# Modeling and performance analysis of Artificial Intelligence (AI) based controllers for AVR of a Synchronous Generator (SG).
**By**

Ntombenhle Mazibuko
20818546

**Submitted in fulfilment of the requirements of the degree of Master of Engineering in Electrical Engineering in the Department of Electrical Power Engineering, Faculty of Engineering and the Built Environment**

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**Supervisor: Dr Kayode T Akindeji**
**Co-Supervisor: Dr Gulshan Sharma**

# ABSTRACT

An automatic voltage regulator (AVR) is an electronic device used to control, adjust, and maintain a constant voltage level at the stator terminals of a synchronous generator (SG). Hence, the voltage stability of a power system network is affected by AVR's performance. Maintaining constancy and stability of the nominal voltage level in power systems remains a major control problem. Another critical reason for effective control of the generator's terminal voltage is that real line losses are determined by the real and reactive power flows and variation in terminal voltage has a large effect on reactive power flow and thus on these losses.

A large power system consists of several synchronous generators that operate in synchronism; the terminal voltage and frequency are to be kept constant with minimal variation to ensure the stability of the power system. The voltage stability of a synchronous generator is highly affected when the terminal voltage varies above the nominal acceptable range. To maintain a constant voltage at a SG's terminal, an AVR is used. The performance of an AVR is highly dependent on efficient controller design, which improves the output of the AVR by restoring the voltage of the synchronous generator to its nominal value in the presence of disturbances.

The selection of a suitable controller is one of the most challenging aspects of AVR system design. This study presents the design, modeling, and performance analysis of an AVR system employing a Proportional Integral and Derivative (PID) controller, a Fuzzy Logic controller (FLC), and a Model Predictive Controller (MPC) for the performance enhancement and transient response of the AVR system with these controllers.

Initially, a transfer function is used to develop a mathematical model of an AVR in order to observe its step response when the terminal voltage of a generator is disturbed. A PID controller is then added to the system and tuned to enhance the step response of an AVR. The third model develops and implements an AVR system based on MPC, while the final model implements an FLC for an AVR system. Simulating the models in Matlab Simulink 2021a, the results have demonstrated the need for a controlling mechanism to enhance the dynamic performance of the AVRS, and MPC has shown to be the most effective controller.

# DECLARATION

This dissertation is the student's own work, all cited work or text has been appropriately referenced. It has not partially or fully submitted at any other University.Dr. K.T Akindeji and Dr. G Sharma at the Durban University of Technology duly supervised this research.

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Ntombenhle Mazibuko Date

Durban University of Technology

Department of Electrical Power Engineering

Student Number: 20818546

………………………..

23 January 2023

……………………..

Supervisor: Dr Kayode T Akindeji Date

Durban University of Technology

Department of Electrical Power Engineering

………………………..

23/01/2023

……………………..

Co-Supervisor: Dr Gulshan Sharma Date

University of Johannesburg

Department of Electrical Engineering Technology

# PUBLICATIONS ARISING

Ntombenhle Mazibuko
Faculty of Engineering and Built Environment
Master of Engineering in Electrical Power Engineering

**The following publications emanated from this research investigation and form part and/or include research presented in this dissertation.**

1. N. Mazibuko, K. T. Akindeji and G. Sharma, "Implementation of a FUZZY logic controller (FLC) for improvement of an Automated Voltage Regulators (AVR) dynamic performance.," 2022 IEEE PES/IAS PowerAfrica, 2022, pp. 1-5, doi: 10.1109/PowerAfrica53997.2022.9905407.

2. N. Mazibuko, K. T. Akindeji and G. Sharma, "Modeling and Performance Analysis of an Automatic Voltage Regulator (AVR) using Model Predictive Controller (MPC)," 2022 IEEE PES/IAS PowerAfrica, 2022, pp. 1-5, doi: 10.1109/PowerAfrica53997.2022.9905313.

# DEDICATION

This work is dedicated to my Late mother Philile Margaret Sibisi and my kids Amahle, Abongwe and Mnotho

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I would like to thank God for equipping me with the skills necessary to conduct this study. My family, particularly Mnotho, and Lindelwa, for their constant support throughout. The Electrical Power Engineering department staff members for encouragement and inspiration, Dr. G. Sharma, Dr. K.T. Akindeji, Dr. Ojo, Mr. Leoaneka, and Mr. Laflein. I would also like to thank my fellow postgraduate students, particularly Mr. K.W. Ntuli.

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| | |
|---|---|
| AVR | Automatic voltage regulator |
| PID | Proportional Integral and Derivative |
| FLC | Fuzzy logic controller |
| MPC | Model predictive controller |
| ISE | Integral of square error |
| ITSE | Integral of Timing-Weighted-Square-Error |
| IAE | Integral of absolute error |
| ITAE | Integral of Timing-Weighted-Absolute-Error |
| REIPPP | Renewable Energy Independent Power Producers Procurement Programme |
| RES | Renewable Energy Sources |
| IBG | Inverter-based generators |
| SG | Synchronous generator |
| PSS | Power systems stabilizer |
| IDC | incompatible decentralized control |
| CDC | compatible decentralized control |
| ARPCS | Automatic reactive power control |
| PSAT | Power systems analytic toolbox |
| CPF | Continuation power flow |
| OEL | Over excitation limit |
| AC | Alternating current |
| DC | Direct current |
| VT | Terminal Voltage |
| VSG | Virtual synchronous generator |
| DG | distributed generation |
| PMSG | Permanent magnet synchronous generator |
| FEM | Finite element method |
| SCIG | Squirrel cage induction generator |
| DFIG | Double fed induction generator |
| WECS | Wind energy conversion system |
| SMC | Sliding mode control |

| | |
|---|---|
| ERL | Exponential reaching law control |
| OLTC | on-load tap changer |
| SMIB | Single machine infinite bus |
| AGC | Automatic generator control |
| HN | high negative |
| LN | Low negative |
| Z | zero |
| LP | low positive |
| HP | high positive |
| LN | large negative |
| MN | Medium negative |
| SN | Small Negative |
| Z | Zero |
| SP | Small Positive |
| MP | Medium Positive |
| LP | Large Positive |
| FIS | Fuzzy Interface System |

# LIST OF SYMBOLS

| | |
|---|---|
| $K_R$ | sensor gain |
| $K_A$ | amplifier gain |
| $K_E$ | exciter gain |
| $K_G$ | generator gain |
| $T_R$ | sensor time constant |
| $T_A$ | amplifier time constant |
| $T_E$ | exciter time constant |
| $T_G$ | generator time constant |
| $V_R(s)$ | sensor voltage |
| $V_T$ | terminal voltage |
| $e(t)$ | error voltage |
| $de(t)/dt$ | rate of change of error voltage |
| $K_D$ | derivative gain |
| $K_P$ | proportional gain |
| $K_I$ | integrator gain |
| $T_S$ | settling time |
| $T_R$ | rise time |
| $E_{ss}$ | steady state error |
| $U(s)$ | error signal for a PID controller |
| $E(s)$ | control signal of a PID controller |
| $T_s$ | sampling time |
| $T_I$ | integral time constant |
| $T_P$ | proportional time constant |
| $T_D$ | derivative time constant |
| M | control weights for the MPC controller |
| $Y(k)$ | output signal for the MPV controller |
| $U(k)$ and $X_p(k)$ | plant state-space model for MPC |

# CHAPTER ONE

## INTRODUCTION

### 1.1 Background

The power system's stability (PSS) is assessed by the frequency and voltage values. Frequency is designated as a global parameter because its value is the same for the across the entire network of the power system and the voltage is marked as a local parameter because its value changes for each node of the system [1].Power system stability is divided into three categories: rotor angle stability, frequency stability, and voltage stability. Figure 1.1 depicts the power stability classification. Small signal stability issues have existed in the power system for many decades.

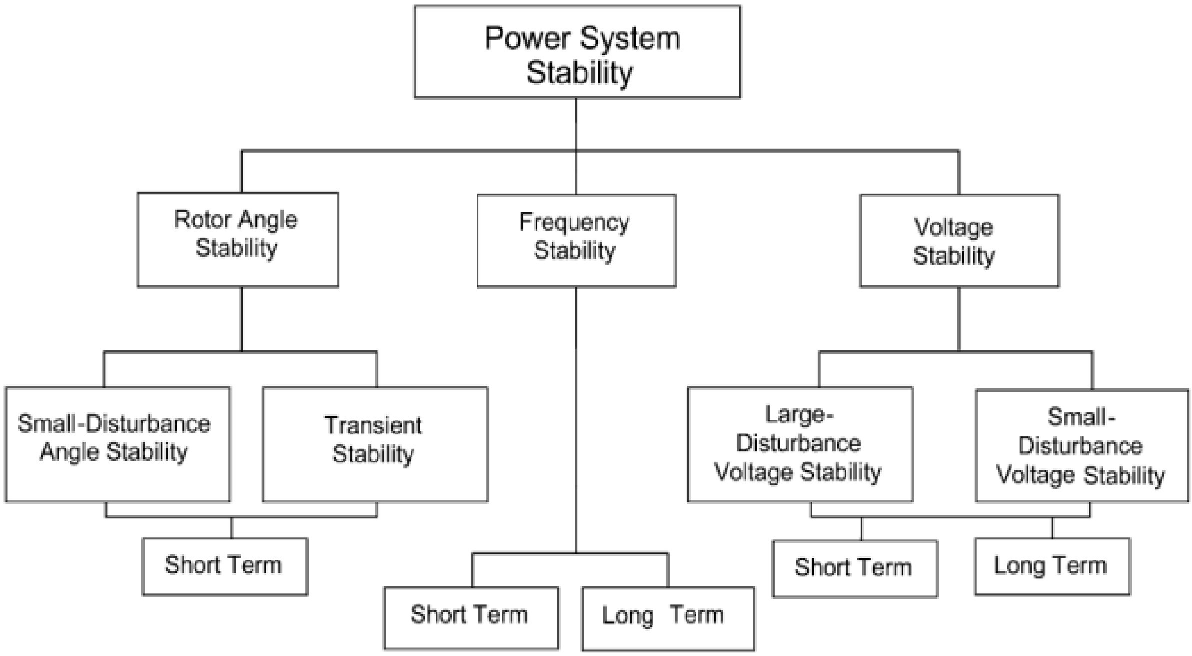



Figure1. 1 Classification of power systems stability [2]

Voltage stability is defined as the system's ability to maintain a constant voltage under normal operating conditions and even after being subjected to disturbance/ disruption [3]. The creation of flux by flowing current through the field winding of an SG is referred to as excitation.

Direct current is necessary to excite the rotor's field winding. DG’s are the major component of an electrical generating system; their control has been accomplished in a variety of ways and may be divided into two control requirements: frequency control and output voltage control. AVR is used to adjust the SG output voltage for field voltage excitation and regulated capacitors are used for Induction generator’s voltage control. Fig.1 depicts the frequency and voltage control techniques for the synchronous generator. Both controllers have an impact on the system's overall stability.

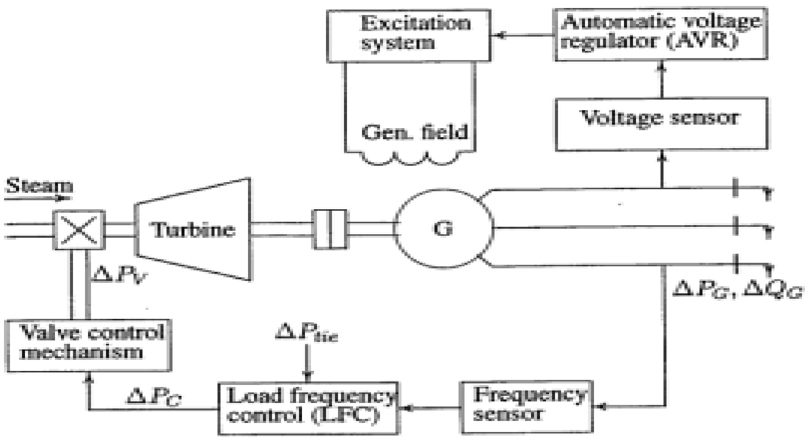



Figure1. 2 The schematic diagram of frequency and voltage control for a synchronous generator [4]

To improve an AVR's dynamic performance, the design must include an appropriate controller. The selection of a suitable controller is one of the most difficult aspects of developing an AVR system [5]. Hence, this research investigates the use of AI controllers on AVR to maintain voltage stability hence keeping synchronous generators in synchronism by keeping SGs terminal voltage within an acceptable range and with minimal variation. PID controllers are utilized in a wide range of automatic process control applications. Optimal tuning of the controller's gain has existed for a long time. The main benefit of the MPC technique is the ability to predict future control input based on the best future feature of the plant output.

There is a scarcity of literature in the field of MPC for AVR. Because the fuzzy logic control is nonlinear and adaptive, it exhibits resilience to parameter variations [6]. By incorporating fuzzy logic technology into the design of an embedded system, engineering experience and experimental results can be utilized, it also enables model-free estimation of the system which eliminates the need for the designer to specify a mathematical relationship between the outputs and the inputs [7]. All of these controllers are investigated in order to enhance the dynamic performance of an AVR system.

## 1.2 Problem statement

Load variations and abnormal conditions significantly affect the frequency and scheduling of power in all aspects of power system operation. These changes have a direct effect on the terminal voltage of the SG. Maintaining the constancy and stability of the standard voltage level in power systems with all connected equipment designed for a specified voltage level is one of the fundamental control challenges. As the terminal voltage of the SG will be affected by the unavoidable change in load demands, it is essential to provide a control mechanism that can keep up with these changes while maintaining voltage stability. An AVR is used to control synchronous generator excitation, thus also maintaining a constant terminal voltage; however, due to the high inductance characteristic of the SG field windings and load variation, it is difficult to achieve an AVR's steady and rapid response. Consequently, the controlling mechanism is crucial for improving the dynamic performance of an AVR system.

## 1.3 Significance of the research

The reactive power is an important factor in the power system's operation and design. The system's reactive power balance implies a constant output voltage [8]. Analytical models are important tools in the controller design for AVR systems and Predictive analysis and stability limitations can be predicted using various control laws and system factors. AI is a new technological science that investigates and develops the theory, technology, and application systems for imitating and expanding human intellect, integrating together specialties such as psychology, cognitive science, reasoning science, machine learning, computer science, and biomedicine [7]. The application of artificial intelligence technology in electrical automation control is becoming more widespread, providing a solid foundation and strong support for the development of automation control technology [9].

As a result, the application of these techniques to address power system stability issues is critical for researchers and power system designers.

## 1.4 Aims and objectives

The aim of this study is to design, model and analyse  an AVR system performance when subjected to disturbances that affect the terminal voltage of an SG and also to design and implement the control mechanism that will improve the dynamic response of an AVR. These aims can be achieved through the following objectives:

- Mathematically modelling of an AVR using a transfer function. Implement the model on MATLAB SIMULINK 2021a to observe the dynamic response of the AVR system without an appropriate controller (a normal AVR) when subjected to disturbances.
- To model, tune and implement a PID-based-AVR in MATLAB and analyse its performance.
- To design a Model Predictive controller for the AVR system and compare its performance with a normal AVR and PID-based AVR.  Critically analyse and compare the three models
- To designing modelling and critically analysing a fuzzy logic controller for an AVR to compare its performance with the above mentioned controllers

## 1.5 Dissertation structure

**Chapter one**: This chapter elaborates on the research background of the study introducing the problems and stability challenges on the power systems network. This chapter will also introduce voltage stability and the need for improving the performance of an AVR to constantly and continuously maintain the terminal voltage of a SG and reactive power.

**Chapter two:** This chapter provides an overview of the generation, transmission, and distribution components of a complete power system network. A focus will also be placed on excitation control techniques and an automatic voltage controller.

This chapter will also provide a comprehensive review of the existing technologies implemented in the control strategy for AVR systems.

**Chapter three**: This chapter provides a comprehensive review of an AVR. MATLAB Simulink is used to design and implement the AVR mathematical model. This model will be used to disturb an AVR's terminal voltage and observe its response when subjected to disturbances such as load variations.

**Chapter four: This chapter** describes the modelling of AVR systems with PID controllers. In addition, the chapter will discuss PID optimization techniques for enhancing the performance of an AVR. Presented are the mathematical model and simulation results of a PID-based-AVR.

**Chapter five**: This chapter expands on the MPC technique review for the AVR system. Modelling, design, and implementation of MPC for an AVR are discussed in this chapter. Results will be presented and compared with those found in chapters three and four.

**Chapter six:** This chapter presents modelling, design, and simulation of an FLC for the AVR system is presented in this chapter. MATLAB Simulink and the FSI design interface system were used to complete the execution of an FLC-based AVR system. This chapter also compares the dynamic performance of an FLC-based-AVR and those of MPC and PID controller based AVR.

