a controller based on fuzzy logic is incorporated in the considered MHPP. Validation of the FLC is established through comparison of dynamic performance output of the conventional controller.

3.1. Performance Specifications and Basic System Architecture

3.1.1. Performance Specifications

The main objective of this work was to design controllers for MHPPs in order to ensure their availability, stability and flexibility during operation. These three key characteristics define goals that should be met when designing the controller. In this research, only stability considerations were studied. It is assumed that the improvement of stability has an impact to availability and flexibility improvement: a stable power system is available and flexible.

The controller should be able to bring the system back to its steady state after the occurrence of faults or disturbances. A properly designed controller should be able to bring the system back to its steady state condition in a short period of time with small overshoot [8]. In this research work, a controller that reduces the response time and the overshoot was designed.

The MHPP was simulated in steady state and values of voltage and frequency (speed) were observed. These values defined specifications that the MHPP should meet with small overshoot and quick response time.

3.1.2. Basic System Architecture

A typical hydropower plant consists of several elements among which there are turbine and generator. This study focuses on these two main components. The actual speed of the turbine's shaft is measured and regulated via the speed controller (speed governor) as depicted on Figure 3.1. Similarly the output voltage of the generator was measured and regulated via the automatic voltage regulator as depicted on Figure 3.1. Both controllers are based on the fuzzy logic theory. Details on each components of this design are given in section 3.2.

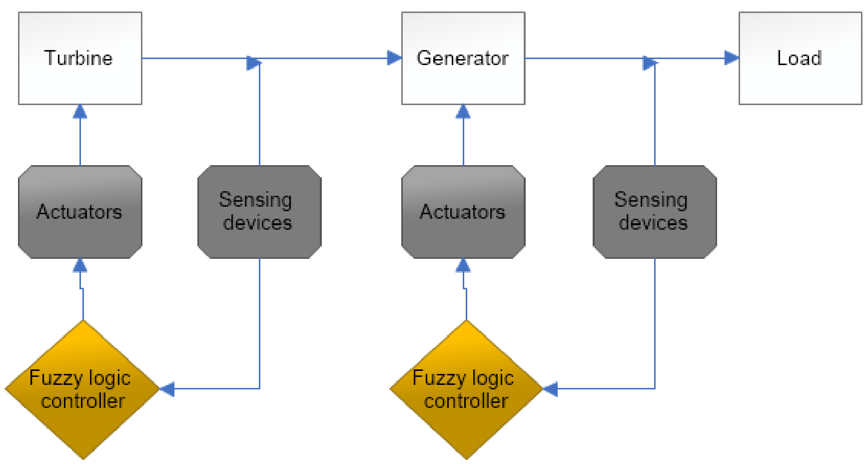


Figure 3.1. Basic system architecture (this work)

3.2 Design of the Considered MHPP

The power system is a highly nonlinear, stochastic and complex system whose stability is determined by different devices that participate in its construction. Each device possesses its characteristics and response rate. The knowledge of these characteristics would contribute in better understanding of the power system dynamic behavior and easy stability studies. A number of hydro power plants models have been proposed by several researchers [14], [45], [19], [46]. Most of models available in relevant literature are generally simplified and don't consider important parameters that greatly affect power system stability. Power system nonlinearity and complexity have to be considered in order to obtain the best dynamic behavior. In this research work, studies were conducted based on the model developed in [47] and its dynamic stability performance was improved by using a fuzzy logic controller. The hydropower power generating unit modeled in Matlab/Simulink 2018a is presented on figure 3.2.

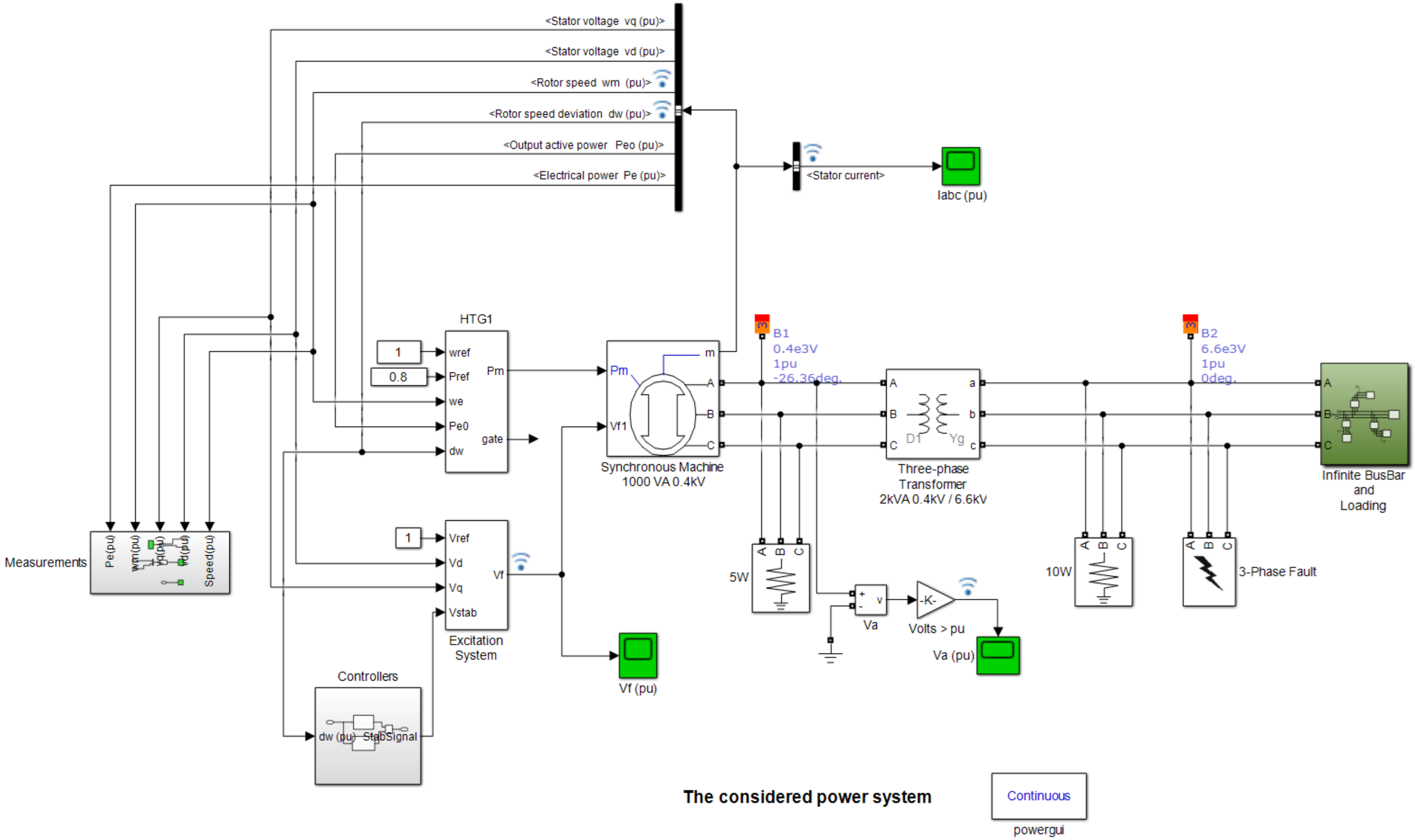


Figure 3.2. A screen shot of the MHPP under consideration

The MHPP consisted of:

A Hydro Turbine Governor Block (HTG)

The Hydro Turbine Governor shown on figure 3.3 consisted of a nonlinear hydraulic turbine, a servomotor and a governor based on conventional PID controller [47], [48].

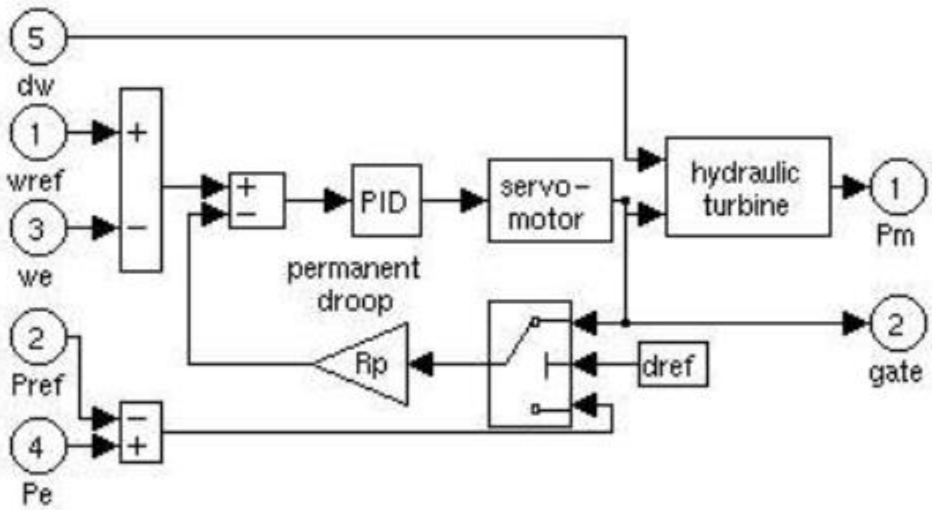


Figure 3.3. Model of the Hydraulic Turbine Governor [47]

where, *dw* is the rotor speed deviation (pu), *wref* is the speed reference (pu), *we* is the machine actual speed (pu), *Pref* is the reference mechanical power in *pu*, Pe is the actual power, Pm is the mechanical power output(pu), gate is gate opening in *pu* , *Rp* is the permanent droop and Pe is the actual electrical power (pu).

Values of parameters shown in figure 3.3 of the HTG model are given in Table 3.1.

Table 3.1. Parameters of the HTG model

Parameter	**Value**
Servo-motor [Ka Ta(s)]	[10/3 0.07]
Gate opening limits [gmin, gmax(pu) umin umax(pu/s)]	[0.01 0.97518 -0.1 0.1]
Permanent droop and regulator [Rp Kp Ki Kd Td(s)]	[0.05 1.163 0.105 0 0.01]
Hydraulic turbine [beta Tw(s)]	[0 2.67]
Initial Mechanical power (pu)	0.81216

Figure 3.4 and figure 3.5 respectively show the model of the nonlinear hydraulic turbine and servomotor modelled by a second-order system.

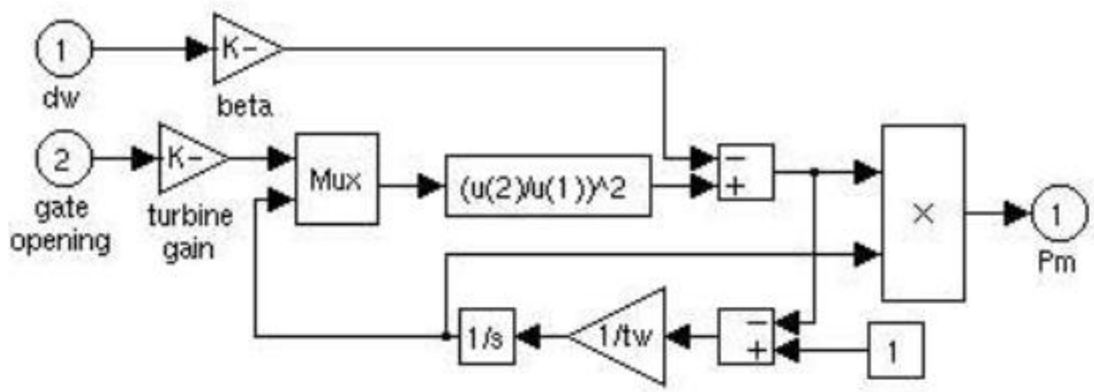


Figure 3.4. Nonlinear system modelling the hydraulic turbine [47]

where, *Tw* is water *starting time constant (pu)* which is a constant proportional to the length of the penstock and the rated speed, *dw* is rotor speed deviation (pu), *beta* is a constant.