**Chapter seven**: Conclusions on the preceding chapters and recommendations for future studies are presented in this chapter.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Introduction

This chapter discusses traditional and modern power systems, as well as the challenges that these networks face. One of the major challenges is power system stability, which include voltage instability. Because this research is investigating the maintenance of voltage variation at the generator terminal using an AVR via the excitation system of a synchronous generator, the chapter also discusses power system stability, voltage stability, synchronous generators, induction generators, excitation systems, AVR, and existing control techniques to improve AVR performance. Existing literature from various sources are reviewed and discussed to identify gabs and conclude on best suitable option on improving the AVRs perfomance.

## 2.2 Power Systems overview

A power system (PS) is a complex enterprise that can be categorized into three: generation, transmission, and distribution. Figure 2.1 depicts a comprehensive overview of a conventional power system. A power system network is made up of several synchronous generators that operates in synchronism; the terminal voltage and frequency of these generators must be kept constant with minimal variation in order to maintain power system stability; consequently, the safe and stable operation of large generators is essential for the maintenance of power system stability.

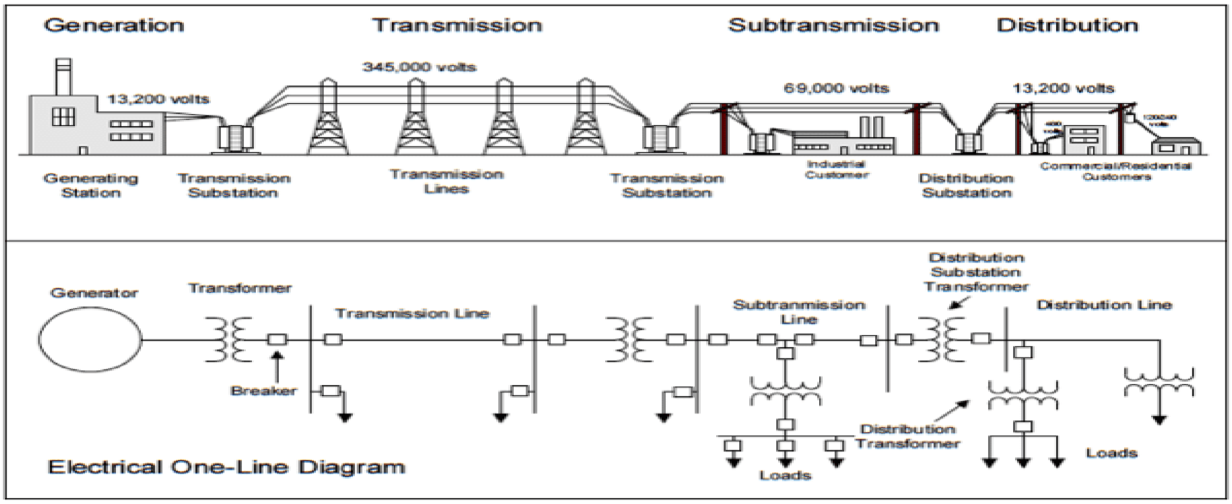



*Figure 2. 1 A single line diagram of a traditional power systems* [10]

The power systems network has been experiencing new developments and technologies, which encourages the establishment of new control strategies to sustain and maintain the power systems network's stability. The grids architecture is shifting toward a higher proportion of renewable energy sources (RES) including wind, solar, biogas etc.; due to depletion of fossil hence, it is critical to consider alternative energy sources such as renewables to meet future energy demands. However, traditional power plants, on the other hand, continues to play a major role in voltage and frequency stability and control. In the future, the incorporation of Renewables and traditional power plants must carry out those control actions. Traditional power plant operators are attempting to make their facilities more flexible in order to deal with the continuous changes in the power system. Upgrading the capabilities of the synchronous generator's AVR is one aspect of power plant modernization.

Many wind turbines and photovoltaic cells have been installed around the world in recent decades [11]. Solar has the biggest potential of all renewables in SA due to the country's geographic position, with wind as another significant potential source of energy. Due to the strong winds that frequently blow along the country's coast, Cape Town has constructed numerous wind farms that generate a sizable amount of electricity. As more RESs are  gaining more popularity in the near future the grid will use inverter-based generators (IBGs) rather than synchronous machines [12]. Because IBGs differ greatly in their features from synchronous generators (SGs), notably in their inertia and capacity to generate reactive power, their influence on system dynamics diverge from SGs. As a result, investigations on the stability of power systems incorporating IBGs may be necessary in the future. The characteristics of a Synchronous generator including classifications are discussed in section 2.2.

## 2.3 Synchronous generators

A SG converts mechanical power from a prime mover into alternating current (AC) power at a certain voltage and frequency. The two basic components of a conventional SG, a rotor and a stator, are depicted in Figure 2.2. The primary voltage is induced in a stator by the armature winding. The magnetic field in a rotor is created either by a permanent magnet or by delivering dc current to the rotor winding referred to as a field winding. Based on winding configurations, synchronous machines can be categorized as either rotating-armature or rotating-field.

The armature winding is on the rotor and the field system is on the stator in a revolving armature. Slip rings are used to transfer the generated current to the load. The highest power output and electromagnetic field created are limited by insulation issues and the difficulty associated in passing large currents across the brushes (emf). This type is mostly used as the primary exciter in large alternators with brushless excitation systems and is only utilized in small units. A stator-mounted armature winding and a rotor-mounted field system comprise the rotating field type. The exciter supplies the field current through the slip rings, whereas the armature current is delivered directly to the load. This type is superior in terms of power generation since it can generate high output power.

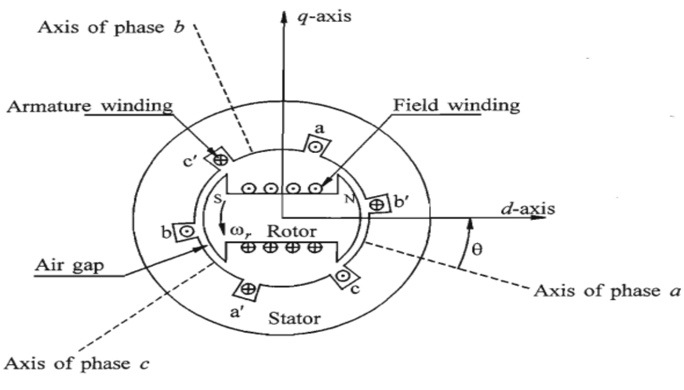



*Figure 2. 2* Synchronous generator Schematic diagram [13]

The behaviour of a synchronous generator under load varies substantially depending on the power factor of the demand and whether the generator is running alone or in parallel with other synchronous generators. Generator terminal voltage is affected by changes in system load thus, the stator current induces flux; this interaction with the field-winding magnetic flux creates a resultant flux that is affected by system load variations. An inductive load increases terminal voltage while the terminal voltage drops when the generator is powering a leading (capacitive) load as a result the voltage stability is highly affected by these load variations.

In the event of small disturbances, the automated voltage regulator (AVR) is used to maintain the synchronous generator's terminal voltage at an acceptable level by adjusting the exciter voltage. Reactive power Q and terminal voltage VT have a relationship that can be established, as illustrated in figure (2.3). When a synchronous generator is supplied with a lagging load, the terminal voltage drops while it increases when the generators load in leading. A generator's frequency-power and terminal voltage vs. reactive power characteristics are crucial for parallel operation these generators.

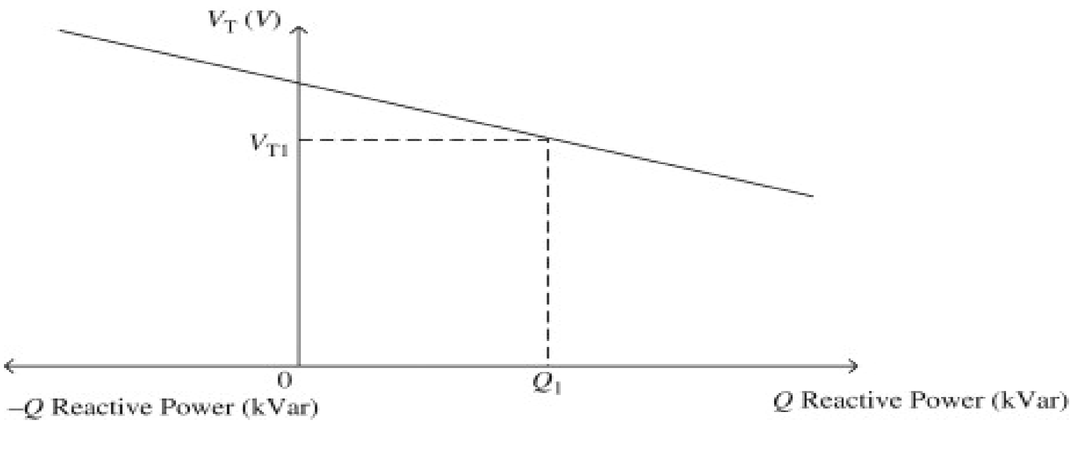



Figure 2. 3 *Reactive power vs voltage curve of a synchronous generator [14]*
The next section discusses the different types of synchronous generators.

## 2.3.1 Different types of synchronous generators.

### 2.3.1.1 Permanent magnet synchronous generators (PMSG)

The permanent magnet synchronous generator called so because in this synchronous generator excitation is provided with the permanent magnet instead of the external excitation source. Its rotor is consists of the permanent that generates a field for excitation and replaces the external supply source for the generator. The schematic diagram of a PMSG is shown in figure 2.4 . Advanced permanent magnet synchronous generator technologies provide high-efficiency in mechanical-to-electrical power conversion. Furthermore, it enables the construction of unique machines with extremely low speed, such as gearless wind and hydro applications, and very high speed, such as micro-gas turbines, which is of importance for numerous regenerative or co-generative power conversion technologies.

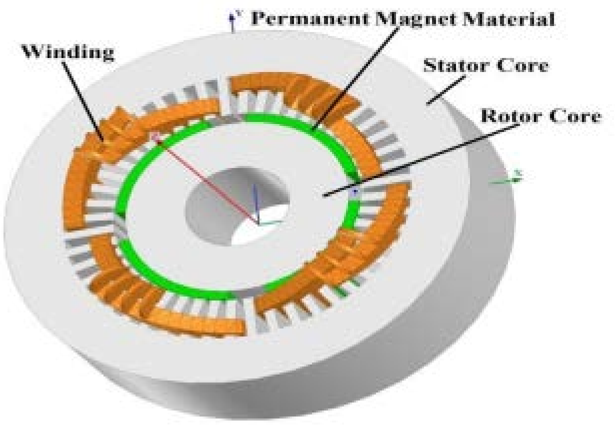



Figure 2. 4 PMSG schematic diagram [15]

When designing a permanent magnet, the working point should be chosen. When the working point of permanent magnet generator is 0.5, the maximum power is attained, according to He et. al [16], this can be achieved by using narrower torque angle to achieve high overload capacity, which increases the magnet strength and air-gap size, and the magnet embrace impacts the cogging torque and efficiency. In wind energy application, variable speed wind turbines are popular mainly because of their capability to capture more power from the wind using the maximum power point tracking (MPPT) algorithm and improved efficiency [17], hence the PMSG is preferred for this application due to its high efficiency, reliability, power density, gearless construction, and light weight and self-excitation characteristics.

There has been some research on the basic design technologies of a PMSG, Yang et.al in [18] developed a large wind generator based on a radial-type permanent magnet synchronous generator (PMSG). Initially the PMSG design method is introduced, and then electromagnetic theory is being used to compute the basic characteristics of the generator's construction. Zhang in [19] developed a suitable rotor structure for high-power performance for a large direct-drive permanent magnet synchronous generator for wind energy (PMSG). Generally, the rotor construction employs a surface-mounted permanent magnet (SPM). The PMSG examines salient pole machines that use both magnet and reluctance torque to achieve high-power performance.

However, researchers has mainly focused on the application of PMSG-based-wind turbines including the control strategies to ensure maximum power is achieved. In [20] the PMSG wind turbine's control scheme is described in detail, including both the wind turbine's own controls as well as those of its power converters. Chen et. al in [21] used perturbation observation based nonlinear adaptive control for a robust maximum power point tracking (MPPT) control strategy of a grid-connected permanent magnet synchronous generator based wind turbine (PMSG-WT). The authors of [22] discusses the power and possibilities of wind energy in meeting future energy demand. The thorough representation of the generator and wind turbine has emphasized on the interconnection of the generators and the challenges associated with it. MATLAB/Simulink is used to develop software models of wind turbines and PMSGs for wind power generation. Hence, it can be concluded that the PMSG is most suitable for wind generation applications.

#### 2.3.1.2 Virtual synchronous generators (VSG)

The dynamics of the electricity system have been significantly changed as a result of the widespread integration of RES around the world. Synchronous Generators' (SG) rotating masses have traditionally been employed to deliver the stored kinetic power following a generating deficiency however, the widespread installation of RES has resulted in the displacement of these traditional SGs [23]. In the future, the overall rotational inertia of the synchronous generators will be greatly reduced as small non-synchronous generation units replace a significant portion of synchronous power producing capacity. Therefore, electronically interconnected DGs cannot enhance system stability. However, a solution to this difficulty is established by applying the appropriate control techniques to the grid-connected inverter and managing its switching pattern so that it mimics the behaviour of SG and operates as if it were an SG [24]. Virtual synchronous generators VSGs are grid-connected inverters that mimic the steady-state and transient characteristics of SG.

Currently, VSG control is predominantly employed in grid-connected inverters of conventional distribution networks, whereas direct current control based on the principle of phase-locked loop synchronization is used to achieve voltage tracking and power transmission of the power grid[25]. Parallel operations of synchronous generators (SGs) and virtual synchronous generators (VSGs) are becoming more prevalent on a micro grid with the advent of VSG technology. The disparities between paralleled systems will influence the system's transient stability, which will likely jeopardize the system's stable operation, especially under fault conditions [26]. Depiction of the synchronous generator in power systems is first provided by M. Chen in [27] as the foundation for the VSG. VSG modelling approaches are thoroughly evaluated and contrasted. The VSG's applications in power systems are also outlined, as are the problems and future trends of VSG implementation.

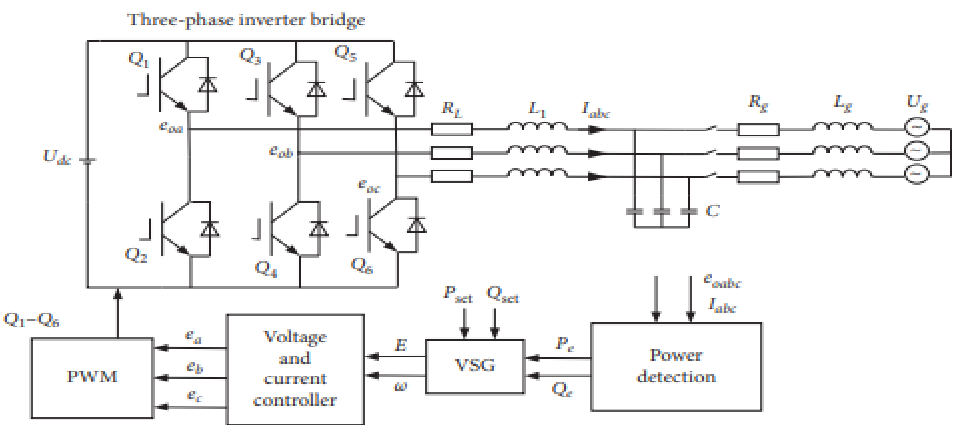



*Figure 2. 5* control topology for a VSG [28]

It may be inferred that the new method of generating electricity has offered a challenge to the existing power system's control system, and researchers are working to overcome this difficulty. Figure 2.5 depicts the VSG's primary circuit architecture and control block diagram, which includes a direct current (DC) voltage source, three-phase inverter bridge, LC filter, and transmission line impedance [28]. In conventional voltage regulation, the AVR modifies the SG's field voltage, hence controlling the transformer grid-side voltage's nominal set point. A rise in field voltage results in an increase in the reactive power produced by the generator, which causes a rise in terminal voltage. In a typical VSG architecture, a PI controller is employed to manage voltage and reactive power by adjusting the phase voltage of the inverter and evaluating the reactive power reference value [29]. AVR is beneficial in high-voltage networks but not in low-voltage networks due to the fact that a minor fluctuation in voltage optimum values coupled with high impedance in distribution lines causes a significant circulation of reactive currents between inverters [30].

## 2.4. Induction generators

An induction generator, also known as an asynchronous generator, is a form of alternating current (AC) electrical generator that produces electricity using the principles of induction motors. Because induction machines are non-self-exciting devices, when an induction generator is connected to a grid, it draws reactive power from the grid. To give reactive power to the induction generator, a capacitor bank is often connected across the stator terminals. These generators are divided into two types: Squirrel-Cage Induction Generators (SCIG) and Doubly-Fed Induction Generators (DFIG), as seen in figures 2.6 and 2.7, respectively.

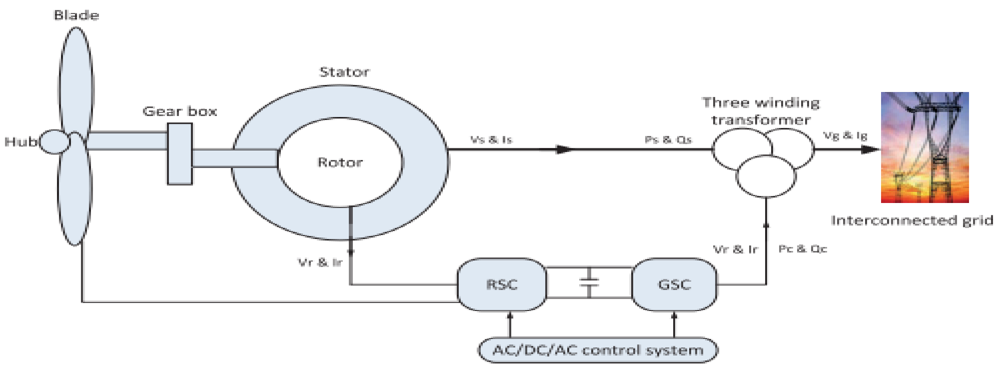



*Figure 2. 6* Double fed induction generator (DFIG)schematic diagram [31]

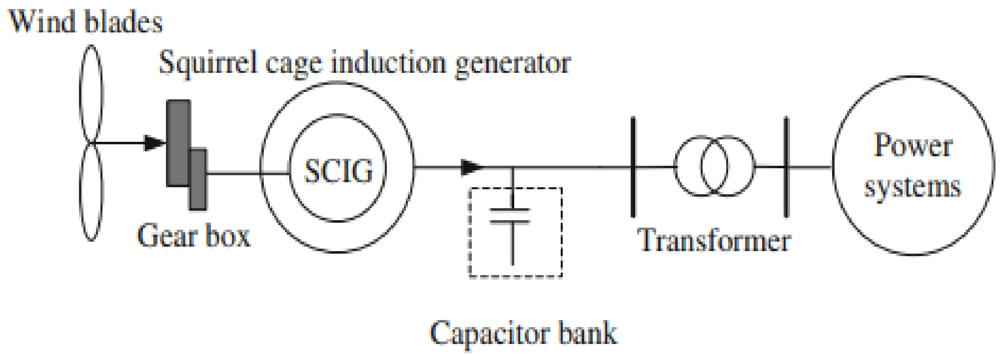



*Figure 2. 7* Squirrel-Cage Induction Generator (SGIG) schematic diagram[32]

Large synchronous generators are more efficient than asynchronous generators due to their ability to accommodate load power factor variations more easily. Due to the continuous increase in energy demand, there is now a greater emphasis on harnessing energy from non-conventional sources such as wind, biogas, and small hydro heads. Small hydro and wind power plants may benefit from an induction generator due to its reduced maintenance needs and simplified controls.

In isolated places where grid extension is not economically feasible, a small self-excited stand-alone induction generator may be found, hence these type of generators are also gaining popularity for wind energy conversion systems (WECS) application. Literature has been strongly recommending the application of DFIG and SCIG in the wind energy conversion systems. Many academics have emphasized the history of this technology's development, its significance, and its unique characteristic.

Because of the dynamic nature of DFIGs, It is vital to focus on developing high-performance control techniques [33]. According to Barambones et. al in [34] efficiency is a critical concern for these systems, and the use of robust control algorithms can significantly increase it, these generators are significantly more versatile than fixed speed generators since the turbine speed may be adjusted to enhance overall system efficiency. Bedoud et. el in [35] provided a performance evaluation of a variable-speed wind turbine based on a DFIG powered by a matrix converter, using the maximum power point tracking technique to extract the maximum possible power.

Azzouz et.al in [36] provided a fuzzy logic control of a DFIG wind turbine, to examine simulations, first create a mathematical model of the doubly fed induction generator expressed in an appropriate d-q reference frame. To control the stator powers of DFIG, a power active and reactive control rule is created using PI controllers. The design is also compared to that of the PI controller. In [37] a robust method dubbed nonlinear sliding mode control (SMC) with exponential reaching law control is used to provide a novel control system for a double feed induction generator for wind turbines with exponential reaching law control (ERL). The SMC with ERL demonstrates the ability to reduce system chattering while also speeding up the approaching process

The squirrel-cage motor is relatively inexpensive, extremely durable, and requires minimal maintenance in addition, rare earth minerals used in PMSG machines have recently experienced a shortage in supply as well as a significant increase in demand, which is anticipated to drive up their prices thus non-permanent-magnet-based generators such as the squirrel-cage machine are gaining renewed interest [38]. D.A Gorski et.al in [39] discussed connection technique of a converter-controlled squirrel-cage induction generator driven by an unregulated speed prime mover, this method major purpose is to reduce generator grid connection inrush currents.
Synchronization procedure is carried out by loading the induction generator with brake-choppers connected to the DC-link of the NPC converter. While it can be concluded that induction generators are commonly used f for wind energy conversion system, for conventional power plants a synchronous generator is remains the most commonly used generator

## 2.5 Power systems stability

The characteristic of a power system that allows it to remain in a stable state under normal operating conditions and to restore an acceptable state of equilibrium after being subjected to a disturbance is known as power system stability [40]. The classification of power system stability is discussed in section1.1, however the focus of this study will be more on voltage stability as the performance of an AVR affects the voltage stability. Keeping the steadiness and stability of the standard voltage level in an electrical power network with all connected equipment built for a specified voltage level is one of the primary control concerns in power systems. With the terminal voltage of a SG being affected by the unavoidable change in load demands, providing a control mechanism to keep up with these changes while maintaining voltage stability is critical.

The security and stability control system is the power system's second line of defence. Its dependability is critical to the operation of power systems [41], these control techniques are distinguished by three major features:

- The equipment is used to influence the dynamics of the power system.
- The control techniques that controls the device, which can be a breaker, the excitation system of a generator, or FACTS devices.
- The observations made on the power system are sent to the controlling agency. These provide details regarding the system's structure, voltage profile on buses and frequency of the system.

When generating and transmission units are still in design, power system stability is evaluated. Research is necessary throughout the designing phases to identify the relay protection scheme, circuit breakers, ideal clearing time, voltage levels, and transmission capacity between systems.

If the power system becomes unstable, the machines will no longer operate at synchronous speed, resulting in severe swings in voltage, current, and power, which might destroy loads supplied from an unstable system [42].Poor synchronization can cause mechanical stresses in the generator and prime mover due to rapid acceleration or deceleration, bringing the rotating masses into synchronism with the power system. The most common excitation controllers used to maintain generator synchronism in a power systems network are the AVR and power system stabilizer (PSS). One could argue that because voltage stability has a significant impact on generator synchronism, maintaining the terminal voltage is equally important in improving the stability of a power system network.

## 2.6 Voltage stability

Voltage stability is defined as the system's ability to maintain a constant voltage under normal operating conditions and even after being subjected to a disturbance/disruption. Voltage instability in a real power system is caused by a number of other variables, including network transmission capabilities, generator reactive power and voltage control limitations, load voltage sensitivity, and reactive compensation device features, and voltage control action. Among the causes of voltage instability in a power system are:

- centralized generation with a greater distance between the generation station and the loads
- An increase in the demand for reactive power.
- Working closer to the design limits and
- A natural or gradual increase in system load, which, if ignored, could result in a total blackout.

The sensitivity between system voltage response as more reactive power is injected into the system is one of the critical conditions for determining if the system is stable. If the bus voltage rises as more reactive power is injected, the system is said to be stable; if the voltage falls as more reactive power is injected, the system is said to be unstable. The risk of voltage instability on the network is continuous oscillation of the voltage even after attempting to establish the damping mechanism, which could result in a total blackout, thus keeping the voltage within an acceptable range is critical.

To increase voltage stability, power systems networks employ techniques such as automated voltage regulation at the terminal of synchronous generators.Although an AVR can help with synchronous generator terminal voltage maintenance, it has a negative impact on overall system damping. Power system stabilisers (PSS) are used to keep the system's overall damping constant. Literature has explore factors and affecting voltage stability as well as solutions. Kotenev et. al in [43] investigates the voltage instability of the electrical grid and the starting transients of asynchronous motors. Based on the presented model, the automatic reactive power control system (ARPCS) of the power system load node is created; it is an open-loop reactive power system with a closed-loop excitation current controller.

H. Zimmer et. al demonstrated how to utilize particle swarm optimization to optimize the settings of such PID regulators in order to greatly enhance transient voltage behaviour in [44]. The scientific community is not unfamiliar with AVR optimization. However, the majority of techniques use basic linear control circuits to represent the excitation and as PT–elements of a SG. Shimomura et. al in [45] developed a sophisticated over excitation limiter (OEL) that prevents the generator field winding from overheating and permits the generator to provide reactive power up to its threshold point. In turn, this improves the voltage stability of the power system by allowing the full range of a generator's reactive power giving potential to be utilized. Modern OEL's limiting margin is computed utilizing online computing.

In [46] a robust co-ordinated AVR-PSS using a fuzzy logic controller to effectively improve the power system stability of a single and multi-machine system in this case is developed this co-ordinated PSS improved the voltage stability of a single machine system and can then be applied to a multi-machine system. Jabidbonab et.al in [47] presented a stochastic technique for analysing voltage stability and optimizing the efficiency of a wind-integrated power system interconnected with a natural gas supply system. Adetotokun et. al in [3] investigated the influence of expanding wind energy penetration to 100 percent on voltage stability, as well as the resultant impact on system hardware burden.

The voltage stability issue has been a constant difficulty even in Morden grid technologies due to incorporation of large-capacity wind generation into a power system has a considerable effect on voltage stability [48], especially since a flaw in such a system might result in the tripping of a huge quantity of wind power generation . Toma et.al in [49] analysed the effects of incorporating renewables into the grids on voltage stability; Power System Analysis Toolbox (PSAT) and the continuation power flow (CPF) method are used to determine the P-V curves.

In [50] global sensitivity analysis (GSA) approach for completing a priority ranking of sustainable energy factors that may affect voltage stability is proposed. It is argued that the first step is to provide a probabilistic model for computing load margins with renewable energy output. When implemented to models with similar random input variables, the stochastic response surface approach is employed in GSA to increase the data computation efficiency, and the importance index is created to measure the impacts of such variables. This demonstrates that the power system has voltage stability issues that must be thoroughly investigated to prevent unneeded blackouts and equipment damage.

## 2.7 Reactive power control in power systems.

Reactive power is a quantity that has become fundamental to the understanding, analysis, and control of power systems, and there are still serious questions about how traditional controls influence the interaction between the flow of real and reactive power on a system level when the goal is to maximize real power transfer capabilities. Reactive power has a variety of effects on power system operation [51]:

- Loads require reactive power, which must be supplied by another source.
- The reactive power consumed by loads must be supplied by some source.
- The delivery system (transmission lines and transformers) consume reactive power, which must be supplied by some source (even if the loads do not consume reactive power).
- The movement of reactive power from the suppliers to the sinks creates extra heating of the lines and voltage dips in the network.

- Voltage dips are unwelcome. The development of reactive power has the potential to restrict the generation of actual power. As a result, one of the key challenges with reactive power is that although enough of it is necessary to provide loads and losses in the network, having too much reactive power moving around in the network creates extra heating and undesired voltage dips.

The response time of reactive power sources ranges between milliseconds and seconds. The most prevalent source of reactive power is the usage of synchronous machines. The excitation system, which supplies dc current to the synchronous generator's field winding, regulates the reactive power and maintains the desired voltage set point. The limitations of the Automatic Voltage Regulator (AVR) voltage, which indirectly regulates the amount of reactive power production, have a substantial impact on voltage collapse phenomena, and saturation of a unit's AVR voltage limits may result in worsening of voltage stability [52].

## 2.8 Generators excitation control

The creation of flux by flowing current through the field winding is referred to as excitation. Direct current is necessary to excite the rotor's field winding. Synchronous generators are the major component of an electrical generating system; their control has been accomplished in a variety of ways and may be divided into two control requirements: frequency control and output voltage control or automated voltage control (AVR).

The SG's terminal voltage is regulated using an AVR for field voltage excitation. Voltage control in induction generators, on the other hand, requires regulated capacitors. In addition, for them to operate in generating mode, their operating speed must exceed synchronous speed. Figure 2.8 depicts the frequency and voltage control techniques for the synchronous generator. Both controllers have an impact on the system's overall stability. Excitation System refers to the organization or system utilized for synchronous machine excitation. Exciter, a direct current generator, supplies direct current to the generators rotor field. The primary need of an excitation system is dependability under all operating situations, control simplicity, ease of maintenance, stability, and quick transient response.

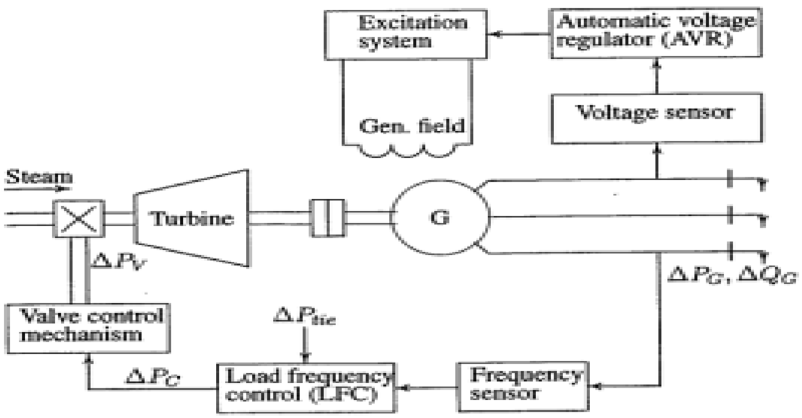



*Figure 2. 8* The concept of frequency and voltage control for a synchronous generator [4].

The conventional generating unit composed of a classical, wound-field, salient-pole, or cylindrical rotor synchronous generator that is stimulated by a separate smaller machine known as an exciter. Excitation energy source is used to categorize excitation systems. The quantity of excitation required is determined by the load current, load power factor, and machine speed. When the load current is high, the system requires additional excitation, which reduces speed and causes the power factor to lag. Barde et.al in [53],discusses the primary types of excitation systems, which include rotational either AC or DC and static excitation systems. This classification is divided into two primary groups: separate-excitation systems and self-excitation systems. These systems are further subdivided as follows:

- Brushless excitation system
- Static Excitation system
- Hybrid excitation systems

From the perspective of power engineering, the generator's excitation system serves two primary functions: controlling the terminal voltage and improving the power system's performance and stability mainly the Voltage stability. The excitation system of classical, wound-field, synchronous generators (SGs) is a component of a somewhat sophisticated feedback control system, the major role of which is to keep the output voltage constant at the stator terminals of the main machine.

This function is carried out by adjusting the exciter's output voltage through field current control. To investigate the performance of the synchronous generator and its excitation system, as well as to establish how the synchronous generator influences the stability of the electric power system, models of the generator and excitation system must be established.

Cheng et. al in [54] has primarily concentrated on Electric Excitation and Permanent Magnet Excitation in Brushless Pulsed Alternator System, extensive analysis and comparison of these excitation systems . In a study of the synchronous generator excitation system models that have been categorized thus far, as well as the various ways to govern those systems, excitation system models are explained, and their benefits and limitations are explored. According to Schaefer et. al in [55] previously, controlling the generator response using an analogue excitation method required tweaking potentiometers or adding or removing capacitors and resistors in the control loops of the voltage regulator stability circuit, which was time consuming and inefficient. Ma et. al in [56] proposed a DSP excitation controller based on TMS320F2812.

According to Zhu in [57] , the use of solid-state power electronic rectifiers for regulating field currents has significantly enhanced the responsiveness of excitation systems. It is considered rather difficult to build an appropriate model, in the excitation control system model, which includes dynamic, nonlinear, and complicated issues [58].
As a result, there have been significant advancements in the current technology addressing controls in power systems networks, including synchronous generator excitation systems. At the moment, more mature intelligent control approaches include fuzzy control, neural network control, expert control, learning control, fuzzy neural network control, and fusion control. Based on the present research status of excitation adjustment devices at home and abroad during those times.