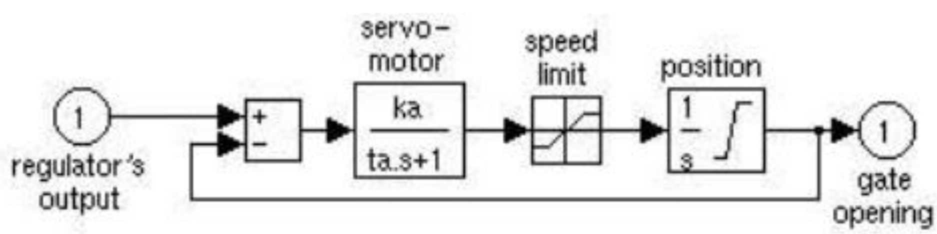


Figure 3.5. Second order system to represent the servomotor [47]

Equation 3.1 to Equations (3.5) were used to model the nonlinear hydraulic system as in [14];

$$P_m = U - U_{NL}\left(\frac{U}{A_T g}\right)^2 P_R \tag{3.1}$$

$$U_{NL} = A_T g_{NL} (H_0)^{1/2} \tag{3.2}$$

$$A_T = \frac{1}{g_{FL} - g_{NL}} \tag{3.3}$$

$$P_R = \frac{TurbineMWrating}{BaseMVA} \tag{3.4}$$

$$T_W = \frac{LU_r}{a_g H_r} \tag{3.5}$$

where, U is the rated speed, U_{NL} is the no load speed (or speed at steady state), A_T is the turbine gain (beta), P_R is the rated power (*pu*), g is the normalized gate opening position, g_{FL} is the gate position at full load, g_{NL} is the gate position at no load, Tw is the water starting time, L is the length of the penstock, Ho is the initial steady state value the hydraulic head at wicket gate, a_g is the acceleration due to gravity and P_m the mechanical power.

A Synchronous Machine Block

The synchronous generator was connected to the HTG block by means of the mechanical power output. It operates in generator mode and modelled based on model find in [49]. The model take into account the dynamic of the field, stator and damper-winding. In [49] the direct and quadratic axes of synchronous machine dynamic model is modelled with the following equations:

$$V_d = -i_d R_s - \omega \psi_q + \frac{d\psi_d}{dt} \tag{3.6}$$

$$V_q = -i_q R_s - \omega \psi_d + \frac{d\psi_q}{dt} \tag{3.7}$$

$$V_0 = -i_0 R_0 + \frac{d\psi_0}{dt} \tag{3.8}$$

$$V_{fd} = i_{fd} R_{fd} + \frac{d\psi_{fd}}{dt} \tag{3.9}$$

$$0 = i_{kd} R_{kd} + \frac{d\psi_{kd}}{dt} \tag{3.10}$$

$$0 = i_{kq1} R_{kq1} + \frac{d\psi_{kq1}}{dt} \tag{3.11}$$

$$0 = i_{kq2} R_{kq2} \frac{d\psi_{kq2}}{dt} \tag{3.12}$$

$$\begin{bmatrix} \psi_d \\ \psi_{kd} \\ \psi_{fd} \end{bmatrix} = \begin{bmatrix} L_{md} + L_l & L_{md} & L_{md} \\ L_{md} & L_{lkd} + L_{f1d} + L_{md} & L_{f1d} + L_{md} \\ L_{md} & L_{f1d} + L_{md} & L_{lfd} + L_{f1d} + L_{md} \end{bmatrix} \begin{bmatrix} -i_d \\ i_{kd} \\ i_{fd} \end{bmatrix} \tag{3.13}$$

$$\begin{bmatrix} \psi_q \\ \psi_{kq1} \\ \psi_{kq2} \end{bmatrix} = \begin{bmatrix} L_{mq} + L_l & L_{mq} & L_{mq} \\ L_{mq} & L_{mq} + L_{kq1} & L_{mq} \\ L_{mq} & L_{mq} & L_{mq} + L_{kq2} \end{bmatrix} \begin{bmatrix} -i_q \\ i_{kq1} \\ i_{kq2} \end{bmatrix} \tag{3.14}$$

where subscripts are defined as follow:

- *d*, *q*: d and q axis quantity
- *R*, *s*: Rotor and stator quantity
- *l*, *m*: Leakage and magnetizing inductance
- *f*, *k*: Field and damper winding quantity and $R_s, L_l, L_{md}, L_{mq}, L_{lfd}, R_f$ are respectively, stator resistance per phase (Ω), stator leakage inductance (H), direct-axis magnetizing inductance viewed from stator (H), quadrature-axis magnetizing inductance viewed from stator (H), leakage field inductance and field resistance.

Values of parameters for the Synchronous Machine block are given in table 3.2.

Table 3.2. Values of parameters for the Synchronous machine block

Parameter	**Value**
Mechanical Input	Mechanical Power Pm
Rotor type	Salient-Pole
Nominal Power	1000 VA
Line-to-line voltage	400V (1pu)
Frequency	50Hz
Stator Resistance (Rs (pu))	0.019
Inertia (s) and Pole pairs	2, 2
Generator type	PV

Initial conditions [dw, ia, ib, ic vf](pu)	[0 0.8 0.8 0.8 1.19167]
Active generating power (W)	800

The Excitation Block

This block provide excitation for the synchronous generator and regulate its terminal voltage output. The excitation block was implemented based on the model of a DC exciter in [48]. The main components that form the excitation system are the voltage regulator and the exciter. The exciter is represented by the following transfer function between the exciter voltage *Vfd* and the regulator's output *Ef*.

$$\frac{V_{fd}}{e_f} = \frac{1}{Ke + sTe} \tag{3.15}$$

The excitation block is shown on figure 3.6, where inputs and outputs are: *vref* is the desired value of the terminal voltage in *pu*, *vd* is the *vd* component of the terminal voltage in *pu*, *vq* is the *vq* component of the terminal voltage in *pu*, *vstab* is an input to be connected to a power system stabilizer for stabilization improvement and *vf* is the field voltage. Table 3.3 show values of the different parameters of components used the model of the excitation system (figure 3.6).

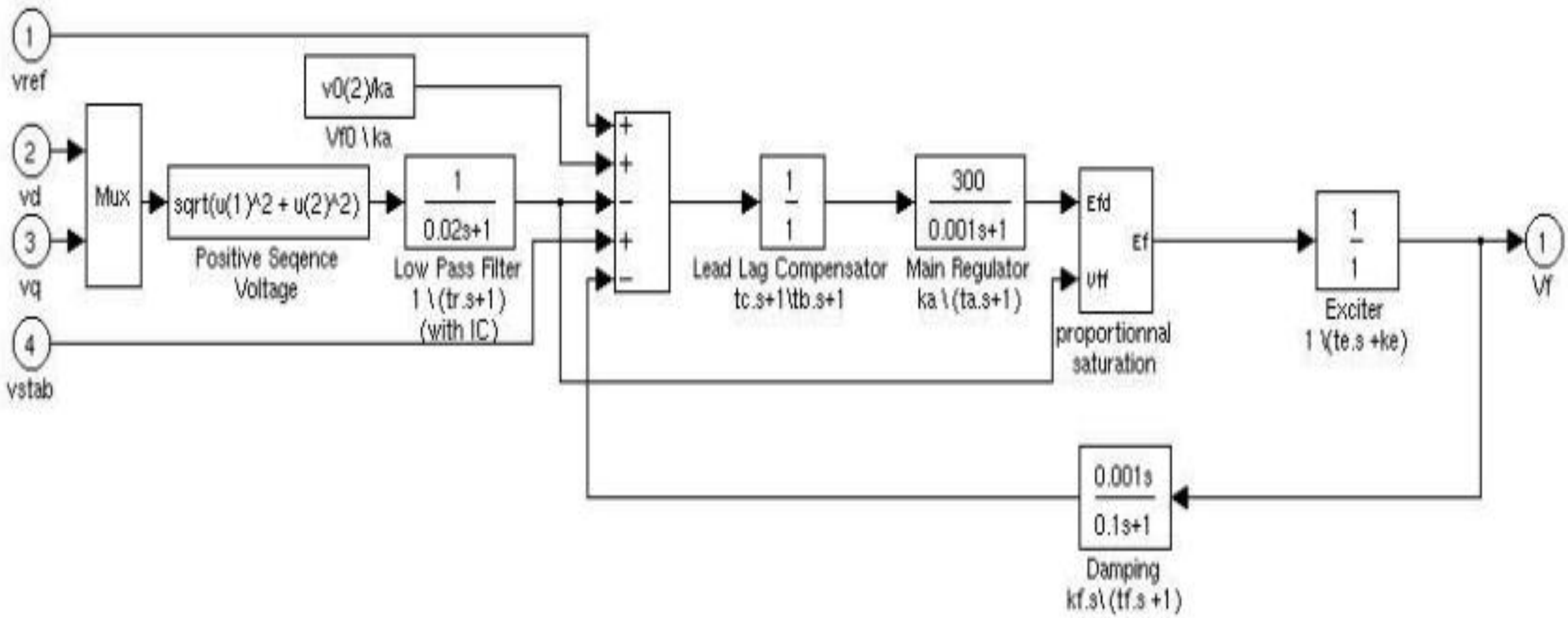


Figure 3.6. The excitation system block [48]

Table 3.3. Parameters of components used the excitation block

Parameter	***Value***
Low-Pass filter time constant Tr(s)	0.02
Regulator gain and time constant [Ka Ta(s)]	[300, 0.001]
Exciter [Ke Te(s)]	[1, 0]
Transient gain reduction [Tb(s) Tc(s)]	[0, 0]
Damping filter gain and time constant [Kf() Tf(s)]	[0.001, 0.1]
Regulator output limits and gain [Efmin, Efmax(pu) Kp]	[-11.5 11.5 0]
Initial values of terminal voltagEe and field voltage [vt0 (pu) vf0(pu)]	[1 1.1917]

A Transformer Block

This block implements a three-phase transformer using three single-phase transformers. The leakage inductance and resistance of each winding are given in pu based on the transformer nominal power and the nominal windings voltage (V1 and V2). Table 3.4 shows values of parameters for the transformer block:

Table 3.4. Values of parameters used in the transformer block

Parameters	**Values**
Type	Three single-phase transformers
Winding 1 connection	Delta (D1)
Winding connection 2	Yg
Nominal power and frequency [Pn (VA) fn(Hz)]	[2000 50]
Winding 1 parameters [V1 Ph-Ph(rms) R1(pu) L1(pu)]	[400 0.0027 0.08]
Winding 2 parameter [V2 Ph-Ph(rms) R2(pu) L2(pu)]	[6600 0.0027 0.08]
Initialization fluxes [phi0A phi0B phi0C] (pu)	[0.8 -0.8 0.7]

The Infinite Bus Bar with Loads

The infinite bus bar was modeled as a source of voltage with infinite impedance and loading were set to 0.4pu and 0.8pu active load with 0.2pu reactive load.

Controllers and Measurements Subsystems

Controller's subsystem contains the conventional and fuzzy logic controllers. Design process of the fuzzy logic controller is explained in section 3.1.2.

A Three-Phase Short-Circuit Fault Block

The Three-Phase Fault block implements a three-phase circuit breaker where the opening and closing times were internally controlled. The three-phase short-circuit fault was initiated at 0.1s and cleared 0.2s later.

3.3. Design of the Fuzzy Logic Controller

The fuzzy logic designer Matlab toolbox was used in order to design and optimize the FLC. Fuzzy Logic Designer is a Matlab tool that is found under the Matlab Apps in Matlab Software. The design procedure was, as below:

- Two inputs (the speed deviation (Er) and the change of speed deviation (CEr)) were used to feed in the FLC. The output was a stabilizing signal (Vfout) that should be sent to the excitation or servo motor in order to take proper actions.
- An interval of discourse (scaling factors) was chosen for input and output signals.
- Crisp values were transformed into fuzzy linguistic variables through the usage of seven triangular membership functions for both signals (inputs and outputs).

Figures 3.7, 3.8 and 3.9 represent membership functions for the error, change of error and Vfout signals, respectively. In these Figures; membership functions are represented by:

- NM: Negative Medium
- N: Negative
- Z: Zero
- P: Positive
- PM: Positive Medium
- PB: Positive Big

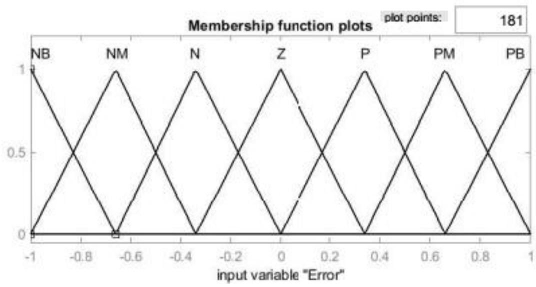


Figure 3.7. *Membership functions of the error*

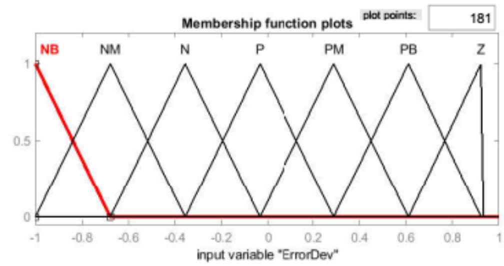


Figure 3.8. *Membership function of the change of error*

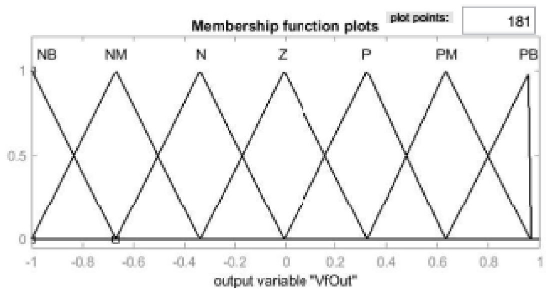


Figure 3.9. *Membership functions of the output*

- Rules were set using the Takagi-Sugeno fuzzy inference system. 49 rules were elaborated depending on the experience with the system and proper understanding of controller actions. These rules are shown on the rule's matrix of Table 3.5 and in Appendix A and B (Fuzzy Logic Algorithm and Fuzzy Logic Rules Viewer). A 3D plot, shown on figure 3.10 representing relationship between error, change of error and Vfout was generated.