Dang et. al in [59] presents an excitation controller architecture based on fuzzy PID. The input and output variables of the fuzzy controller, the domain of language variables and membership functions, the selection of quantization factor, an average weighted fuzzy method, and scale factor in the fuzzification process have been determined based on excitation control experience, and 49 fuzzy control rules have been established.

Shengji et.al in [58] presented a fuzzy-PID control technique based on the Mamdani fuzzy model, which is suggested by merging fuzzy theory with traditional PID control legislation. The fuzzy Mamdani model is introduced based on developing a basic model of an excitation control system. The voltage control effects of two types of fuzzy models of a PID excitation control system are examined using a MATLAB Simulink. The fuzzy type II system is utilized in [60] to construct the PID controller coefficients. To demonstrate the efficacy of the suggested technique, the simulation results of three controllers in the presence of uncertainty are compared: standard PID, type I fuzzy PID, and type II fuzzy PID. Kumar et.al in [61] proposed the design of a cascaded integer order (IO) PID - fractional order (FO) PID controller for a synchronous generator excitation system using an evolutionary multi-objective-based optimization technique. Hence these shown a significance of employing the advance controlling techniques to improve the transient response of a SG excitation systems.

## 2.8.1 Excitation systems technologies

DC exciters were used in excitation systems (ES) in the 1960's these DC generators were used as power sources operated by a secondary motor or the main alternator shaft, and they send DC current to the field windings via slip rings [62]. DC excitation methods represent early commercial systems (from the 1920s through the 1960s) and now have only historical relevance, as AC exciters have surpassed them [63]. Since the 1960s, the most widely deployed ESs have been categorized into three kinds of systems that are static, brushless, and integrated excitation systems. Excitation systems are further classified based on their excitation power gain into independent and dependent excitation systems with a standalone exciter is not linked to the power grid hence its excitation parameters do not have a direct connection with grid parameters [64].

### 2.8.1.1 Brushless excitation systems

Brushless ES are made up of an exciter machine and a spinning rectifier that are positioned on the same shaft as the primary alternator, as seen in Figure 2.9. The expenditures of maintaining and replacing hundreds of carbon brushes used in generators become unnecessary [65] hence, removal of brushes from the excitation system of synchronous generators is thus critical. This lowers the transient characteristics of the generator voltage regulation amid power cuts and may result in a high voltage overshoot at the SG terminal. Authors in [66] developed, a new optimization approach based on improved genetic algorithm (IGA) for predicting the parameters of brushless excitation system incorporating nonlinear blocks. A novel variable-speed constant-frequency power producing system for renewable and distributed energy applications is discussed in detail [67], including its modeling, control, and implementation.

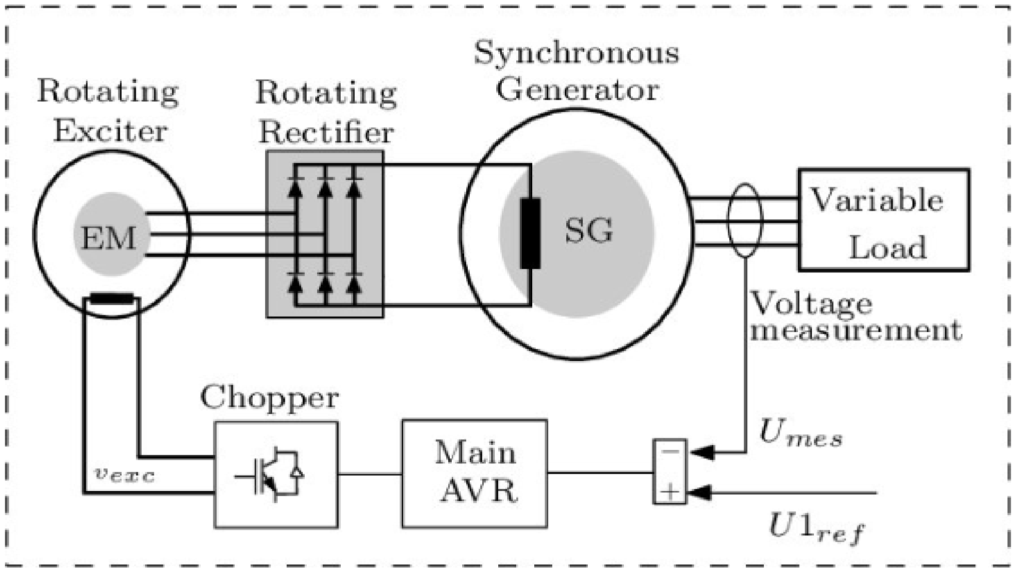



*Figure 2. 9* Schematic representation of a brushless excitation system.

Analog electronics has typically been used in automatic voltage regulators for small to medium scale brushless stimulated synchronous generators however modern voltage regulator systems are beginning to use the microprocessor's power, flexibility, and cost advantage for control [68]. Furthermore, digital voltage regulators have the benefit of being simple to develop compensators for.

#### 2.8.1.2 Static excitation system

All components of this type of excitation system are static, and the generator's field circuit is fed by slip rings [69].Because the field excitation power in a static excitation system is taken from the generator output terminals, it can only operate when the generator is running normally and steadily, during startup, excitation power must be supplied by a different source [70] as seen in Figure2.10 , this is generally made available through the use of a battery bank. This system includes rectifier transformers, an SCR output stage, excitation start-up and field discharge equipment, as well as a regulation and operational control circuit. Because there is no rotating part in this system, there are no windage or rotational losses.Static exciters are mostly utilized for large synchronous generators with power ratings of several MVAs that must meet established technical standards for dynamic performance [63].

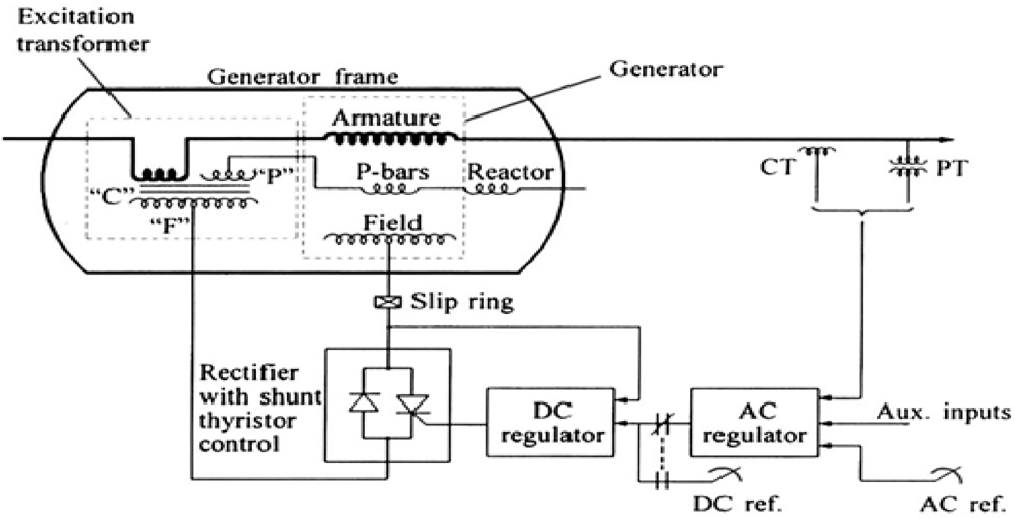



*Figure 2. 10* Schematic diagram of a static excitation system

### 2.8.1.3 Hybrid excitation systems

Hybrid excitation synchronous machines (HESM) machine gained more recognition in recent years as a result of the increased focus on energy saving and wide timing drive system and independence generate electricity system (such as wind power generate electricity) [71]. HESMs are electrical devices with two excitation flux sources: Permanent magnet (PM) and field coil sources of excitation [72]. The hybrid excitation strategy is intended to combine the advantages of PM excited machines with WF synchronous machines. The hybrid excitation idea offers a solution to a number of issues related with electric machines, including flux weakening, energy efficiency, and price fluctuations of PMs [73]. Hybrid excited synchronous generator (HESG) combines benefits of permanent magnet generator and flux control capability in airgap by using additional excitation field windings [74]. The excitation winding is positioned in the rotor's central slot it is then connected to two slip rings and then led out of the stator end cover via a brush. Such a design is prospective for use in autonomous wind energy systems because it extends regulation ranges and increases the efficiency of wind energy electricity [75].

Numerous researchers have investigated this type of wind application excitation system. Based on traditional permanent magnet synchronous generators, the author [76] developed a new axis-flux hybridexcitation generator for wind turbines this compensate for the ripple of axial force fluctuation, the asymmetric primary design generates a controllable suspension levitation force. In A hybrid excited flux switching Vernier machine's are developed, this device is intended for renewable energy conversion applications such as wind turbine generators and tidal turbine generators the design is based on finite element models.

Mseddi et. al in [77] developed a Hybrid Excitation Synchronous Generator (HESG)-based WCS with an isolated load and first integrated a H∞ controller. After that, a CRONE controller is developed; analyses indicated that it outperforms the H∞ controller in terms of mechanical stress reduction and parametric uncertainty, but the H∞ controller is superior in its ability to filter out unwanted inputs. The schematic diagram of a HESG is shown in figure 2.11. According to et. al [78] the HESG offers flux control through enclosed excitation coils advantage as compared to PM generators.

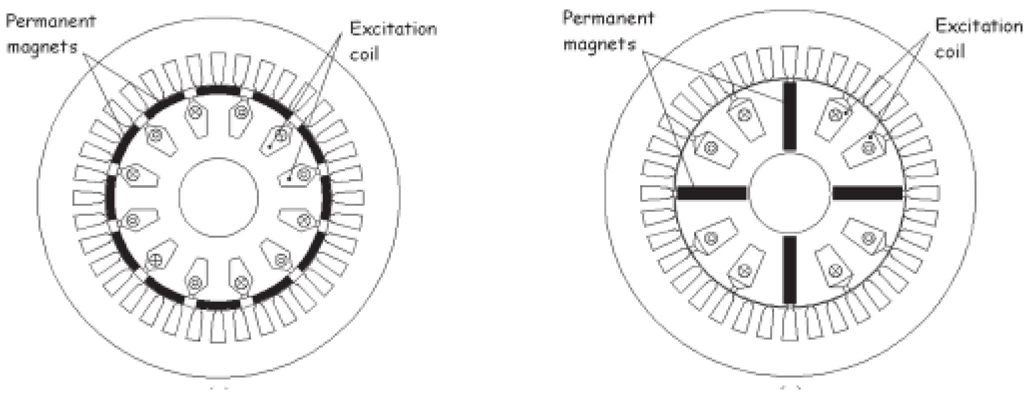



Figure 2. 11 Hybrid excitation systems [79]

## 2.9 An Automated Voltage Regulator (AVR)

Every time there is a change in the reactive power of the central load, there will be a corresponding change in the voltage at the generator terminal. Different types of reactive power , such as that produced by field amplifiers, are monitored and controlled by an automatic voltage regulators (AVR) in the power grid. The voltage profile, including the voltage at the generator terminal, is affected by variations in reactive power in the system [80].

Each generator in a power system is provided with a load frequency control (LFC) system and an automated voltage regulator (AVR) to maintain a steady frequency and a constant voltage output respectively [81]. One of the stability difficulties in electrical power systems is small signal stability around an operational point, which involves minor variations in voltage and frequency of the power systems AVR, LFC, and power system stabilizers (PSS) are employed to counteract this impact.

The automated voltage regulator (AVR) is a controller in most modern systems that monitors the generator output voltage (and occasionally current) and then takes corrective action by adjusting the exciter control in the appropriate direction. The kind of AVR control approach used can significantly affect the capability of each form of excitation control circuit. Typically, the AVR serves a critical function in power system management and control by maintaining the terminal voltages of the generator at a predetermined level even when the load fluctuate.
It also plays a critical role in monitoring reactive power sharing across parallel-connected generators. AVR operation should be so efficient that precise control over reactive power, decrease in active power loss, and fixed terminal voltages of the AVR are possible. It operates on the error detection concept. The output voltage of an ac generator is acquired via a potential transformer, rectified, filtered, and compared to a reference. The error voltage is the discrepancy voltage to the reference value. An amplifier amplifies the error voltage before supplying it to the main exciter or pilot exciter. The management of the exciter output leads to the control of the main alternator terminal voltage. Figure 2.12 depicts an AVR architecture. The type of controller employed has a significant influence on the performance of an AVR.

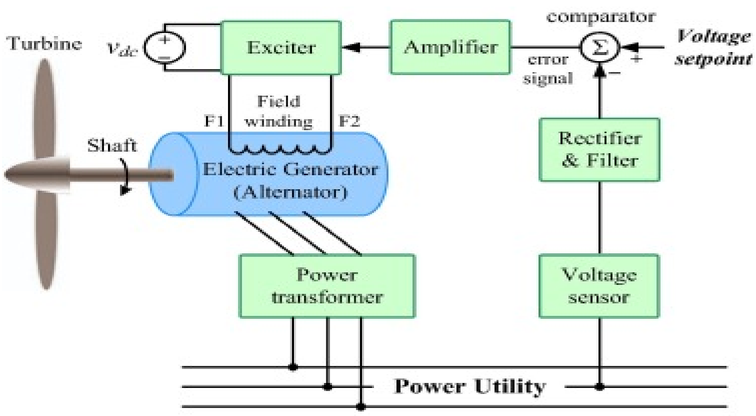



Figure 2. 12 The Schematic diagram of an AVR of a power system [82]

The type of controller employed has a significant influence on the performance of an AVR. Achieving stable and fast response of an AVR system is challenging as a result of the high inductance of the windings of a synchronous generator (SG). As a result, improving AVR performance is critical, and an adequate controlling technique is required to achieve this, the next section (section 2.10) will discuss the controlling techniques available in literature. There has been some existing literature in the context of modeling and analyzing the performance of an AVR. Gozde et. al in [83] discusses an AVR controller simulation model constructed in power system using real data. In [1, 84-88], a transfer function model of an AVR was used to investigate the performance of various controllers. Reduced-order modeling is utilized in [89] to create an AVR model. Gupta et. al in [90] presents a mathematical model of an AVR.

The AVR is not strong enough against disturbances on its own, necessitating the use of an extra controller to increase the AVR's dynamic performance. Controlling the Automatic Voltage Regulator intelligently, robustly, and reliably is critical [91]. Hence, this research will use the transfer function model of an AVR to critically investigate its performance when subjected to disturbances.

## 2.10 Controllers for an AVR system

Because of the system's complexity, the key issues in the power system include nonlinearities, uncertainties, interaction between control loops, and the sorts of disturbances [92]. Control strategies in the AVR system have been devised to tackle these nonlinearities, uncertainties, and disturbance concerns. The performance of an AVR is greatly dependent on effective control design, which improves the output of the AVR by restoring the voltage of the synchronous generator to its nominal value in the presence of minor disturbances. The selection of a suitable controller is one of the most difficult aspects of developing an AVR system [5]. According to S Chatterjee in [9] Genetic algorithms, fuzzy logic, and neural networks are all AIs -based modern computing techniques that are prominent in informatics, but applications focus on these novel approaches to digital computing are progressively being established for potential implementation in science and engineering.

Because of the complexities of the power system, such as variable operating points and non-linear load characteristics, the existence of extra mathematical calculation may render standard self-tuning control strategies ineffective in specific operating situations [93]. Hence, the need for application of latest control technologies such as PID and AI technologies to improve the AVR performance.PID has long been the most popular controller for industrial applications such as automatic voltage regulators. According to Ahcene et.al in [88] studies shows that one of the difficulties in its control system design is identifying the controller's gain settings. To overcome this difficulty, researchers investigated several methods.

Ekinci et. al in [86] proposes a novel tuning design of a proportional integral derivative (PID) controller using an improved kidney-inspired algorithm (IKA) with a new objective function, where after obtaining the optimal values of the PID controller's three gains (KP, KI, and KD), a transient response analysis is performed and compared with some of the current heuristic algorithm-based approaches. Pole/zero map analysis and Bode analysis are used in the literature to assess the stability of an AVR system. Chatterjee et. al in [94] used optimization to build PID controllers for AVR of power systems. The author also tested the robustness of the proposed controller by permitting 50% uncertainty in the automated voltage regulator system. To assess the stability of an AVR system, root-locus and bode plots are employed.