Table 3.5. Rules matrix table

Er/CEr	***NB***	***NM***	***N***	***Z***	***P***	***PM***	***PB***
NB	PB	PB	PB	PB	PM	P	Z
NM	PB	PB	PB	PM	P	Z	N
N	PB	PB	PM	P	Z	N	NM
Z	PB	PM	P	Z	N	NM	NB
P	PM	P	Z	N	NM	NB	NB
PM	P	Z	N	NM	NB	NB	NB
PB	Z	N	NM	NB	NB	NB	NB

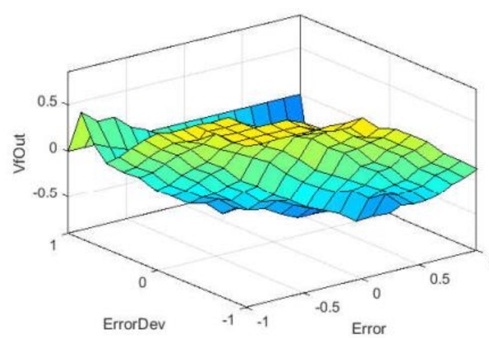


Figure 3.10. *Control surface*

- The centroid method of deffuzification was used in order to transform fuzzy linguistic values into crisp values that is used to control the system.

A flow chart showing the working process of fuzzy logic controller is shown on figure 3.10. The goal is to make the error and the change of error reach zero in a short period of time with small overshoot.

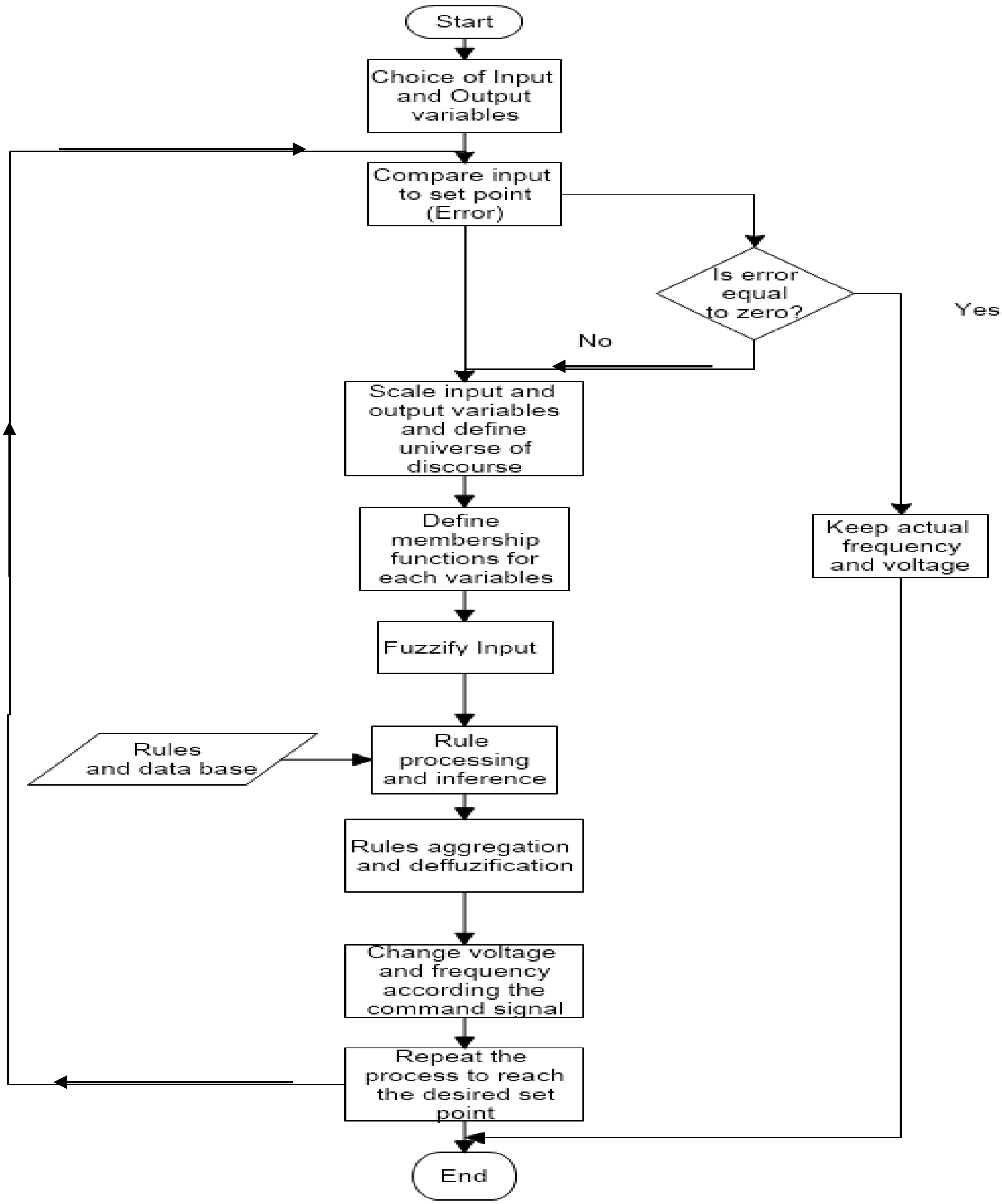


Figure 3.11. Flowchart showing the working process of FLC

3.4. Evaluation of the Dynamic Performance

3.4.1. Definition of Terms

The response time of a parameter defines the time required for the response to reach and remain in a specified error band about the steady state.

The peak overshoot is the ratio between the maximum response at the first peak time to the desired response value,

$$Pov(\%) = \frac{Pr_1}{refR} \times 100 \qquad (3.16)$$

where: $Pov(\%)$ is the peak overshoot in percent, Pr_1 is the peak response at the first time and $refR$ is the reference or desired response at first time.

3.4.2. Evaluation of the Dynamic Performance

The dynamic performance of the designed controller was evaluated in term of stability performances and robustness. Stability performances included transient tests and performance tests. For each test, the dynamic behavior was measured through the voltage and speed response time and overshoot.

Table 3.5 summarizes tests that were conducted in order to study the dynamic performance of the controlled MHPP.

Table 3.5. Tests conducted for the dynamic performance evaluation

Performance tests	***Actions***	***Measured or observed parameters***
Performance stability	Step load change *(from 0.4pu to 0.8pu active power)*	Speed deviation, terminal voltage, electrical torque and field voltage: Response times (s) and peak overshoot (%)
Transient stability	Three phase short circuit fault *(0.1s to 0.3s)*	Speed, terminal and field voltage: Response time and peak overshoot
Robustness	Change of the synchronous machine's inertia *(from H=2s to H=3s).* Change of operating conditions *(from 0.6pu to 0.8pu active power)*	Speed deviation, electrical torque, field and terminal voltage: Time to response and peak overshoots

3.5. Comparison of Dynamic Performance and Validation of the Controller

Figure 3.12 shows how both conventional and fuzzy logic controllers were incorporated in the MHPP. A manual switch was used to connect either the fuzzy logic controller or the conventional PID controller.

The first step consisted in evaluating the dynamic performance of the MHPP controlled with Conventional PID controller. Then the dynamic performance of the same MHPP controlled with fuzzy logic controller was evaluated. A comparative analysis was carried out and MHPP controlled with fuzzy logic was validated for its stability improvement in the considered MHPP. This validation was carried out in Matlab simulation environment Simulink 2018a. The fuzzy logic tool was chosen because of its rules approach, simplicity and practical knowledge base. It measures real time event and doesn't require the exact mathematical model for its realization. Results of the

Fuzzy Logic Controller incorporated in the power system and compared to Conventional Controllers is seen in Chapter 4.

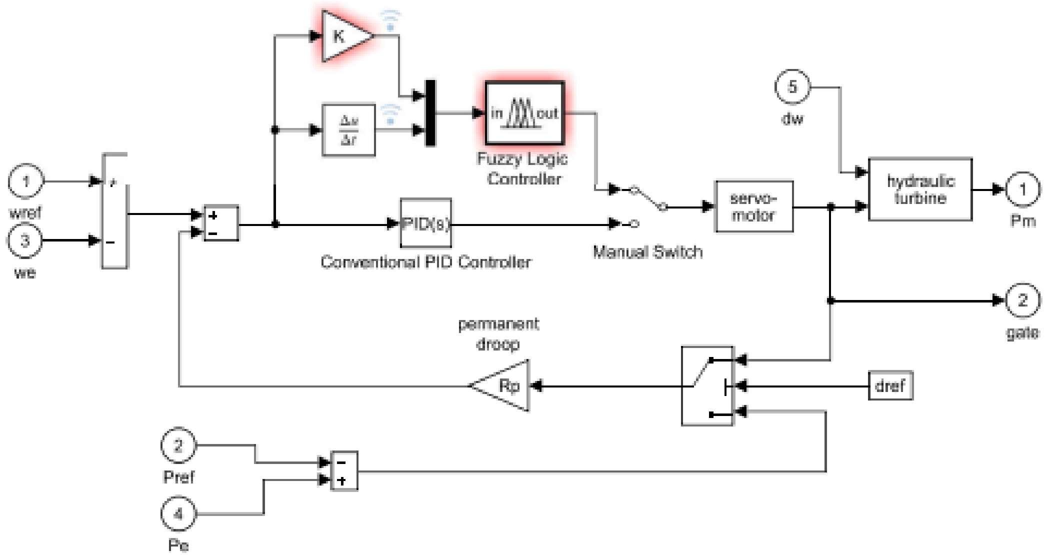


Figure 3.12. Implementation of both PID and FLC in the MHPP

CHAPTER FOUR

RESULTS AND DISCUSSION

4.0. Introduction

This chapter describes results obtained during simulations and attempts to verify the effectiveness of the proposed solution for the stated problem of this work. A set of simulations describing different scenarios and tests are presented both for speed (frequency) and voltage control. Performance stability, transient stability and robustness tests are presented for each type of controller. Effects of disturbances on the power system are observed through speed, speed deviation, terminal voltage, field voltage or electrical torque parameters. The stability is then measured through the response time and peak overshoot. A discussion leading to determine the extent to which the improved stability impacts to the overall efficiency and reliability of the hydropower system closes the chapter.

4.1. Steady State Simulation and Performance Specifications

The MHPP was simulated under steady-state conditions and load flow analysis was carried out. Table 4.1 presents values of considered parameters under steady state conditions. After the occurrence of disturbance, voltage and speed are supposed to regain their specified values in steady state.

Table 4.1. Specifications on values of parameters for a simulation in steady state

Parameter (or Machine)	***Value***
Active and reactive power (P and Q)	800W (0.8pu) and 0.48221 Vars (0.0004822pu) (1000KVA base)
Current [Ia, Ib, Ic]	1.1547 Arms (0.8pu) [-26.40˚, -146.40˚, 93.60˚]
Excitation field voltage (Vf)	1.1917pu (400V base)
Mechanical Power (Pmec)	812.16W (0.8122pu)
Synchronous Machine (SM)	PV bus with 0.1KVA 0.4kV nominal, H=2s
Terminal voltage (Vt)	1pu (0.4kV)
Torque	5.1704 N.m (0.8pu)
Voltage (Vab, Vbc, Vca)	0.4KV (1pu); [3.64˚, -116.36˚, 123.64˚]
Voltage to neutral phase (Van)	-26.36˚

The Speed deviation, the speed (frequency at times about 6.28), field excitation voltage and terminal voltage are depicted on figure 4.1. Their values are respectively: 0pu, 1pu, 1.1917pu and 1pu in steady state.

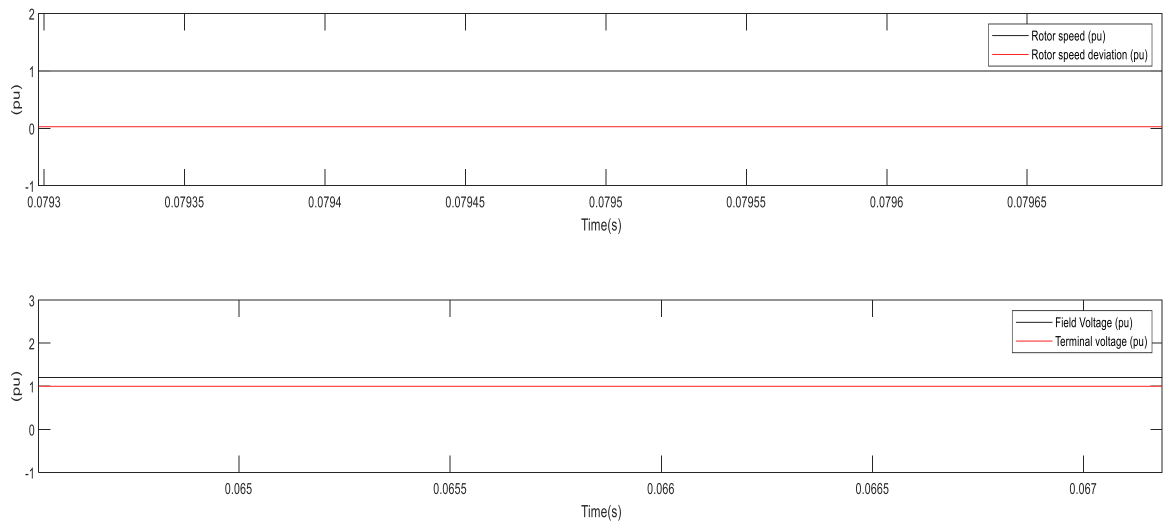


Figure 4.1. Values of parameters under steady state conditions

4.2. Evaluation of Dynamic Performance of the MHPP Controlled with Conventional PID Controller

The conventional PID controller was tuned to give the optimal performance for the specified performances and steady state shown in Table 4.1 of section 4.1. Tests of performance were conducted and results are shown from Figure 4.2 to Figure 4.7.

4.2.1. Transients Stability Tests

In order to study the transient stability of the system, a three phase short circuit fault was initiated at 0.1s and cleared at 0.3s. The dynamic behavior of the terminal voltage, field voltage and rotor speed deviation was observed. Figure 4.2 shows the dynamic response of the terminal voltage. During the short-circuit fault, the terminal voltage decreased to 0.2pu and passes through transients before settling at its reference value (1pu) after approximately 3.3s. The peak overshoot was calculated at 40% with Matlab/Simulink.

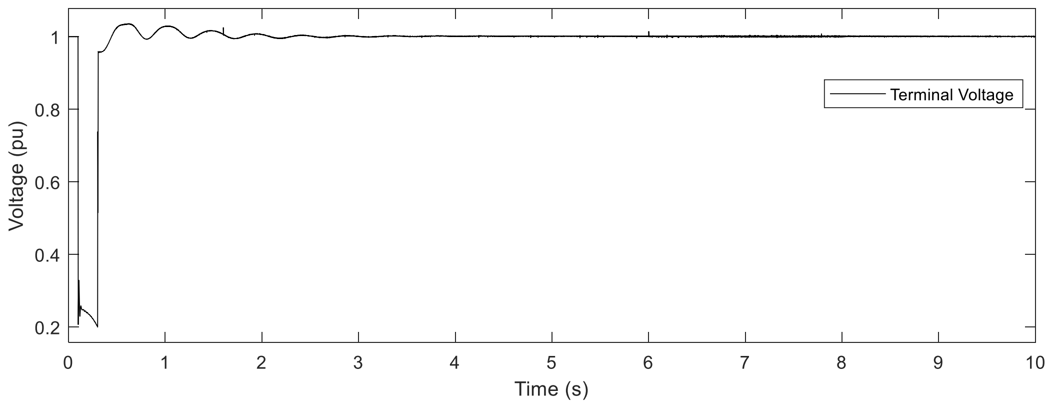


Figure 4.2. PID Terminal voltage response under 3 phase short-circuit test

Figure 4.3 shows the response of the excitation system due to three phase short circuit fault initiated in the system. It can be observed that during the fault (from 0.1s to 0.3s), the field voltage increased up to 11.4pu. At 0.3s, it started decaying and settled at 1.1pu after approximately 3.3s with an estimated overshoot of 40%.

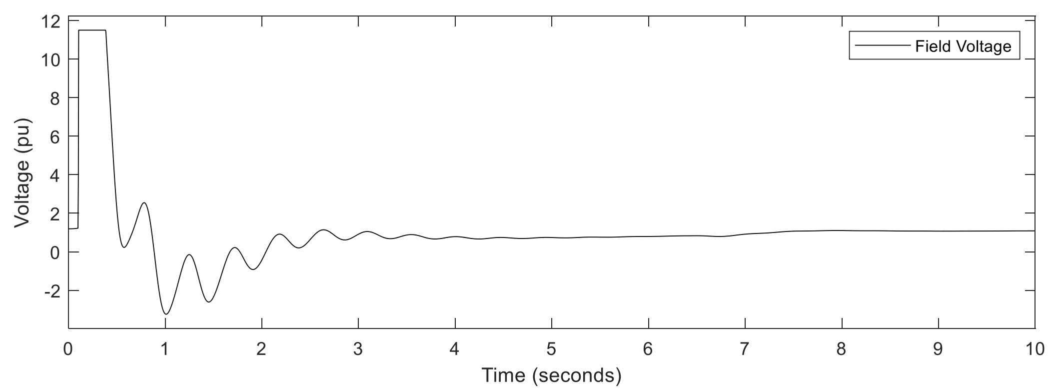


Figure 4.3. PID Field voltage or excitation voltage under three phases short-circuit

To show the response in frequency damping, the speed deviation was observed (figure 4.4). The fault initiated fluctuations of speed (frequency) for more than 5s with overshoot of 50% and peak value of 0.15pu. This implies that a peak speed of 1.15pu was reached during the occurrence of the fault. The steady state was then retrieved at 6s.

As compared to voltage response, the speed takes much longer to settle down due to the rate of wickets gate/valve opening limitation set to 0.1pu.

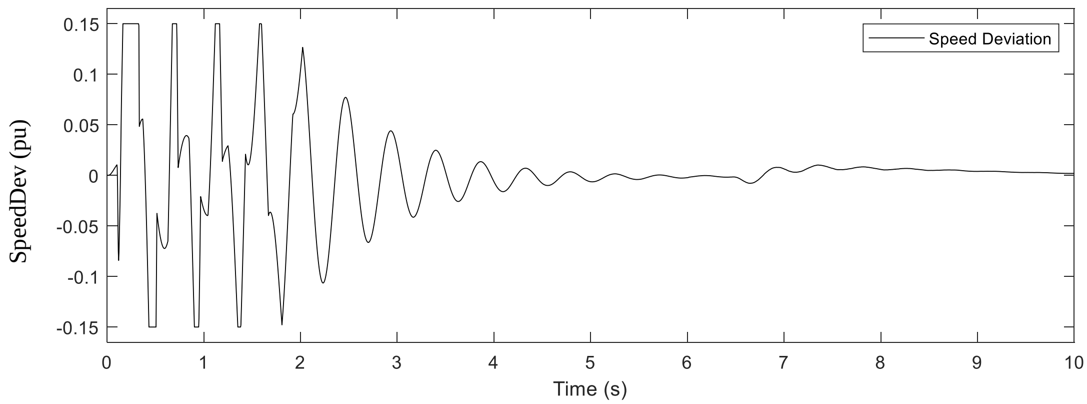


Figure 4.4. PID Speed deviation under three phase short circuit test

4.2.2. Performance Stability Tests

Performance stability tests consisted in changing the active demanded power of the system. An increase of 50% (0.4pu: 400W, at 1s) active power was initiated to the system functioning under the operating point of 0.4pu. Thus the system was required to reach a total active power of 0.8pu (800W) as it can be seen on Figure 4.5 by observing the electrical torque.

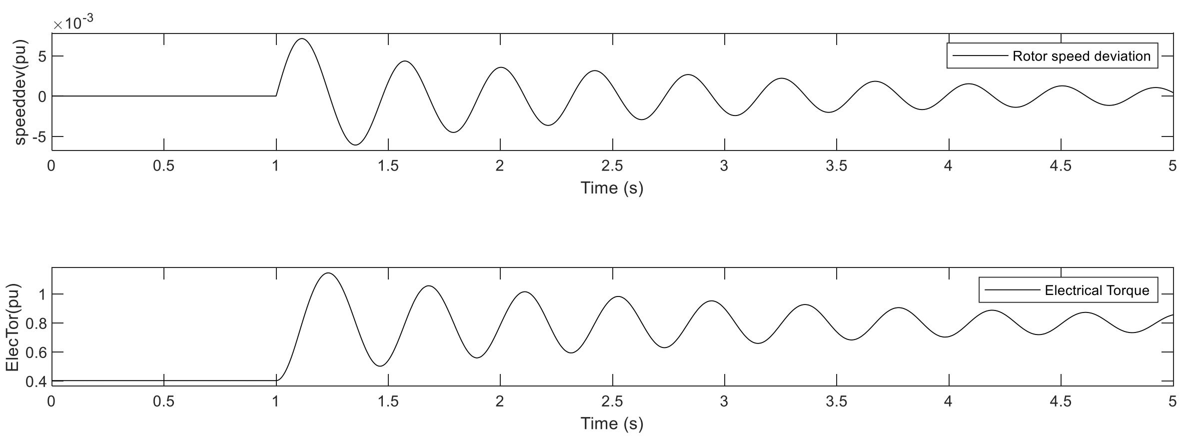


Figure 4.5. PID Performance stability test under changing load (0.4pu to 0.8pu at 1s): electrical torque and rotor speed outputs

The followings are observations from figure 4.5:

- The electrical torque goes through a series of oscillations before stabilizing to its new value of 0.8pu. Response time and peak overshoot are respectively evaluated to 8s and 52%.
- The rotor speed deviation response time is evaluated at 9s and 53.2% peak overshoot.

Figure 4.6 shows the response output of the terminal voltage and the field voltage.

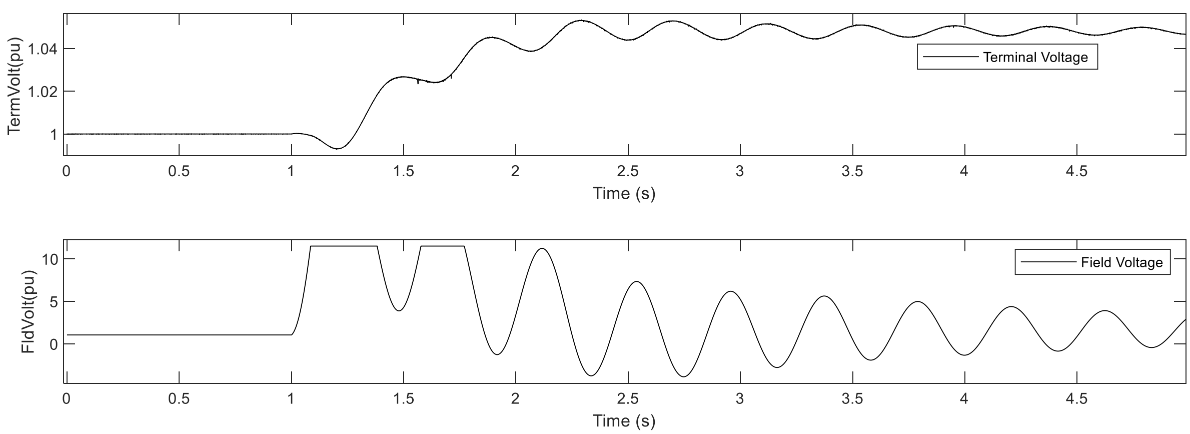


Figure 4.6. PID Performance stability test under changing load (0.4pu to 0.8pu at 1s): terminal and field voltage.