PID controllers are utilized in a wide range of automatic process control applications. Optimal tuning of the controller's gain has existed for a long time. These parameters are determined using trial and error or using established Ziegler-Nichols, Cohen-Coon, and other techniques. Most manual approaches are no longer employed due to better optimization software. According to Ekinci et. Al in [86], the PID gains are obtained by the ZN method at nominal operating condition these gains are specificly for the model under the study and they are $K_P$=1.0210 , $K_I$=1.8743 and $K_D$=0.1390. The step response is highly oscillatory (Mp % = 51.495) and the settling time (ts=3.0516 s) is quite long this is illustrated in figure 2.13

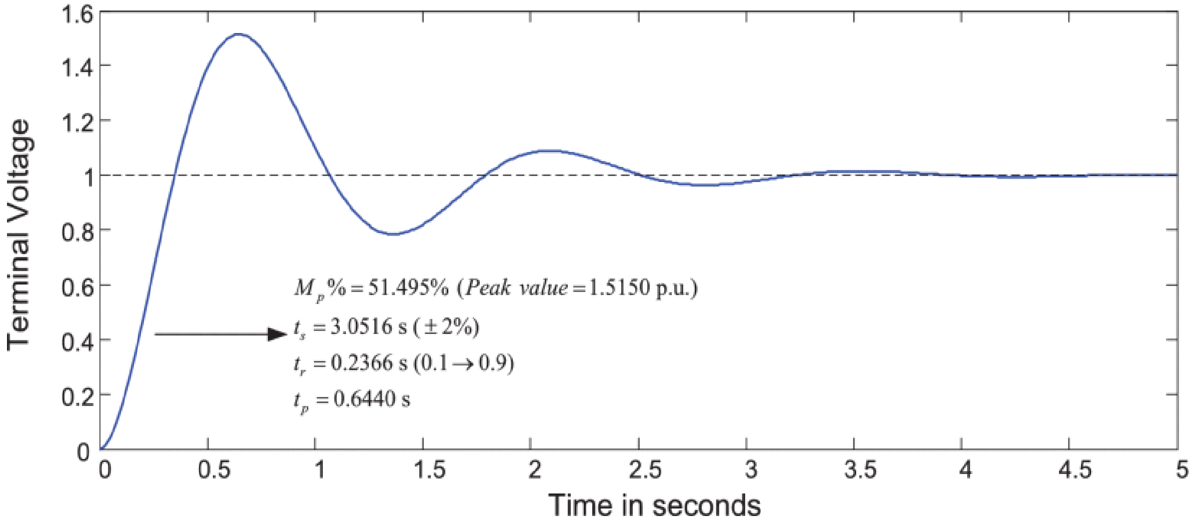


Figure 2. 13 The response of a PID-based-AVR tuned using ZN technique[86].

In recent years, evolutionary-based heuristic optimization techniques for establishing PID gain settings for an AVR have been presented as an alternative to the previously described standard tuning approaches that fail to work. According to M. Ćalasan [87], several algorithms of optimization have been used in designing a PID for an AVR , indicating a common challenge in establishing the perfect algorithm in the context of PID-based-AVR. In the available literature, the methods and optimization methodologies are particle swarm optimization (PSO)[88, 95, 96], symbiotic organism search (SOS) [97], genetic algorithm (GA) [98], grasshopper optimization algorithm (GAO) [99, 100], gravitational search algorithm (GSA) [101], artificial ecosystem-based optimization (AEBO) [87, 102], salp swarm optimization (SSO) [103, 104], improved whale optimization algorithm (IWOA) [105], water cycle based optimization (WCBO)[106], improved kidney inspired optimization [86], neural network algorithm (NNA) [107], cuckoo search (CS) algorithm [108, 109].

These optimization techniques have shown to be an excellent study topic for increasing PID controller performance. However, each has advantages and disadvantages when compared to the other. The concept of PID controllers is further discussed in chapter four. The summary of controller gains using several optimization technique is presented in appendix E as referenced to [87] , and typical step response PID tuned with different algorithms is shown in figure 2.14.

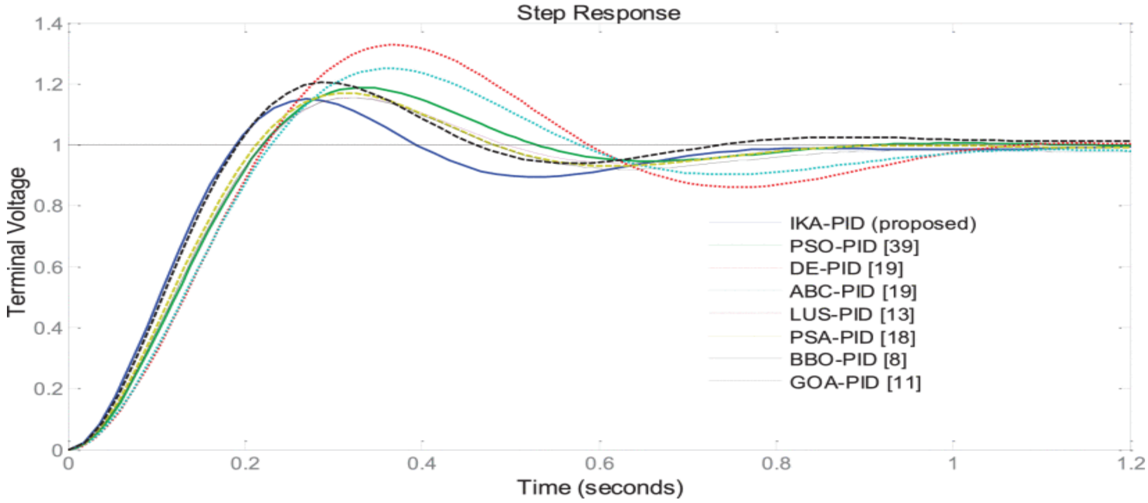
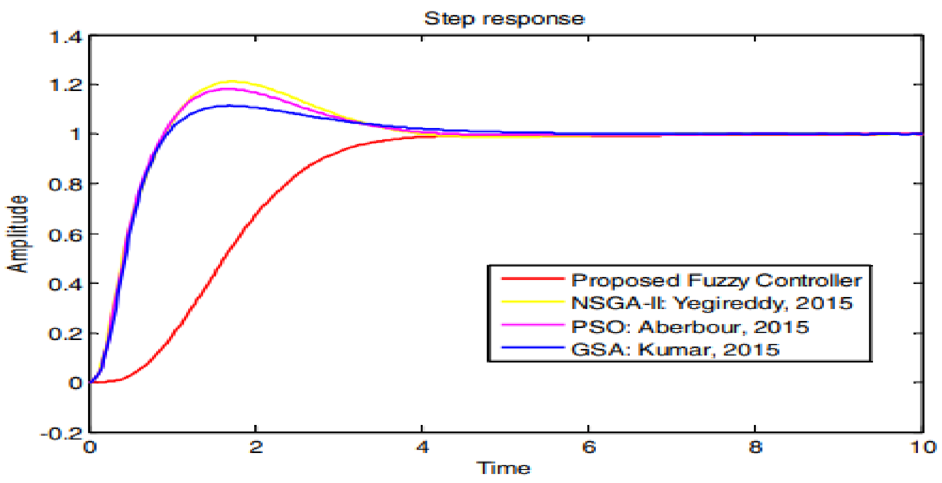
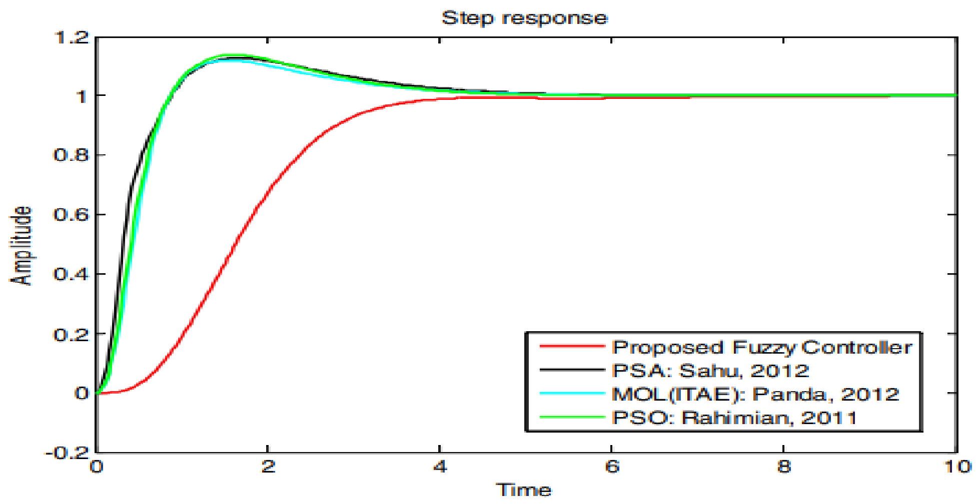



Figure 2. 14 Comparison of different tuning algorithms for tuning a PID-based AVR [87].

Artificial Intelligence (AI) technologies have been shown to be effective in tackling a variety of power system challenges, and when combined with conventional mathematical approaches, they can be much more effective. Artificial Neural Networks (ANN), fuzzy logic, intelligent optimization, hybrid artificial intelligent methods, and expert systems are examples of these techniques. There has been some research on fuzzy logic-based controllers for applications involving synchronous generator voltage regulation. Two robust controllers have been developed in [110] that utilize a single-machine infinite bus (SMIB) structure to autonomously adjust the synchronous generator voltage across a wide range of system parameters. The authors of [111] addressed the performance of a FLC used in conjunction with an AGC/AVR loop in a single area power system. In [112], a fuzzy-FOPID is utilized as a controlling mechanism to regulate the output of an AVR. In this investigation AVR system with FLC and compare with conventional PID controllers such as NSGAII, PSO-PID, PSA-PID, GSA-PID, MOL (ITAE). In the presented work, proposed FLC based AVR system generate the uniformly stable operation in comparison to others and also peak is completely reduced the results are illustrated in figure 2.15.




(a)




(b)

Figure 2. 15 Fuzzy-PID step response [112]

Heng at.al in [113] developed a controller using particle swarm optimization and fuzzy proportional integral derivative (PSOFPID). In [114], a unique concept for a fuzzy PID controller with interval type-2 fractional order is proposed. Falahati et.al in [115] employed a fuzzy-PID controller. Dang et. al in [116] examined application of Interactive Adaptive Fuzzy Algorithm (IAFA). Cuesta et. al in [117] a solution based on non-traditional component control approaches, such as fuzzy logic, was developed for enhancing the performance of an AVR. It is verified that the suggested fuzzy control may enhance both the rise time and over oscillation time (see Fig. 2.16), as this response stabilizes 6 seconds earlier than the traditional PID.

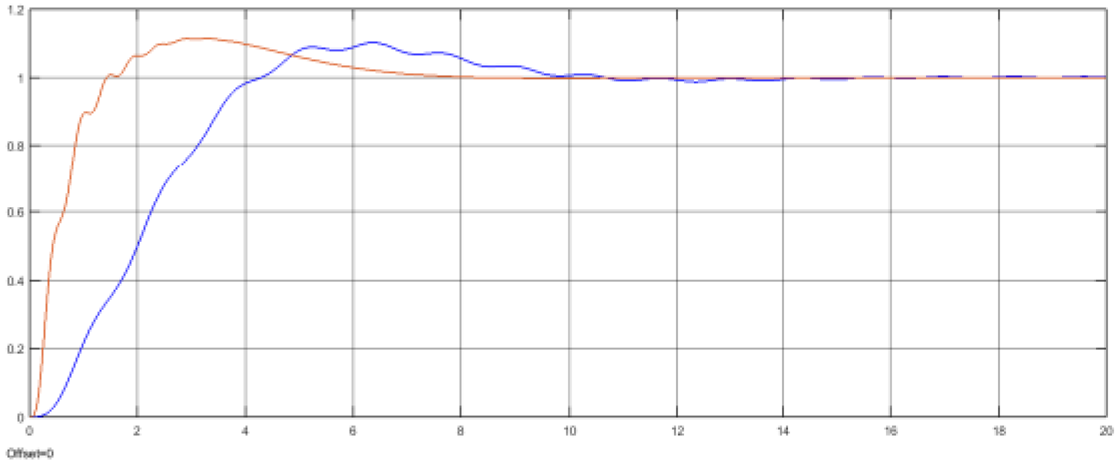



Figure 2. 16 PIV vs conventional PID step Response[117].

An automatic voltage regulator (AVR) based on artificial neural network (ANN) is presented for a standalone synchronous generator is presented in[118]. The author has setup a SG, asynchronous motor, frequency inverter and load groups and trained the ANN using obtained data, three learning methods are defined on MATLAB. To improve the transient stability limit of the power system, Butto et al. [119] proposed and implemented an AVR based on a probabilistic neural network. In order to enhance the responses, a newly born file containing the neural network's computations the model is simulated in parallel with the PID controller. Figure 2.15 illustrates the corresponding step response, which shows an improvement over the original experiment, with a rise time of 0.03 seconds, an overshoot of less than 1.4 percent (very negligible), and a settling time of 0.28 seconds. However, by experimenting with additional control methods, this percentage can be reduced to zero.

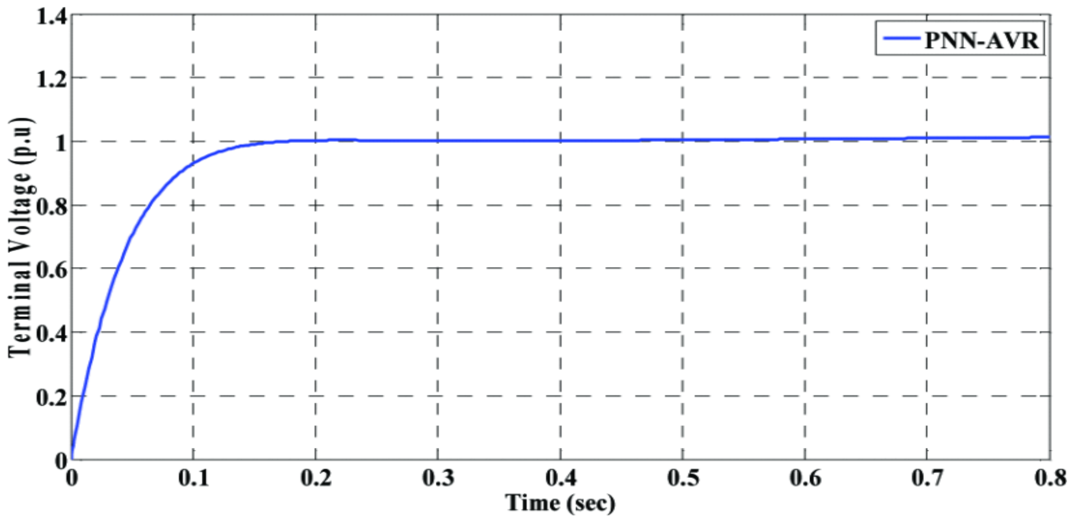



Figure 2. 17 PNN-based AVR step response [119]

Another emerging controlling mechanism for AVR system is the Model Predictive controller (MPC). The main benefit of the MPC technique is the ability to predict future control input based on the best future feature of the plant output. There is a scarcity of literature in the field of MPC for AVR. MPC is developed to enhance an AVR and frequency control loops in [120], the authors applied Harris Hawks Optimization (HHO) to tune the MPC's weights. Orusun et. al [121] used MPC to maintain the overall voltage profile of a single area power system within the acceptable limits. The excitation voltage was automatically regulated to keep the power system in a steady state. The authors of [122] developed a new technique for designing fractional-order MPC for the liner-time invariant class. The concept of this controlling mechanism is further discussed in chapter five.

## 2.11 Conclusion

This chapter has expanded on the existing literature in the context of the power system overall network, as well as the condition of the power system network in South Africa. The chapter also discussed various types of generators used at power plants, voltage and reactive power regulation, such as excitation systems used to maintain the terminal voltage of a synchronous generator and improve power system voltage stability. The chapter also looked at several control strategies for improving the dynamic performance of excitation systems. The authors have proved that the traditional method of managing the terminal voltage of synchronous generators is ineffective and time consuming.

As a result, the development of cutting-edge control techniques such as electronics and artificial intelligence has had a substantial influence on boosting the dynamic performance of an AVR. This study will explore PID controllers, which are one of the most often utilized control strategies in the industry owing to its simplicity and efficacy. Later on, AI methods like as MPC and FLC are used to increase the responsiveness of a PID-based AVR. These control approaches are developed and presented in chapters four to six. The AVR is initially explored without a controller to determine the vital requirement for improving its dynamic responsiveness, which is discussed in chapter three. All of the models are simulated using 2020a version of MATLAB SIMULINK.