The followings are observations from Figure 4.6:

- The terminal voltage took 7s to reach the new operating point of 1.05pu with overshoot estimated to 42%.
- The field voltage reached 10.5pu and started decaying to reach its reference value (1pu). The settling time and peak overshoot were respectively, estimated at 7s and 39%.

4.2.3. Robustness Test

A number of tests were conducted with different synchronous machine inertia and power system operating conditions in order to test the system for robustness. Figure 4.7 and 4.8 show one of the realized tests for rotor speed deviation, electrical torque, terminal and field voltage parameters. In this test, the synchronous machine inertia coefficient was set to H=3s (the initial was H=2s) and the system operating condition was changed from 0.6pu to 0.8pu operating active power at 2s. The dynamic behavior of the power system is shown on Figure 4.7 (Electrical torque and speed deviation outputs) and Figure 4.8 (terminal and field voltage outputs).

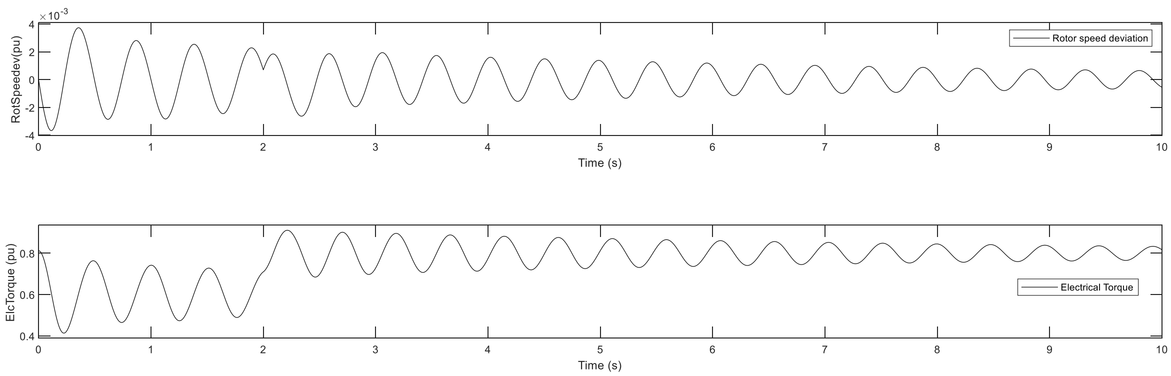


Figure 4.7. PID Robustness test under changing operating conditions and synchronous machine inertia for speed and electrical torque outputs

The followings are observed on Figure 4.7:

- The speed started oscillating before it goes to stabilization after approximately 14s with peak overshoot of 65%. It can be noticed that the system take longer to speed up because of the increase in the inertia constant.
- The electrical torque raised from 0.6pu to 0.8pu but fluctuates for 12s before it reaches the stability at the new operating point. The peak overshoot is estimated at 58%.

Figure 4.8 shows outputs in terminal and field voltage for the robustness test of the MHPP with PID controller.

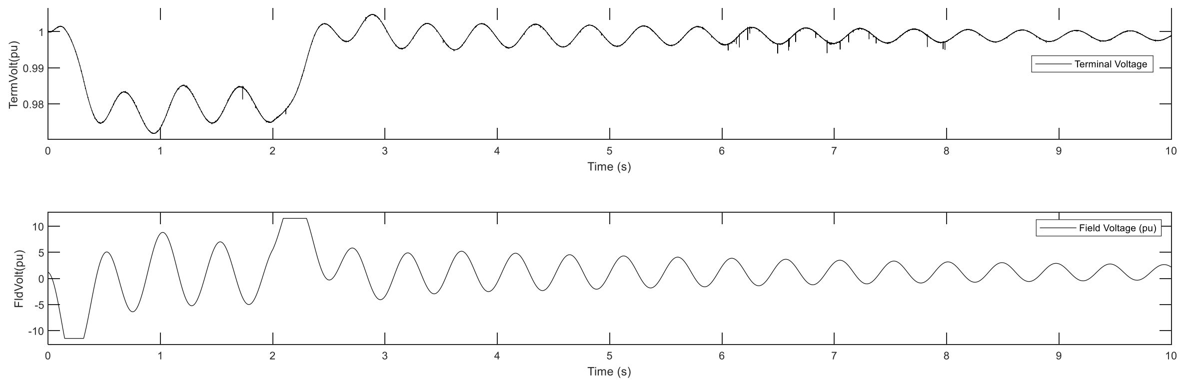


Figure 4.8. PID Robustness test under changing operating conditions and synchronous machine inertia for terminal and field voltage outputs

The followings are observed from Figure 4.8:

- The terminal voltage increased from 0.98pu to 1pu after fluctuation that last 10s with 52% peak overshoot.
- At 2s, the field voltage raised up to 10.4pu in order to compensate to the change in the system. Before it reaches the stability for the new operating point, fluctuations lasting 11s with 55% overshoot were observed.

4.2.4. General Observation on PID Dynamic Performance Evaluation

Table 4.2 summarizes results obtained for tests conducted in the previous section (section 4.2). It shows the dynamic characteristic (response time and peak overshoot) of each parameter under observation during the test. Speed deviation and speed (frequency) have the same characteristic with 0pu and 1pu as their respective reference value.

Table 4.2: Summary of dynamic performance of observed parameters for PID tests conducted

Parameters		***Dynamic characteristics***	
		Response time in sec.	*Peak overshoot (%)*
Terminal voltage	*Transient test*	3.3	36
	Performance test	7	42
	Robustness test	10	52
Field voltage	*Transient test*	3.3	36
	Performance test	7	39
	Robustness test	11	55
Frequency (speed) or speed deviation	*Transient test*	6	50
	Performance test	9	53.2
	Robustness test	14	65
Electrical torque	*Transient test*	--	--
	Performance test	8	52
	Robustness test	12	58

4.3. Evaluation of Dynamic Performance of the MHPP Controlled with Fuzzy Logic Controller

Using the principle of fuzzy logic, a power system controller was modeled and incorporated in the MHPP in order to improve its dynamic behavior. The controller was applied to the considered MHPP and results of simulation under the same test as for conventional controller are shown below.

4.3.1. Transient Stability Tests

Response output of the different parameters of the power system under a three phase short-circuit fault with FLC are shown in this section. The short circuit fault was initiated at 0.1s and cleared 0.2s later.

Figure 4.9a plots the response output of the terminal voltage. Figure 4.9b is the enlargement of Figure 4.9a.

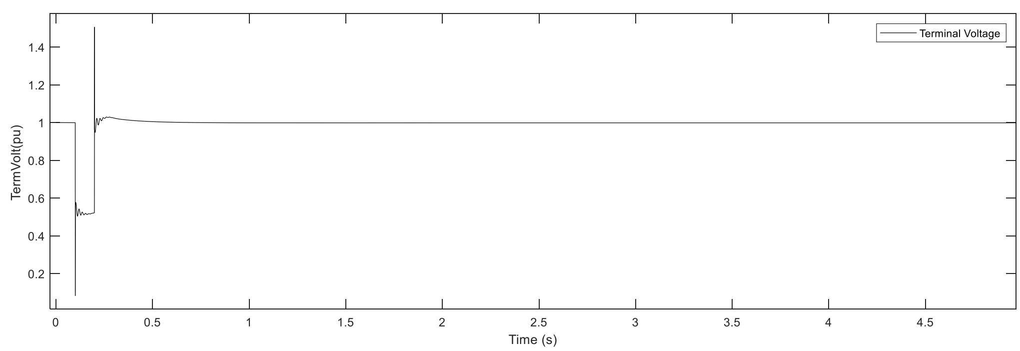


Figure 4.9a: Terminal voltage with FLC under 3 phase short circuit fault

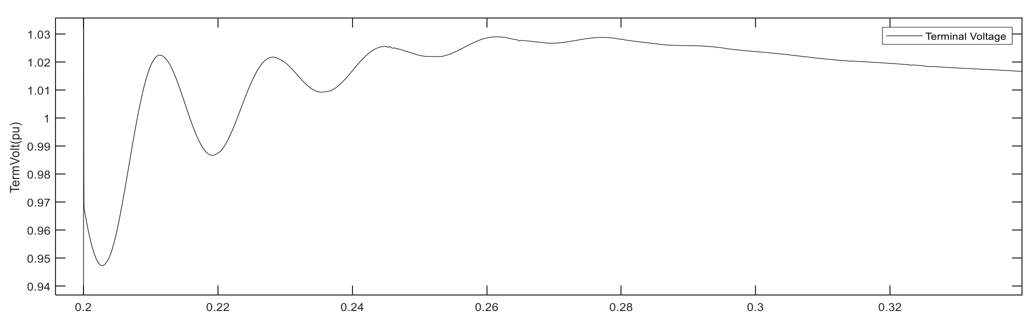


Figure 4.9.b: Zoom of Figure 4.9.a, Terminal voltage with FLC under three phase fault

The flowing was observed in Figure 4.9a and Figure 4.9b: At time 0.1s the terminal voltage decreased up to 0.1pu due the fault circuit in the system. The settling time was evaluated at 0.45s with a peak overshoot of 39%.

Figure 4.10 plots the response of the excitation system due to three phase short circuit fault initiated in the system.

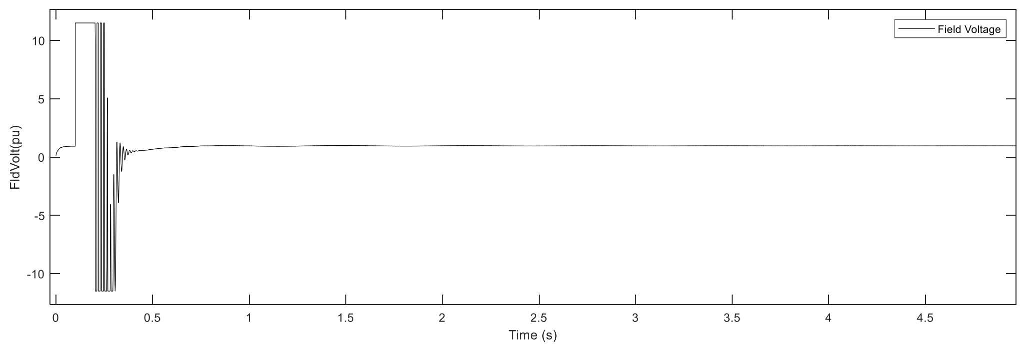


Figure 4.10: Field or excitation voltage output with FLC under 3 phase fault

It can be observed from Figure 4.10; that during the fault (from 0.1s to 0.3s), the field voltage increased up to 10.4pu (from 0.1s to 0.2s) and decreased to -10.4pu at 0.2s. At 0.3s, it started decaying and settled at 1.1pu after approximately 0.6s with an estimated overshoot of 36%.

Figure 4.11 shows the rotor speed deviation response.

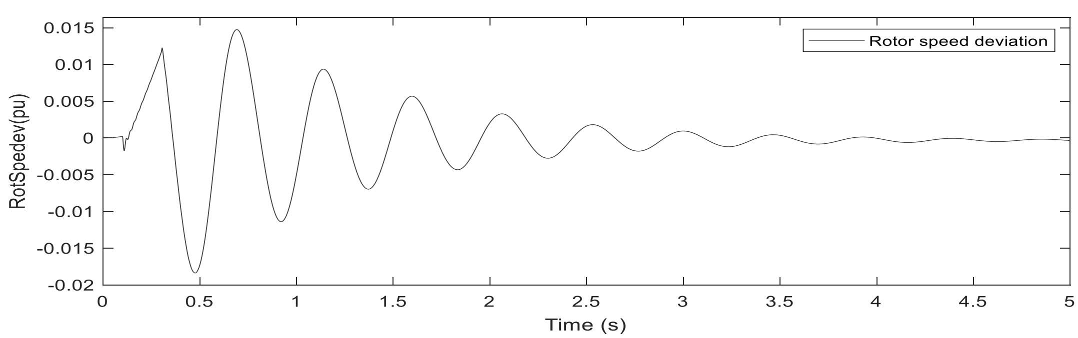


Figure 4.11: Rotor speed deviation with FLC under 3 phase short circuit fault

In Figure 4.11, the fault initiated fluctuations of rotor speed for more than 1s with overshoot of 30% and peak value of 0.015pu. This implies that a peak speed of 1.015pu was reached during the occurrence of the fault. The steady state was then retrieved after 1.5s.

4.3.2. Performance Stability Tests

Performance tests with fuzzy logic controller were conducted as in section 4.2.2. Figure 4.12 and Figure 4.13 show results of the test.

Figure 4.12 shows the response of the speed (frequency) and electrical torque.

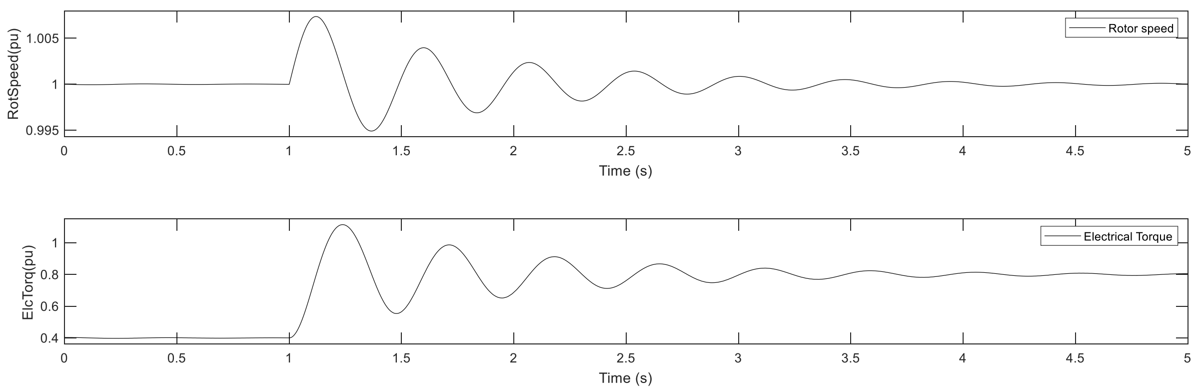


Figure 4.12. FLC Performance stability test under changing load (0.4pu to 0.8pu at 1s): electrical torque and rotor speed outputs

The following are observed from Figure 4.12:

- The electrical torque goes through a series of oscillations before stabilizing to its new value of 0.8pu. Response time and peak overshoot are respectively evaluated to 5s and 30%.
- The speed response time is evaluated at 1.5s and 32% peak overshoot.

Figure 4.13 shows the response of the terminal and field voltage:

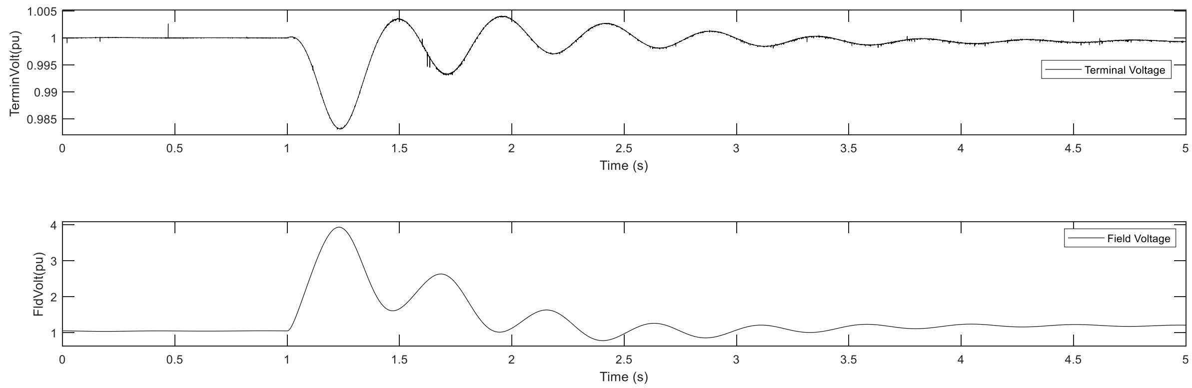


Figure 4.13. FLC Performance stability test under changing load (0.4pu to 0.8pu at 1s): terminal and field voltage outputs

The following were observed from Figure 4.13:

- The terminal voltage took 4.5s to reach the new operating point of 1.05pu with overshoot estimated to 40%.
- The field voltage reached 3.8pu and started decaying to reach its reference value (1pu). The settling time and peak overshoot were respectively, estimated at 2s and 29%.

4.3.3. Robustness Tests

In order to show the robustness of the new proposed controller, tests of robustness were carried out under conditions specified in section 4.2.3 (The synchronous machine inertia constant set to H=3s and operating point changed from 0.6pu to 0.8pu). Figure 4.14 and Figure 4.15 show simulation results.

Figure 4.14 shows the response in electrical torque and speed in the MHPP controlled with FLC.

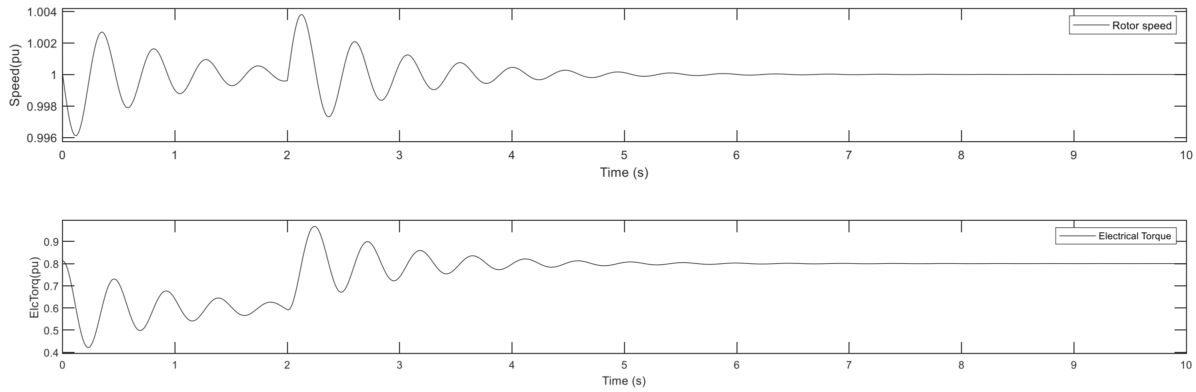


Figure 4.14. FLC Robustness test under changing operating conditions and synchronous machine inertia for speed and electrical torque outputs

The following were observed from Figure 4.14:

- The speed started oscillating before it goes to stabilization after approximately 7s with peak overshoot of 39%. It can be noticed that the system take longer to speed up because of the increase in the inertia constant.
- The electrical torque raised from 0.6pu to 0.8pu but fluctuates for 4s before it reaches the stability at the new operating point. The peak overshoot is estimated at 29%.

Figure 4.15 shows the response in terminal and field voltage in the MHPP controlled with FLC.

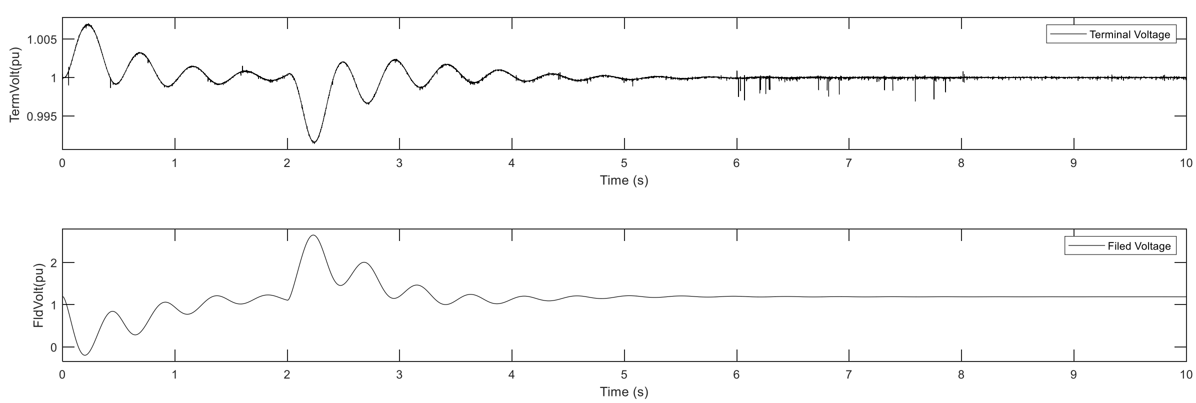


Figure 4.15. FLC Robustness test under changing operating conditions and synchronous machine inertia for terminal and field voltage outputs

The following were observed from Figure 4.15:

- The terminal voltage increased from 0.98pu to 1.005pu after fluctuation that last 6s with 43% peak overshoot.
- At 2s, the field voltage raised up to 2.9pu in order to compensate to the change in the system. Before it reaches the stability for the new operating point, fluctuations lasting 4s with 44% overshoot were observed.

4.3.4. General Observation on FLC Dynamic Performance Evaluation

Table 4.3 summarizes results obtained for tests conducted in the previous section (4.3). It shows the dynamic characteristics (response time and peak overshoot) of each parameter under observation during the test. Speed deviation and speed (frequency) have the same characteristic with 0pu and 1pu as their respective reference value.

Table 4.3: Summary of dynamic performance of observed parameters for FLC tests conducted

Parameters		***Dynamic characteristics***	
		Response time in sec.	*Peak overshoot (%)*
Terminal voltage	*Transient test*	0.45	39
	Performance test	4.5	40
	Robustness test	6	43
Field voltage	*Transient test*	0.6	36
	Performance test	2	29
	Robustness test	4	44
Frequency (speed) or speed deviation	*Transient test*	1.5	30
	Performance test	1.5	32

	Robustness test	7	39
Electrical torque	*Transient test*	--	--
	Performance test	5	30
	Robustness test	4	29

4.4. Comparison of Performance Output

In this section a comparative study of dynamic performances of between MHPP controlled with fuzzy logic controller and the MHPP controlled with conventional controller was conducted. Results are shown in form of graphs and Table 4.4 shows the summary of the comparison. The column labeled "improvement" shows the difference of dynamic performance between the two controllers. To show the validity of the proposed fuzzy logic controller, a comparison to tests with conventional controller conducted in [50] was also discussed.

4.4.1. Comparison of Transient Stability Tests

The dynamic response of terminal voltage, field voltage and speed deviation of FLC and conventional controller are respectively shown on Figure 4.16, 4.17 and 4.18.

Figure 4.16 shows the comparison of terminal voltage between MHPP controlled with PID and MHPP controlled with FLC under a three phase short circuit fault (From 0.1s to 0.3s).

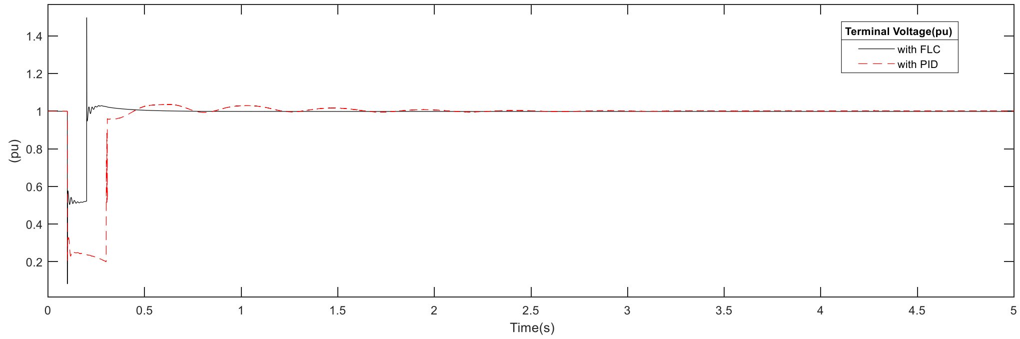


Figure 4.16: Terminal voltage comparison between FLC and conventional controller under transient condition

The following were observed from Figure 4.16: the terminal voltage of both controllers are having approximately the same peak overshoot but the response of the FLC settles slightly faster.

Figure 4.17 shows the comparison of field voltage between MHPP controlled with PID and MHPP controlled with FLC under a three phase short circuit fault (From 0.1s to 0.3s).

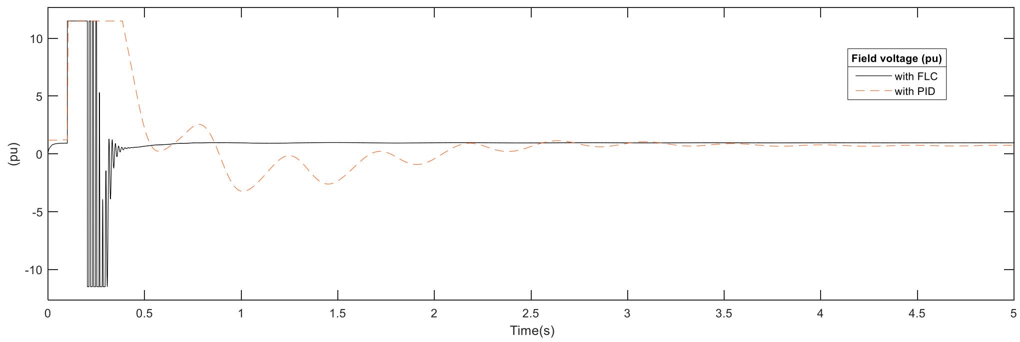


Figure 4.17: Field voltage comparison between FLC and conventional controller under transient conditions

It is observed from Figure 4.17 that the response of the field voltage with FLC is much faster and has small overshoot as compared to that of conventional controller.