## CHAPTER THREE

## AUTOMATIC VOLTAGE REGULATOR (AVR)

### 3.1 Introduction

This chapter describes the modeling, design, and performance analysis of a synchronous generators Automatic Voltage Regulator (AVR). To study the reaction of the system when subjected to disturbances, a mathematical model of an AVR is developed and simulated using MATLAB Simulink version 2021a. The disturbance on the terminal voltage is introduced by adjusting the generator gain (Kg) while maintaining the time constant (Tg) at 1. For the purposes of this study, the close loop transfer function is investigated, and the AVR is represented by the transfer function.

### 3.2 Modelling of an AVR system

An AVR's function is to keep the generator terminal voltage constant at different load levels. To manage the terminal voltage, the excitation control system's AVR loop uses terminal voltage error to change the field voltage. An AVR system is made up of four major components: an amplifier, a sensor, an exciter, and a generator. Sections (3.2.1) to (3.2.4) [123] defines a mathematical model for each component. Figure 3.1 depicts the entire transfer function model of an AVR on MATLAB Simulink 2020a.

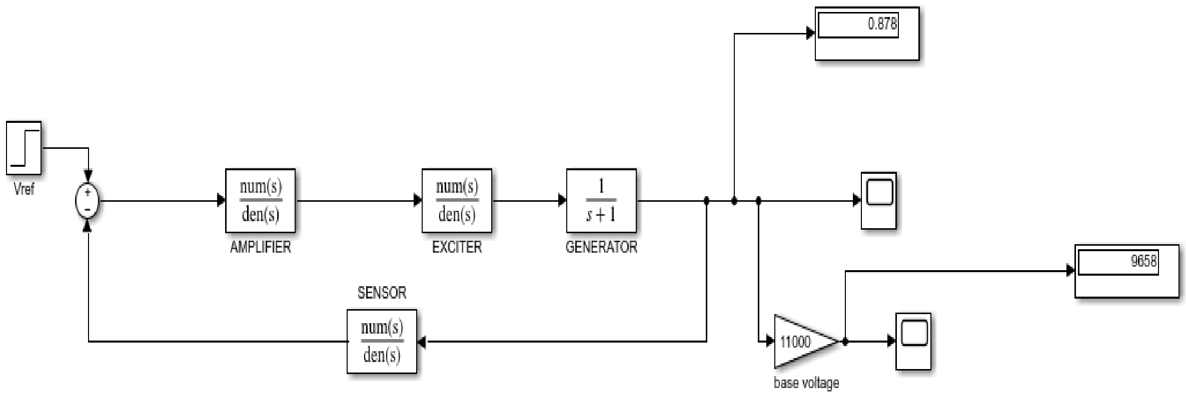



*Figure3. 1* Model of an AVR under this research work

### 3.2.1 Amplifier model

Amplifier model expressed by a gain with $K_A$ and time constant $T_A$ the transfer function is with the value of $K_A$ ranging from 10 to 400 and time constant $T_A$ with the range of 0.02 to 0.1 seconds. The transfer function is defined by equation 3.1

$$\frac{V_R(s)}{V_e(s)} = \frac{K_A}{1+T_A s} \qquad 3.1$$

### 3.2.2 Exciter model

The exciter model can be expressed by a gain with $K_E$ symbol and single time constant $T_E$ , and the transfer function is denoted in the equation below. Gain ranges from 10 to 400 and time constant ranges from 0.5 seconds to 1 seconds, the transfer function is defined by equation 3.2

$$\frac{V_F(s)}{V_R(S)} = \frac{K_E}{1+T_E s} \qquad 3.2$$

### 3.2.3 Generator model

In a linearized model the relationship transfer function of terminal voltage of a generator to field voltage can be expressed by gain $K_G$ and time constant $T_G$ the transfer function is defined by equation 3.3

$$\frac{V_T(s)}{V_F(s)} = \frac{K_G}{1+T_G s} \qquad 3.3$$

### 3.2.4 Sensor model

Sensor model expressed by a gain with $K_R$ and time constant $T_R$ the transfer function is with the value of time constant $T_A$ ranging from 0.001 to 0.06 seconds the transfer function is defined by equation 3.4

$$\frac{V_S(s)}{V_T(s)} = \frac{K_R}{1+T_R s} \qquad 3.4$$

As described in section 3.2, the AVR detects terminal voltage variations caused by changes in load demand or power supply failures and feeds them back to the comparator after they have been corrected.

At the comparator, the feedback signal is compared with the reference signal to generate an error signal, which is then amplified and delivered to the exciter. The exciter, which controls the field to reduce the error to zero, plays the most important part in the complete loop. The exciter's output is then delivered to the generator to generate a step response with constant and rated terminal voltages.

The AVR model's open loop GOL(s) and closed loop GCL(s) transfer functions are calculated using equations (3.5) and (3.6), respectively. These two transfer functions are utilized to study the AVR system's stability and dynamic performance. The value of Kg is adjusted from 0.7 to 1 while TG is held constant to examine the effect of changing the terminal voltage on the step response, hence analysing the transience response of an AVR under diverse load conditions. Table 3.1 displays the model values for this research.

Table 3. 1 Model description for each component

| Description | Value |
|---|---|
| Ka | 10 |
| $T_A$ | 0.05 |
| $K_R$ | 1 |
| $T_R$ | 0.01 |
| $K_E$ | 1 |
| $T_E$ | 0.05 |

$$GOL = \frac{K_A K_E K_G}{(1+T_A s)(1+T_E s)(1+T_G s)} \quad 3.5$$

$$GCL = \frac{K_A K_E K_G (1+T_R s)}{(1+T_A s)(1+T_E s)(1+T_A s) K_A K_E K_G} \quad 3.6$$

## 3.3 Results and discussion

The examination of the transient response of the AVR system is recorded when the terminal voltage of the generator is adjusted. The corresponding step response of the system without a controller is shown in Figure 3.2. According to these findings, the system terminal voltage deviates from the nominal value of about 50%, and the voltage after settling time is less than the nominal voltage of a SG (below 1pu). Such performance is entirely undesired in a power systems, because the complex equipment linked to the network is very sensitive to voltage changes and either starts malfunctioning or trips inadvertently. Table 3.2 displays the numerical results of the system's response when the voltage is disrupted. It is concluded that as the value of KG increases, so does the generator's peak terminal voltage. The best performing model for the AVR without a suitable controller is when KG IS 0.7; for this reason, its step function is utilized for comparison when the controller is implemented in the next analysis where the AVR is equipped with a controller.

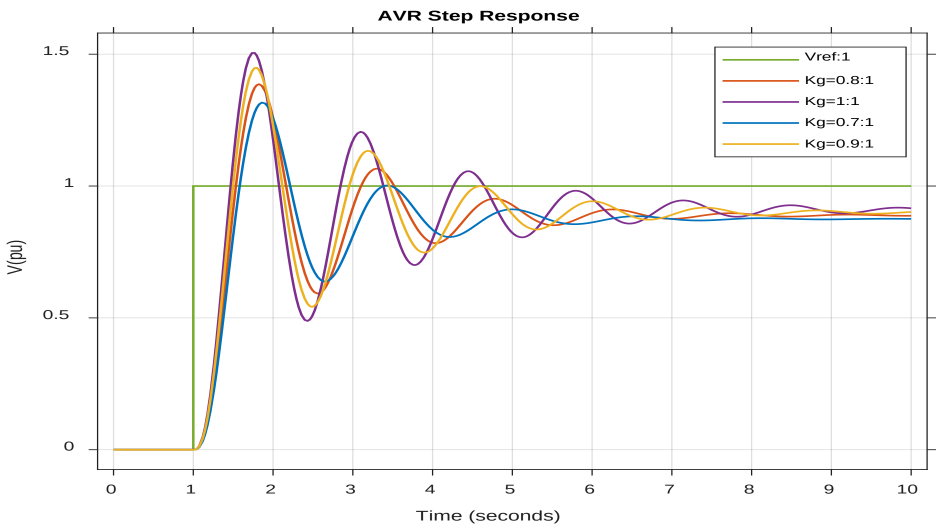



*Figure3. 2* AVR step response when the terminal voltage is disturbed

Table 3. 2 Numerical results of an AVR system subjected to disturbances without a controller

| Kg | % Os | Rise time(s) | Settling time (s) | Peak |
|---|---|---|---|---|
| 0.7 | 50.52 | 0.318 | 4.91 | 1.32 |
| 0.72 | 51.6 | 0.313 | 4.9 | 1.33 |
| 0.75 | 53.2 | 0.306 | 4.78 | 1.35 |
| 0.8 | 55.9 | 0.295 | 5.42 | 1.39 |
| 0.85 | 58.5 | 0.285 | 5.59 | 1.42 |
| 0.9 | 61 | 0.276 | 6.43 | 1.45 |
| 1 | 65.6 | 0.261 | 7 | 1.51 |

## 3.4 Conclusion

A simple model of an AVR is developed and simulated in this chapter. The model demonstrated a poor performance of the AVR system in the absence of the controller. The synchronous generator's terminal voltage has deviated more than 50% and has settled below the rated terminal voltage of a synchronous generator; such performance is undesirable for a power systems network. It has been established that an effective controlling mechanism is essential to improve the dynamic responsiveness of an AVR and hence improving power system's voltage stability.

# CHAPTER FOUR

## Implementation of a PID controller for an AVR system.

## 4.1 Introduction

This chapter discusses the application of a conventional PID for the AVR systems in order to enhance its transient responsiveness. The control method is studied by mathematically modelling and simulating the models on Matlab Simulink. Suitable controller gains (Kp, Ki, and Kd) for the AVR system represented by a transfer function. The effect of the developed controller is evaluated by interpreting transient response and performance indices (ITA, ITE, ITSA, and ITSE) data. The Model is implemented on MATLAB Simulink for investigation and tuning of appropriate gains parameters.

## 4.2 The concept of a PID controller

Commonly used in industrial control systems is a feedback mechanism called a proportional-integral-derivative (PID) controller. The PID controller determines the error value as the deviation of the process variable from the desired set point. The goal of the controller is to alter the process with the help of a regulated variable in an effort to minimize error. Due to its use of the proportional, integral, and derivative values (P, I, and D, respectively) as constant parameters, the PID controller approach is also known as "three-term control.

### 4.2.1 Proportional term

The proportional term delivers a value proportional to the error value currently in effect. Adjusting the proportional response is accomplished by multiplying the error by the proportional gain constant, Kp. The proportionate term is determined by the equation 4.1.

$$P_{out} = K_p e(t) \qquad 4.1$$

### 4.2.2 Integral term

The contribution of the integral component is proportional to the amount and duration of the mistake. It is the sum of the instantaneous errors throughout time, representing the cumulative offset that had previously needed to be rectified. The cumulative error is then multiplied by the integral gain KI and added to the output of the controller. Integral term is calculated using Equation 4.2.

$$I_{out} = KI\int_{0}^{T} e(t)dt \qquad 4.2$$

### 4.2.3 Derivative term

The process error's derivative is computed by estimating the slope of the error over time and multiplying this rate of change by the derivative gain KD. The derivative gain, KD, is the magnitude of the derivative term's contribution to the total control action. Equation 4.3 determines the derivative term.

$$D_{out} = KD\frac{de(t)}{dt} \qquad 4.3$$

Some controllers may only require two controller parameters, such as PD, PI, and so on. This can be accomplished by setting the third parameter to zero. As seen in table 4.1, each of the three PID parameters contributes to the controller's performance in its own way. Figure 4.1 depicts a full PID controller architecture.

Table4. 1 The impact of increasing parameters of a PID controller independently

| parameter | Rise time | Overshoot | Settling time | Steady state error | Stability |
|---|---|---|---|---|---|
| $K_P$ | Reduces | Rises | less change | Reduces | Degrades |
| $K_I$ | Reduces | Rises | increases | Eliminates | Degrades |
| $K_D$ | Less change | Reduces | Reduces | No effect | Improve if $K_d$ is small |

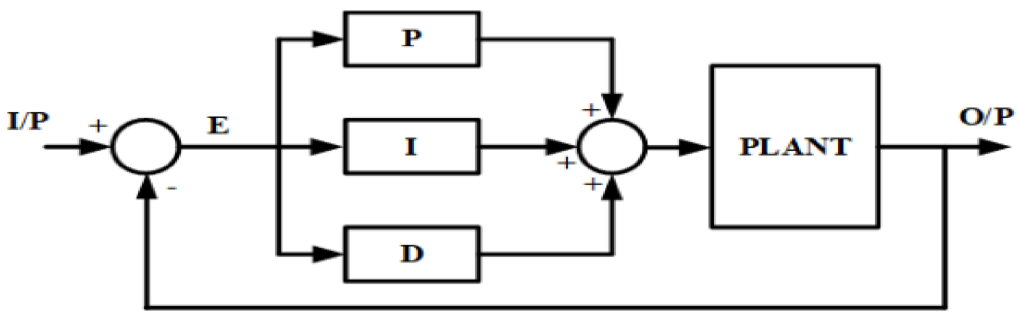



*Figure4. 1* PID controller configuration [124]

### 4.2.4 PID Controller Tuning

The optimal tuning of the PID controller's gain parameters is a complicated problem that has existed for centuries. These gains can be determined by trial and error or through established approaches including Ziegler-Nichols and Cohen-Coon. Most manual approaches like these are no longer employed due to improved optimization software. However, even with computer assistance, the two approaches listed below are still used today and are regarded among the most prevalent. Furthermore, these two approaches involve a huge amount of mathematical computations, making it difficult to determine ideal controller gain parameters.

The main objective of PID tuning is to determine the optimal values of its gain such that the following transient response parameters are improved:

- The maximum overshoot percentage ($M_P$ %)
- Settling time ($t_S$ )
- Rising time ($t_R$ )
- Peak time ($t_P$ )
- Steady state error ($E_{SS}$ )

In recent years, evolutionary-based various heuristic optimization techniques for the setting of PID controller parameters in the AVR system have been presented as an alternative to the previously described standard tuning approaches that fail to operate [86]. According to [87] , several algorithms from many optimization are utilized in PID modelling for an AVR these algorithms are also discussed in 2.10 of this work and further elaborated in APENDIXD , this shows a challenge in the frequent research area of implementation of a PID controller to improve electrical power systems performance, also that no approach has yet been demonstrated to be better to other methods in addressing this problem.

## 4.3 Modelling a PID-based AVR

The dynamic responsiveness of the AVR without a controller is evaluated through its step response in chapter3. It was observed that during normal operating conditions, the system terminal voltage deviates from the nominal value by approximately 50 percent and settles below the nameplate voltage of a SG. Such performance is completely unsatisfactory since the complicated equipment attached to the network system either is extremely sensitive to voltage variations and malfunctions or trips when voltage discrepancies last longer. As illustrated in figure 4.2 retrieved from MATLAB Simulink 2020a, a PID controller is introduced into the AVR transfer function to optimize its step responsiveness.

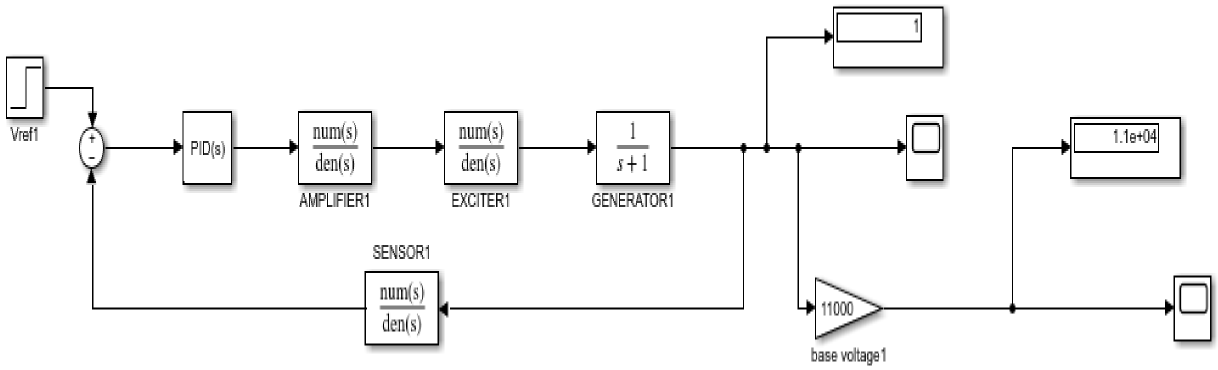



*Figure4. 2* Model of a PID-based-AVR transfer function

One of the most appropriate procedures to follow when designing a PID controller for a given system, the following steps should be followed to obtain a desired step response.

- Obtain an open-loop response and determine what needs to be improved
- Add a proportional control to improve the rise time.
- Add a derivative control to reduce the overshoot.
- Add an integral control to reduce the steady-state error.