Figure 4.18 shows the comparison of speed deviation between MHPP controlled with PID and MHPP controlled with FLC under a three phase short circuit fault (From 0.1s to 0.3s).

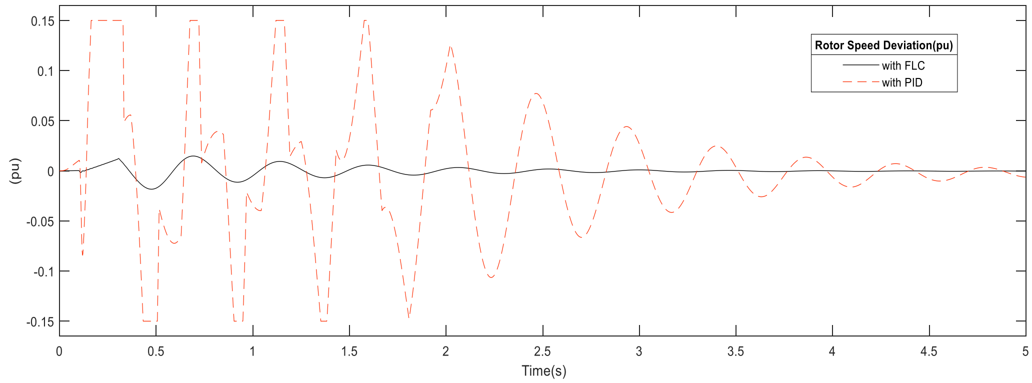


Figure 4.18: Speed deviation comparison between FLC and conventional controller under transient conditions

It was observed from Figure 4.18 that the speed deviation takes longer to clear for conventional controller than for FLC.

4.4.2. Comparison of Performance Stability Tests

Figure 4.19 shows comparison of performance stability between conventional controller and FLC. The improvement in term of response time and overshoot can be observed in both terminal voltage, field voltage, electrical torque and speed. Table 4.4 gives details on the respective values of response time and overshoot for fuzzy logic and conventional controller.

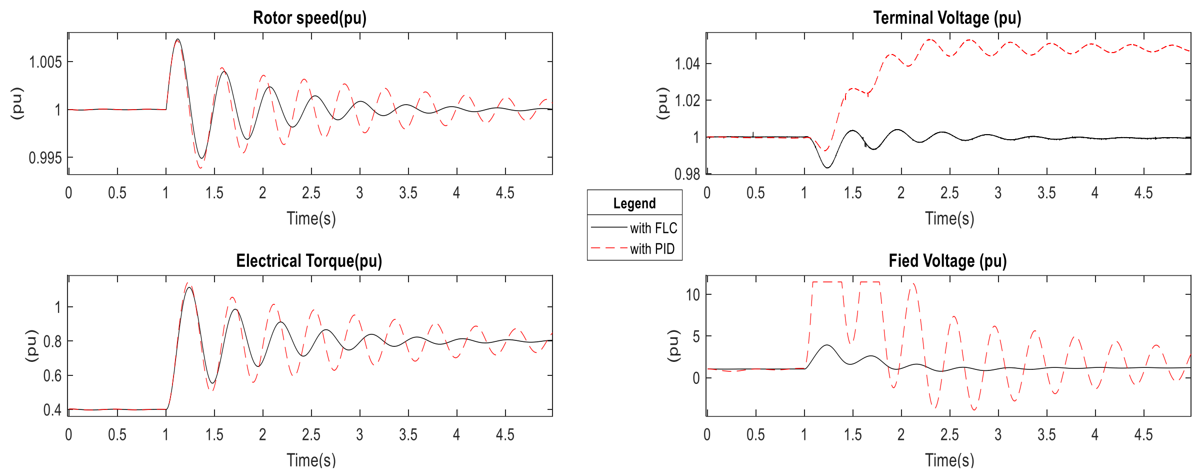


Figure 4.19: Comparison of FLC and conventional controller under performance stability test

4.4.3. Comparison of Robustness Tests

Test for robustness on both FLC and conventional controller were compared and are shown on Figure 4.20. A conclusion was made by observing the response output of speed, terminal voltage, field voltage and electrical torque. The fuzzy logic controller showed a robust control under changing parameters and conditions in the considered MHPP. Details on respective values for the overshoot and response time are shown in Table 4.4.

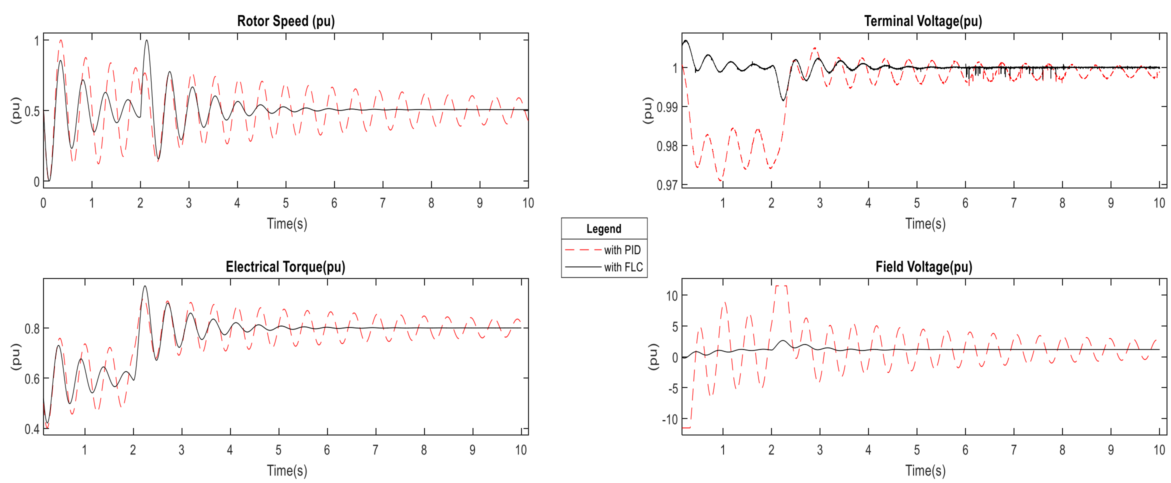


Figure 4.20. Comparison of FLC and conventional controller under robustness test

4.4.4. General Observation on Comparison of Dynamic Performances

Table 4.4 summarizes the comparison study conducted in sections 4.4.1 to 4.4.3. The results of this comparison showed that the response time and the overshoot of FLC were reduced, implying an improvement of stability in the considered MHPP. The average improvement was calculated and results showed an average improvement of 4.91s reduction in response time and 14.11% reduction in overshoot.

Table 4.4: Summary of the comparative analysis

Test	***Parameter***	***Characteristic***	***Conventional controller***	***Fuzzy logic controller***	***Improvement***
Transient test	*Terminal voltage*	*Response time (s)*	3.3	0.45	***2.85***
		Overshoot (%)	40	39	***1***
	Field voltage	*Response time (s)*	3.3	0.6	***2.7***
		Overshoot (%)	40	36	***4***
	Speed deviation	*Response time (s)*	6	1.5	***4.5***
		Overshoot (%)	50	30	***20***
	Electrical torque	*Response time (s)*	--	--	***--***
		Overshoot (%)	--	--	***--***
Performance test	*Terminal voltage*	*Response time(s)*	7	4.5	***2.5***
		Overshoot (%)	42	40	***2***
	Field voltage	*Response time(s)*	7	2	***5***
		Overshoot (%)	39	29	***10***
	Speed deviation	*Response time (s)*	9	1.5	***7.5***
		Overshoot (%)	53.2	32	***21.2***
	Electrical torque	*Response time (s)*	8	5	***3***
		Overshoot (%)	52	30	***22***
Robustness test	*Terminal voltage*	*Response time (s)*	10	6	***4***
		Overshoot (%)	52	43	***9***
	Field voltage	*Response time (s)*	11	4	***7***
		Overshoot (%)	55	44	***11***

	Speed deviation	*Response time (s)*	14	7	***7***
		Overshoot (%)	65	39	***26***
	Electrical torque	*Response time (s)*	12	4	***8***
		Overshoot (%)	58	29	***29***
Improvement average		***Response time (s)***	*8.23*	*3.32*	***4.91***
		Overshoot (%)	*49.65*	*35.54*	***14.11***

4.5. Validation Over Literature

An analysis of dynamic response of a power system subjected to different type of controllers was conducted in [50]. It consisted on the comparison of PID controllers to PSS (power system stabilizer) combined with PID. Two tests were conducted: transient tests (three phase short-circuit) and performance test (load increasing) in a 500MW power system. His results are presented in table 4.5 with the improvement that the fuzzy logic controller of this work has provided to its system that consisted of conventional controllers. The comparative analysis was performed by assuming that the FLC provides the best performance for any power system (near perfect robustness).

Table 4.5. Comparison over literature

Test	***Parameter***	***Characteristic***	***In [50]***	***With FLC***	***Improvement***
Transient stability tests	*Field voltage*	*Response time*	2s	0.6s	1.4s
		Overshoot	50%	36%	14%
	Speed deviation	*Response time*	2s	1.5s	0.5s
		Overshoot	50%	30%	20%
Performance stability tests	*Field voltage*	*Response time*	3s	2s	1s
		Overshoot	75%	29%	46%
	Speed deviation	*Response time*	2s	1.5s	0.5s
		Overshoot	50%	32%	18%
Averaged improvement			***Response time***		***0.85s***
			Overshoot		***24.5%***

The following were observed:

- Fuzzy logic controller shows a reduction in overshoot and response time for all conducted tests. This implies an improvement in the system with FLC.
- After combining a number of conventional controller (PID+PSS) as done in [50], the stability of the system still need improvement. Fuzzy logic controller has contributed to this improvement as evidenced by the comparison in table 5. This general evaluation shows the necessity of using FLC over all other conventional controllers.

4.6. Impacts of Stability Improvement on the MHPP

Stability of a power system is its ability to regain nominal operating point after the occurrence of disturbances. An improved stability has the following impacts on the hydropower plant:

- Stability contribute to enhance the reliability of the power system. Results of transient stability tests show that the proposed fuzzy logic controller react quickly to faults in the system. Thus, the controller contribute to enhance the stability and consequently, the improvement of reliability of the hydropower system.
- Frequency (speed) and voltage are maintained in a specific range despites faults and changes of loads (power quality improvement). Results of performance tests show that the system would quickly reach the increasing load and the change of operating point.
- Prevent equipment from damage. The synchronous generator will not deliver high field voltage as the overshoot (peak value) is reduced during the occurrence of disturbance or load reduction.
- The system will quickly regain the synchronism as the response time in speed and voltage is reduced.
- Reliability improvement implies that the hydropower system will be more available and flexible for every demand in the power system.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.0. Introduction

This chapter summarizes results of the research work. Recommendations and further area of research are also provided.

5.1. Conclusion

5.1.1. Design of a Fuzzy Logic Controller

A fuzzy logic controller was successfully designed, optimized and simulated in this work based on the experience learned on control of hydropower plant. Unlike conventional controllers, which require exact mathematical models and precise numerical value, an important feature of fuzzy logic is that a process can be controlled by a set of rules that describe the dynamic behavior of the controller using linguistic terms which are obtained through membership functions. Therefore, fuzzy logic controllers are appropriate for hydropower plant whose dynamic nature is nonlinear, complex, stochastic and without an exact mathematical model. This was evidenced by the results of a comparative analysis between conventional controller and FLC implemented in the same hydropower plant and subjected to similar tests conditions.

5.1.2. Transient Test Analysis

With the hydropower system operating at specified operating point a three phase short circuit fault was initiated at 0.1s and cleared 0.2s later. Dynamic response of terminal voltage, field voltage and speed (speed deviation) was observed for both conventional controller and fuzzy logic controller. Results showed that the system under conventional controller took longer to stabilize: evidenced by a long response time and high overshoot. However, results of the system under fuzzy logic showed that the response time and overshoot were improved. It can be seen that FLC has effectively enhanced the system transient performance.