Appendix A shows PID-based AVR model under this study on matlab Simulink, the model is constructed such tha the objectives functions used to analyses the dynamic response of a tuned PID. These objective fuctions are integral of time multiplied by weighted squared error (ITSE), integral of squared error (ISE), integral of time multiplied by the absolute value of error (ITAE) and integral of the absolute value of error (IAE). These objective functions are given by equation 4.4 to 4.7.

$$ITAE = \int_{0}^{\infty} \left[ te(t) \right] dt \qquad 4.4$$

$$IAE = \int_0^{\infty} [e(t)] dt \tag{4.5}$$

$$ITSE = \int_0^{\infty} te(t)^2 dt \tag{4.6}$$

$$ISE = \int_0^{\infty} e(t)^2 dt \tag{4.7}$$

While manual tuning technique is time consuming, for an improved step response an approach to use the PID tuning is necessary. Tuning a PID controller is defined as determining appropriate gains of a PID controller. The s-domain transfer function of PID controller is given by equation 4.8 where U(s) is the actuating control signal working on the error signal E(s). The close loop transfer function of P, PI, PD and PID can be defined using equation 4.9 to 4.12 respectively:

$$GPID(s) = \frac{U(s)}{E(S)} = K_P(s) + K_I(s) + K_D(s) \tag{4.8}$$

$$T(s) = \frac{X(S)}{R(s)} = \frac{K_p}{S^3 + 10s + (20 + K_p)} \tag{4.9}$$

$$T(s) = \frac{X(S)}{R(s)} = \frac{K_p s + K_I}{S^3 + 10S^2 + (20 + K_p)S + K_I} \tag{4.10}$$

$$T(s) = \frac{X(S)}{R(s)} = \frac{K_D s + K_P}{S^3 + 10S^2 + (20 + K_D)S + K_P} \tag{4.11}$$

$$T(s) = \frac{X(S)}{R(s)} = \frac{K_D S^2 + K_P S + K_I}{S^3 + (10 + K_D)S^2 + (20 + K_P)S + K_I} \tag{4.12}$$

To determine the most appropriate gain for a PID controller, In [125] For PID controllers, the control station advises using the Internal Model Control (IMC) tuning correlations. These are an extension of the well-known lambda tuning correlations, with the extra sophistication of explicitly accounting for dead time in tuning computations. According to G. Syrcos in [126] the PID laws stated that the velocity form of discrete approximation of an ideal PID controller is described by equation 4.13,

$$\Delta uk = K_c[(1 + \frac{T_s}{T_I} + \frac{T_D}{T_S})e_k - (1 + \frac{2T_D}{Ts})e_k - 1 + \frac{T_D}{T_S} e_{k-2}] \tag{4.13}$$

Where $T_S$ is the sampling time $K_C$ is the controller gain $T_I$ and $T_D$ are integral and derivative time the variables for equation 4.13 can be defined using equation 3.20 to equation 3.22 manipulating equation 4.13 then the controller gains are calculated using Equation 4.14 to 4.19.

$$P_k = e_k - e_{k-1} \qquad 4.14$$

$$I_k = T_s e_k \qquad 4.15$$

$$D_k = \frac{1}{T_s}(e_k - 2e_{k-1} + e_{k-2}) \qquad 4.16$$

$$K_p = K_c \; 4.17$$

$$K_I = \frac{K_C}{T_I} \qquad 4.18$$

$$K_D = K_C T_D \qquad 4.19$$

The compensator formula of a PID and PI controller created in MATLAB Simulink in a parallel form expressed in equation 4.20.

$$PID = P + I\frac{1}{S} + D\frac{N}{1 + N\frac{1}{S}} \qquad 4.20$$

## 4.4 Results and discussion

Terminal voltage varies by up to 50 percent from the normal AVR system (the AVR system without the controller), voltage oscillations last longer than 3 seconds, and terminal voltage cannot be restored to 1pu (the nominal voltage of an SG).

Figure 4.3 demonstrates that the use of a PID controller without tuned gain marginally enhanced the dynamic responsiveness of the AVR system, but with a 35 percent overshoot lasting more than a second, the results are still unsatisfactory. However, the performance indices (ITAE, IAE, ITSE, and ISE) improve significantly based on the data presented in table 4.2 and figure 4.3. To achieve optimal outcomes, the PID was modelled in five distinct ways and categorized as PID1 through PID5.

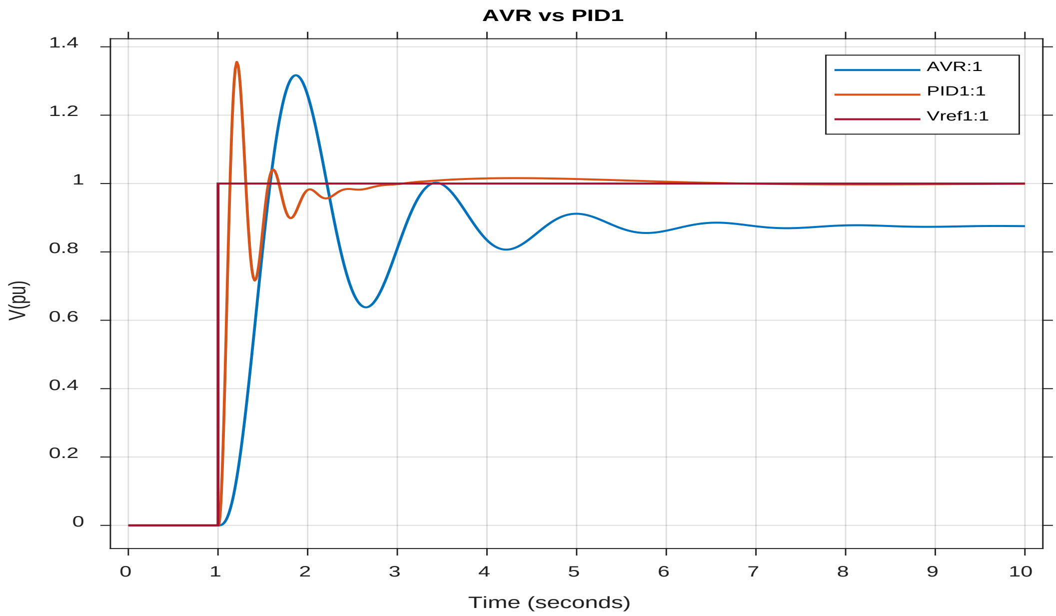



*Figure4. 3* Normal AVR vs PID1 step response

Table4. 2 Numerical results of PID1 controller

| | $K_P$ | $K_I$ | $K_D$ | % OS | $T_R$ (S) | $T_S$ (S) | P (PU) | ITAE | IAE | ITSE | ISE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AVR | - | - | - | 50.52 | 0.318 | 4.91 | 1.32 | 49.5 | 9 | 49.5 | 9 |
| PID1 | 1 | 1 | 1 | 35 | 0.0862 | 1.35 | 1.39 | 17.8 | 3.681 | 8.293 | 1.991 |

The improvement of the dynamic response is dependent on the tuning of optimal controller gains. The attempt to enhance the step response is technically realized and implemented in MATLAB Simulink software program. PID2 has demonstrated an improvement in percentage overshoot, which has reduced by over 30 percent, but the settling time has increased. The performance indicators, including the related step response, have exhibited a considerable improvement, as indicated in table 4.3 and graphical representation figure 4.4.

This figure compares PID2, normal AVR and the expected best output reference.

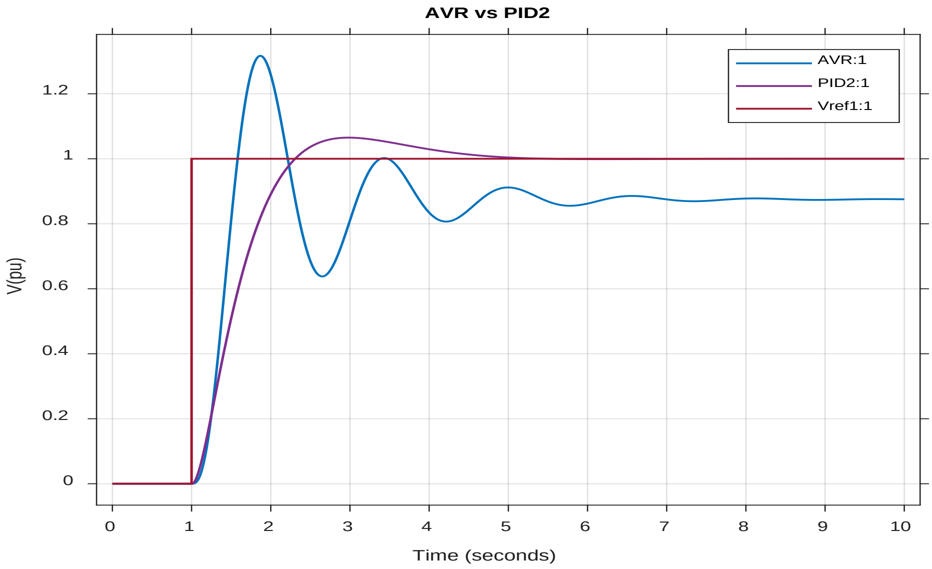



*Figure4. 4* AVR vs PID2 step response

Table4. 3 Numerical results for PID2

| | $K_P$ | $K_I$ | $K_D$ | % OS | $T_R$ (S) | $T_S$ (S) | P (PU) | ITAE | IAE | ITSE | ISE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AVR | - | - | - | 50.52 | 0.318 | 4.91 | 1.32 | 49.5 | 9 | 49.5 | 9 |
| PID2 | 0.21384 | 0.20152 | 0.05361 | 5.53 | 0.872 | 3.31 | 1.06 | 1.11 | 1.073 | 0.7616 | 1.003 |

PID tuning has shown to be the most effective method of increasing the controller's performance and the dynamic responsiveness of the system for which the controller was designed. Furthermore tuning of appropriate gain was implemented for PID3 to PID5 with corresponding numerical results in table 4.5 to 4.7.

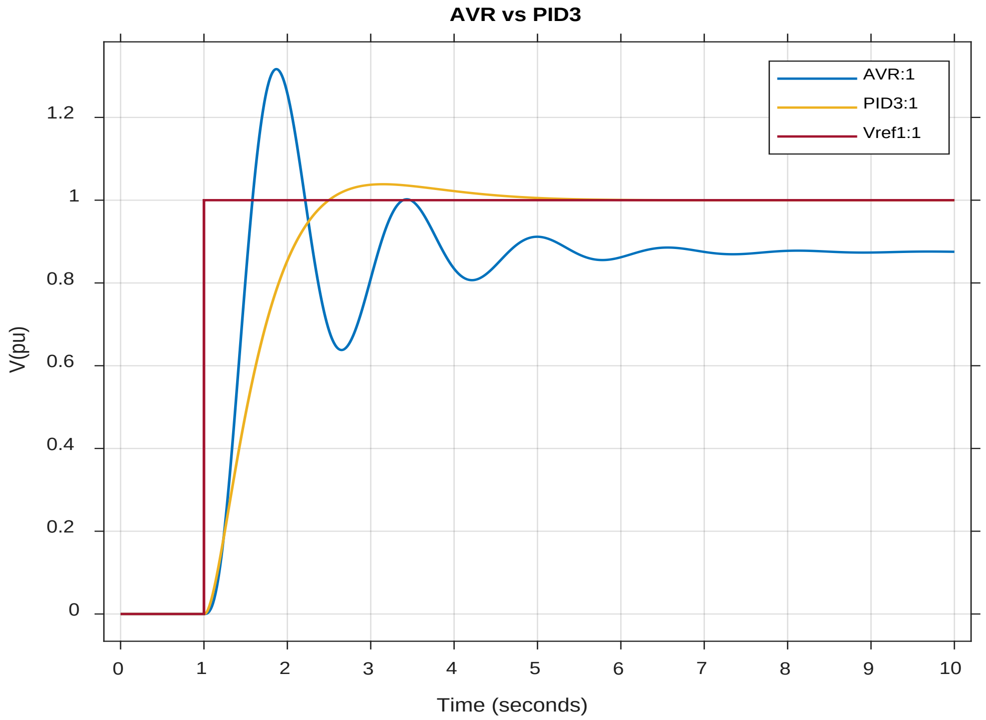



*Figure4. 5* AVR vs PID3 step response

Table4. 4 Numerical Results for PID3

| | $K_P$ | $K_I$ | $K_D$ | % OS | $T_R$ (S) | $T_S$ (S) | P (PU) | ITAE | IAE | ITSE | ISE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AVR | - | - | - | 50.52 | 0.318 | 4.91 | 1.32 | 49.5 | 9 | 49.5 | 9 |
| PID3 | 0.20452 | 0.17584 | 0.050429 | 3.01 | 1.03 | 3.09 | 1.03 | 1.07 | 0.6674 | 0.5194 | 0.402 |

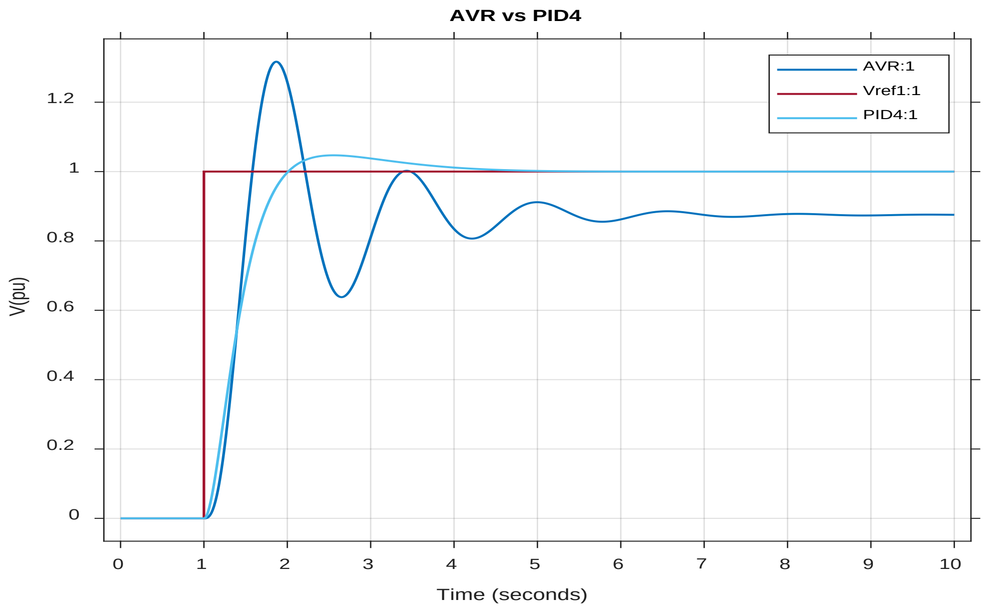



*Figure4. 6* AVR vs PID4 step response

Table4. 5 Numerical results for PID4

| | $K_P$ | $K_I$ | $K_D$ | % OS | $T_R$ (S) | $T_S$ (S) | P (PU) | ITAE | IAE | ITSE | ISE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AVR | - | - | - | 50.52 | 0.318 | 4.91 | 1.32 | 49.5 | 9 | 49.5 | 9 |
| PID4 | 0.29561 | 0.25835 | 0.0821 | 3.67 | 0.716 | 2.68 | 1.04 | 0.7616 | 0.4991 | 0.3552 | 0.2933 |

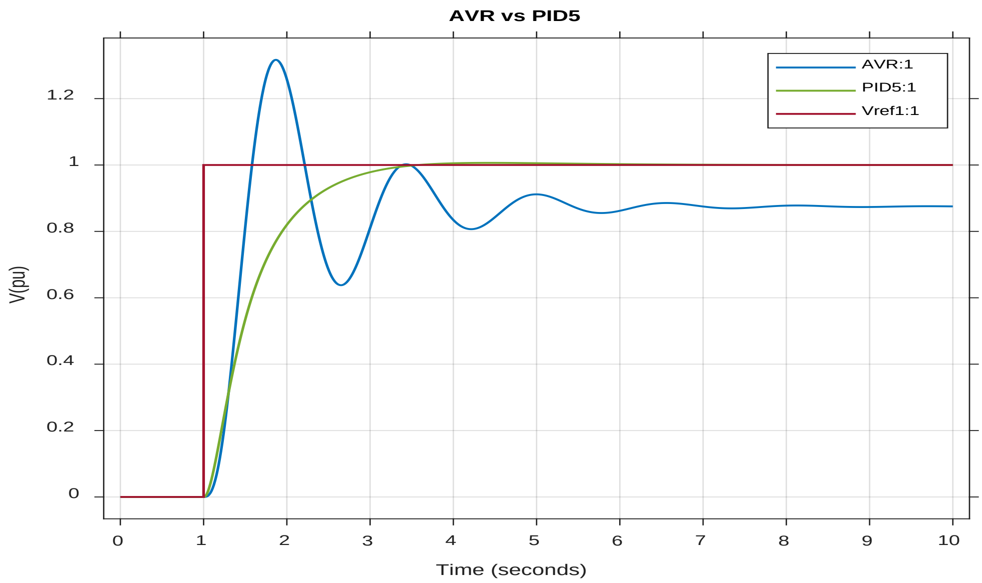



*Figure4. 7* AVR vs PID5 step response

Table4. 6 Numerical Results for PID5

| | $K_P$ | $K_I$ | $K_D$ | % OS | $T_R$ (S) | $T_S$ (S) | P (PU) | ITAE | IAE | ITSE | ISE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| AVR | - | - | - | 50.52 | 0.318 | 4.91 | 1.32 | 49.5 | 9 | 49.5 | 9 |
| PID5 | 0.21868 | 0.16504 | 0.07011 | 0.645 | 1.18 | 2.04 | 1.01 | 1.003 | 0.6336 | 0.4653 | 0.3629 |

When compared to the standard AVR system, PID 5 has shown to be the most efficient controller for the AVR, as it is noted that the percentage over shoot is below 1%. The settling time is 2.04 sec and the Voltage is restored to 1pu (nominal rated voltage) within 3 seconds.