5.1.3. Performance Test Analysis

With the hydropower plant operating at 0.4pu active power, a 0.4pu increase in active power was applied at 0.5s so that the system can reach 0.8pu active power. The response of terminal voltage, field voltage, speed deviation and electrical torque with conventional controller showed large oscillations. However, quick reaction and smaller overshoot were shown with the fuzzy logic controller incorporated in the hydropower plant.

5.1.4. Robustness Test Analysis

Conventional controller are of fixed parameters, they need to be redesigned and retuned for each power system configuration. However, fuzzy logic controllers are capable of accepting imprecision and vagueness in the system parameters. This was evidenced by a test of robustness of the power system for both conventional and fuzzy logic controller. A change of system configuration was performed: the synchronous machine inertia constant and operating parameters were, respectively changed from 2s to 3s and from 0.6pu to 0.8pu at 2s. Results of these tests showed that change of system configuration had minor effect on the dynamic performance of fuzzy logic controller as compared to conventional controllers which had slow reaction and high overshoot before stabilizing.

5.1.5. Validation Over Literature

The proposed fuzzy logic controller of this research work was compared to conventional controllers of [50]. It can be concluded that the proposed fuzzy logic controller would provide better dynamic performance than the combination of conventional controllers (PID and PSS) as designed in [50].

5.2. Recommendations and Areas for Further Research

The following are recommended in order to extend this research work in future research.

1. Enlarge the considered single area power system to multi-area power system with interconnection and load sharing issues.
2. Use self-learning fuzzy logic in order to further improve the controller design.

3. A cost analysis and implication should be done further to ascertain what it takes to construct a hardware of the designed system.
4. A hardware realization on a micro-controller or programmable logic controller is also recommended in order to show the effectiveness of the result obtained in this research work.

5.3. Contribution to Knowledge

This research work has contributed to the existing knowledge in Micro Hydropower plant control in the following ways:

1. By providing a well-designed and optimized fuzzy logic controller that has enhanced the stability of the considered MHPP. This was evidenced by the comparison of conventional PID controller and fuzzy logic controller that gave an average improvement value of 4.91s and 14.11% in terms of response time and overshoot respectively.
2. By contributing to MHPPs reliability and flexibility enhancement through the improvement of stability using FLC.
3. Based on the performance analysis conducted, embedded fuzzy logic algorithm in the MHPP has provided the best performance output so far in regard to literature knowledge as in [50]. This was shown in table 4.5 where an average reduction in response time and overshoot of 0.85s and 24.5% is respectively obtained when all conventional controllers (PID and PSS) are combined.

Appendix A

Fuzzy Logic Algorithm as Designed in Matlab

```
[System]
Name='fuzzy_avr'
Type='takagi-sugeno'
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=49
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'

[Input1]
Name='Error'
Range=[-0.002 0.002]
NumMFs=7
MF1='NB':'trimf',[-0.002 -0.002 -0.00132]
MF2='NM':'trimf',[-0.002 -0.00132 -0.00068]
MF3='N':'trimf',[-0.00132 -0.00068 0]
MF4='Z':'trimf',[-0.00068 0 0.00068]
MF5='P':'trimf',[0 0.00068 0.00132]
MF6='PM':'trimf',[0.00068 0.00132 0.002]
MF7='PB':'trimf',[0.00132 0.002 0.002]

[Input2]
Name='ErrorDev'
Range=[-0.002 0.002]
NumMFs=7
MF1='NB':'trimf',[-0.002 -0.002 -0.001356]
MF2='NM':'trimf',[-0.002 -0.001356 -0.0007118]
MF3='N':'trimf',[-0.001356 -0.0007118 -6.747e-05]
MF4='P':'trimf',[-0.0007118 -6.747e-05 0.0005768]
MF5='PM':'trimf',[-6.747e-05 0.0005768 0.001221]
MF6='PB':'trimf',[0.0005768 0.001221 0.001846]
MF7='Z':'trimf',[0.001221 0.001846 0.001846]

[Output1]
Name='VfOut'
Range=[-0.5 0.5]
NumMFs=7
MF1='NB':'trimf',[-0.5 -0.5 -0.3343]
MF2='NM':'trimf',[-0.5 -0.3343 -0.1687]
```

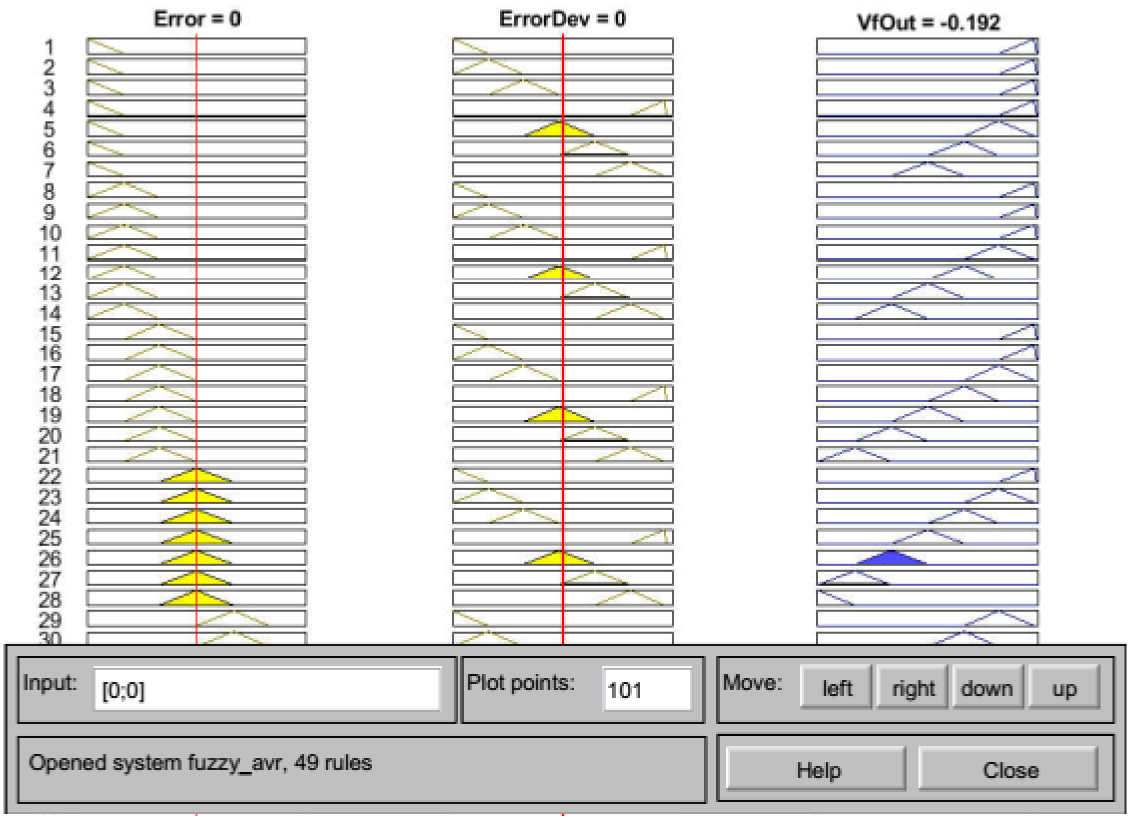
MF3='N':'trimf',[-0.3343 -0.1687 -0.003068]
MF4='Z':'trimf',[-0.1687 -0.003068 0.1626]
MF5='P':'trimf',[-0.003068 0.1626 0.316]
MF6='PM':'trimf',[0.1626 0.316 0.4817]
MF7='PB':'trimf',[0.316 0.4817 0.4817]

[Rules]
1 1, 7 (1) : 1
1 2, 7 (1) : 1
1 3, 7 (1) : 1
1 7, 7 (1) : 1
1 4, 6 (1) : 1
1 5, 5 (1) : 1
1 6, 4 (1) : 1
2 1, 7 (1) : 1
2 2, 7 (1) : 1
2 3, 7 (1) : 1
2 7, 6 (1) : 1
2 4, 5 (1) : 1
2 5, 4 (1) : 1
2 6, 3 (1) : 1
3 1, 7 (1) : 1
3 2, 7 (1) : 1
3 3, 6 (1) : 1
3 7, 5 (1) : 1
3 4, 4 (1) : 1
3 5, 3 (1) : 1
3 6, 2 (1) : 1
4 1, 7 (1) : 1
4 2, 6 (1) : 1
4 3, 5 (1) : 1
4 7, 4 (1) : 1
4 4, 3 (1) : 1
4 5, 2 (1) : 1
4 6, 1 (1) : 1
5 1, 6 (1) : 1
5 2, 5 (1) : 1
5 3, 4 (1) : 1
5 7, 3 (1) : 1
5 4, 2 (1) : 1
5 5, 1 (1) : 1
5 6, 1 (1) : 1
6 1, 5 (1) : 1
6 2, 4 (1) : 1
6 3, 3 (1) : 1
6 7, 2 (1) : 1
6 4, 1 (1) : 1
6 5, 1 (1) : 1
6 6, 1 (1) : 1
7 1, 4 (1) : 1
7 2, 3 (1) : 1

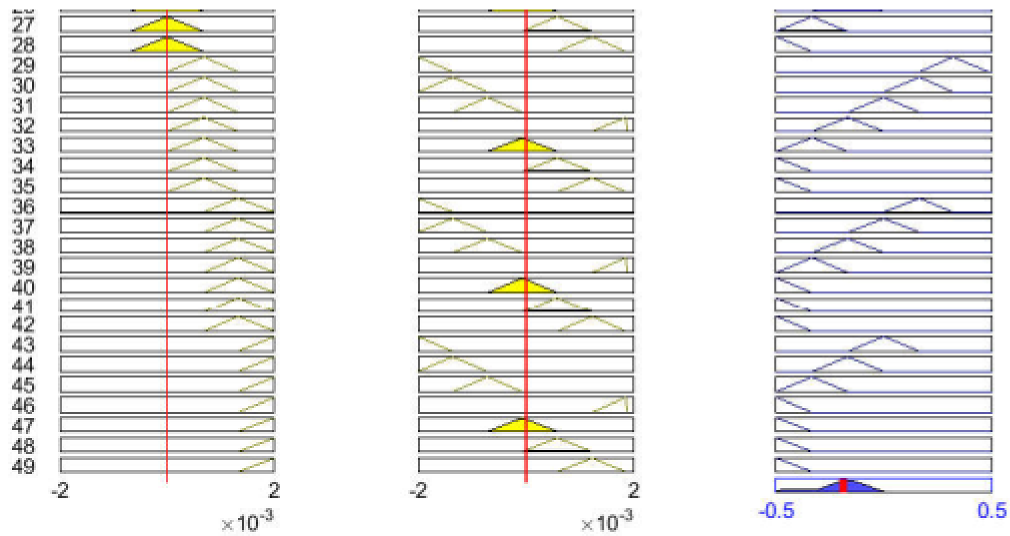
7 3, 2 (1) : 1
7 7, 1 (1) : 1
7 4, 1 (1) : 1
7 5, 1 (1) : 1
7 6, 1 (1) : 1

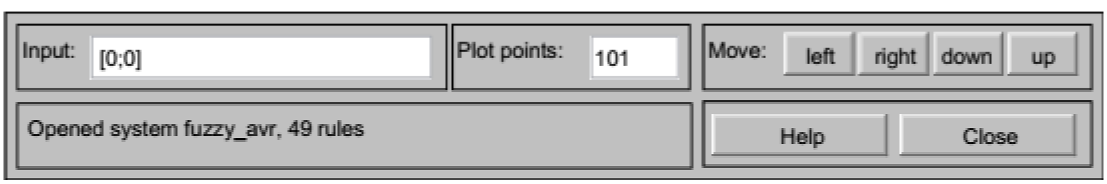
Appendix B

Fuzzy Logic Rules Viewer



Fuzzy Logic Rules Viewer Continuation.





Appendix C

Disseminations

Two journal articles will be published.

1. A comparative analysis of fuzzy logic controller and conventional controller in a Micro Hydropower plant under transient conditions, under review in the *Islamic University Multidisciplinary Journal (IUMJ)*.
2. Design of Frequency and Voltage Controller for Stability Improvement in a Micro Hydro Power Plant, *Presented in the 13th IEEE Conference on Application of Information and Communication Technologies*, Baku, Azerbaijan, 23-25th October 2019. Published in the Proceedings: https://we.tl/t-gLrx5CJi2D

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