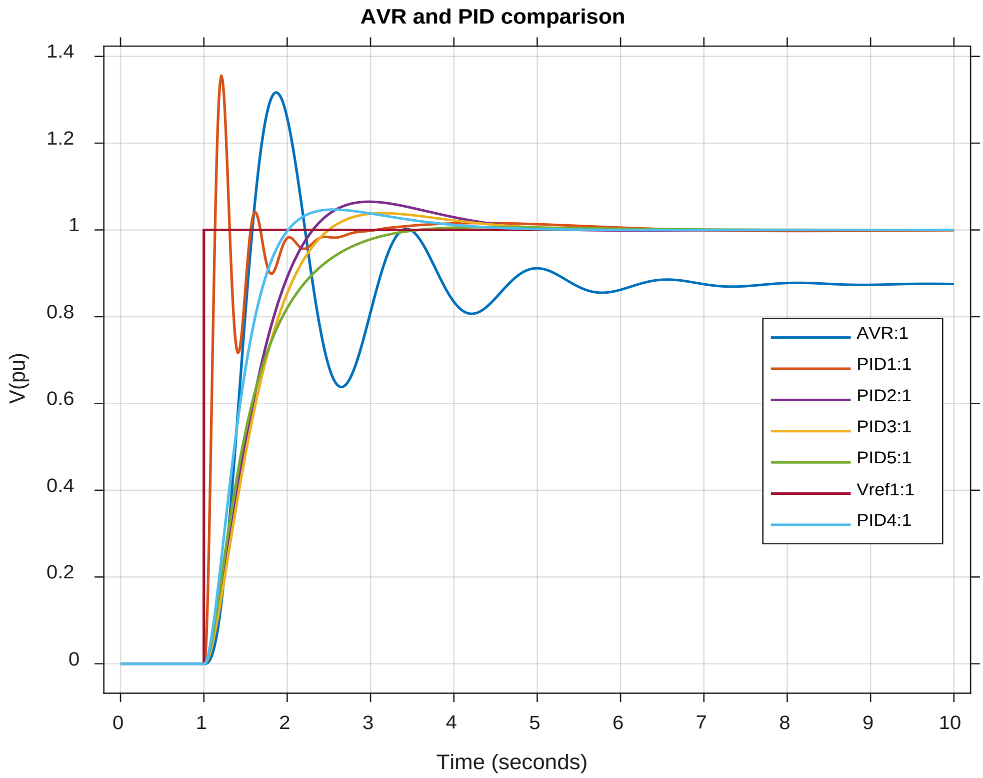



*Figure4. 8* PID comparison step response

## 4.5 Conclusion

A PID controller is added to the system in order to improve the dynamic performance of an AVR system under load variation conditions. The numerical and graphical results demonstrated a substantial improvement in the dynamic performance of the AVR . The voltage was restored to 1pu, which is the rated terminal voltage of the synchronous generator. Based on Figure 4.8 and the discussion in Section 4.4, we can conclude that PID5 is the most effective of the five. In an effort to achieve the best results for the controller-based AVR, these results were extended and compared to the implementation of an MPC controller discussed in chapter 5 .

CHAPTER FIVE

# MODEL PREDICTIVE CONTROLLER FOR AN AVR

## 5.1 Introduction

The nature of systems in control engineering applications includes model and disturbance uncertainty. Under these conditions of uncertainty, systems require strong control mechanisms. Due to the complexity of nonlinear control issues, it is usually required to use various computational or approximation approaches to solve them. Model predictive control (MPC), which focuses on solving a numerical optimization problem online, is a popular solution in this context. This chapter discusses the application of model predictive controller for the AVR system. A mathematical model of MPC is designed and implemented in MATLAB Simulink, and the obtained results are discussed and compared to normal AVR and PID5, which has proven to be the best performing controller on the previous model discussed in chapter 4.

## 5.2 The MPC-based-AVR

Among sophisticated control methods, MPC remains one of the most prominent in the process sector. A sophisticated process control technology is used to govern a process while meeting a set of criteria. This is mostly due to the novel way in which its control problem was formulated. A well-designed model naturally depicts the plant's expected behavior. The solution is optimum, and the optimization problem explicitly takes into account hard operating limitations. The MPC problem is often expressed in the state space domain.. A discrete MPC method is depicted in Figure 5.1.

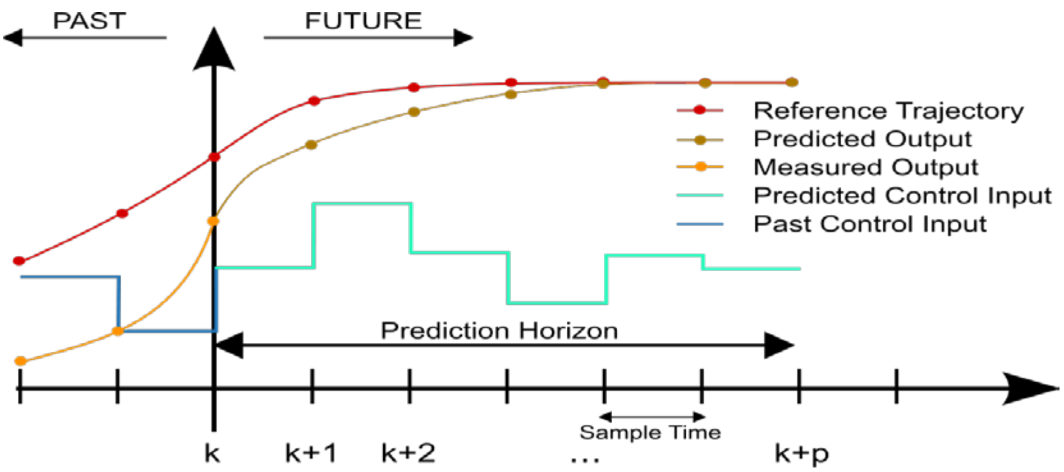


*Figure 5. 1* A discrete MPC Scheme [127]

The MPC predicts a process's future response using an explicit process model and solves an optimum control problem with a finite horizon at each sampling time. As seen in Figure 5.2. The prediction includes two major components: the free response, which is the predicted output behaviour assuming no future control actions, and the forced response, which is an extra component of the output reaction owing to the candidate set of future controls.

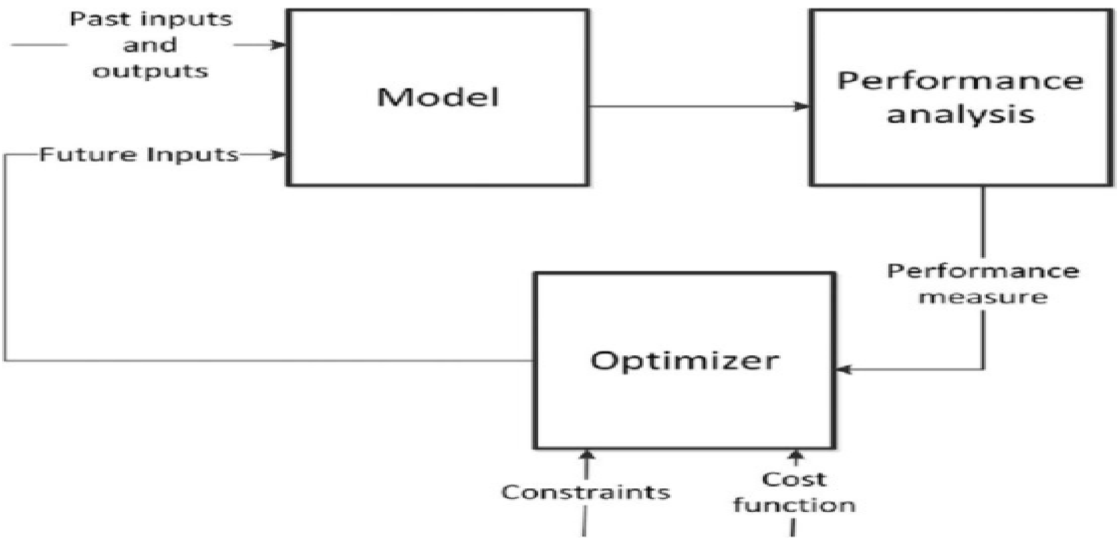



*Figure 5. 2* A sample structure of an MPC [128]

The literature in the context of MPC-based-AVR is limited. Automatic voltage regulation (AVR) of a synchronous generator using a predictive controller is presented for real-time control in [120]. Fast-time linearization of a second-order alternator model is used for the controller. The systems response time is predicted using the fast-time model, and its input is determined by the control logic. Time-optimal control and linear regulation are two concepts used in controller design. Orosun et. al in [121], developed a MPC to keep a single area power system's total voltage profile within acceptable ranges. To achieve this the excitation voltage was automatically controlled using the MPC installed in the forward route of the AVR loop.

Deghboudj at.al in [122] introduced a novel design strategy for fractional order model predictive control (FO-MPC). The suggested model is designed for the class of linear time invariant systems and is used to an AVR. A singularity function technique is used to create the fractional order model. A comparison with the traditional MPC scheme is provided. Figure 5.3 depicts the conceptual framework of FO-MPC.

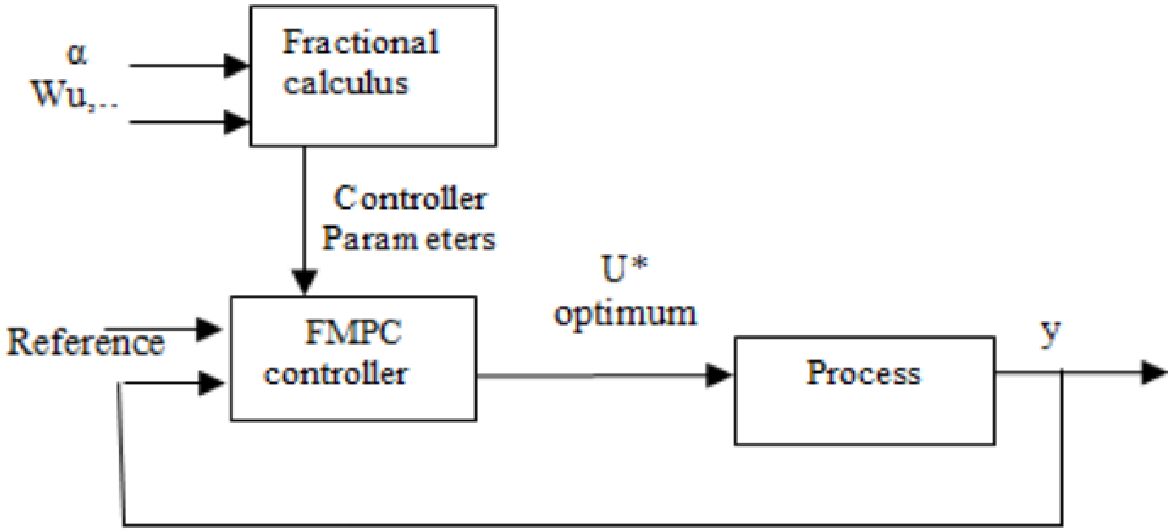



*Figure 5. 3* Conceptual structure of MPC controller [122]

Åkesson in [129] develop an optimal MPC of restricted nonlinear systems is using a neural network controller(NN). A NN approximator that has been trained to minimize a control-relevant cost function represents the control law. Elsisi et.al in [130] proposed a robust model predictive controller (MPC) for controlling an automated voltage regulator (AVR). The design strategy addresses the unpredictability of the AVR parameters. To keep the perturbed system stable, frequency domain criteria are derived using the Hermite–Biehler theorem. The MPC parameters are tuned using a novel evolutionary algorithm called arithmetic optimization algorithm (AOA), while expert designers employ trial and error approaches to attain this goal. The next section discussing the modelling of an MPC under this study.

## 5.3 Modelling of an MPC-based AVR

Choosing the sample time for a model predictive controller is part of the modelling process including determining the prediction and control horizons, limits, selecting weights, and estimating the present plant states. In discrete time, a linear model describes the plant model as equation 5.1, where X (k) represents a state variable and U (k) represents the control input. The performance index for determining optimal control is utilized to promote rapid reaction while avoiding unnecessary control effort.

The open loop optimization problem is described in order to establish a receding horizon using equation 5.2.

$$X(k+1) = A_x(k) + B_n(k), x(0) \quad 5.1$$

$$X(K+1) = \sum_{J=N_1}^{P} [Y_J(k+j) - y_r(k+j)]^2 + \sum_{j=1}^{M} \lambda_j [\Delta u(k+j-1)]^2 \quad 5.2$$

P and N1 represents both maximum and minimum predicted steps. M represents control step and $\lambda j$ denotes a controls weighting sequence. Incremental control vector is obtained by minimizing J (with the constraint equal to zero after M samples). It is worth noting that when the control and prediction horizons approach infinity, the predictive control issue stated in equations 5.1 and 5.2 may be integrated to a typical linear quadratic regulator (LQR) problem. Using a static state feedback controller, we find the best control sequence. Equations 5.3 and 5.4 reflect the plant state-space models used to develop the controller:

$$X_p(k+1) = A_p X_p(k) + B_p u(k) \quad 5.3$$

$$y(k) = C_p x_p(k) + D_p u(k) \quad 5.4$$

Where Ap, Bp, Cp, and Dp are the discrete state-space plant models, u is the modified or input variable, y is the plant output, and xp is the nominal plant's state variable vector. We have assumed implicitly that the input u(k) cannot affect the output y(k) at the same time. As a result, Dp = 0 in the plant model. The variable xp(k) and u(k) increments are represented by equations 5.5 and 5.6, and further manipulation of these equations is achieved by equations 5.7 to 5.9.

$$\Delta x_p(k+1) = A_p \Delta x_p(k) + B_p \Delta u(k) \quad 5.5$$

$$y(k+1) = C_p x_p(k+1) \quad 5.6$$

$$\Delta u(k) = u(k) - u(k-1) \quad 5.7$$

$$\Delta x_p(k+1) = x_p(k+1) - x_p(k) \quad 5.8$$

$$\Delta x_p(k) = x_p(k) - x_p(k-1) \quad 5.9$$

The control horizon allows for a reduction in the number of calculated future controls concerning the relation represented in equation 5.9. Constraints on the control signal, outputs, and control signal change can be applied to the cost function using equations 5.10 to 5.13.

$$\Delta u(k+j) = 0 \, for j \geq N_u \quad 5.10$$

$$U_{\min} \leq u(k) \leq U_{\max} \quad 5.11$$

$$\Delta U_{\min} \leq \Delta u(k) \leq \Delta U_{\max} \quad 5.12$$

$$Y_{\min} \leq y(k) \leq Y_{\max} \quad 5.13$$

## 5.4 Results and discussion

To investigate the dynamic behaviour of the controller for AVR systems applications, an MPC-based AVR model was developed and simulated in MATLB Simulink. Using the MATLAB Simulink 2021a program. Alternative controllers were simulated by altering the value of alpha. These findings are compared to the best outcomes obtained in Chapters 3 and 4. The MPC models are formulated as MPC1 to MPC5 Alpha for the initial mathematical model is 7.389 classified as MPC5, and the graphical data shown in figure 5.4 and numerical results in Table 5.1 reveal a very poor performance compared to PID5, with the terminal voltage shooting up to 1.2pu however these results are better than a normal AVR since the voltage is restored to 1pu. Detailed Numerical results are shown in Table 5.1, comparing the Normal AVR, PID5-based AVR and MPC5 based AVR.

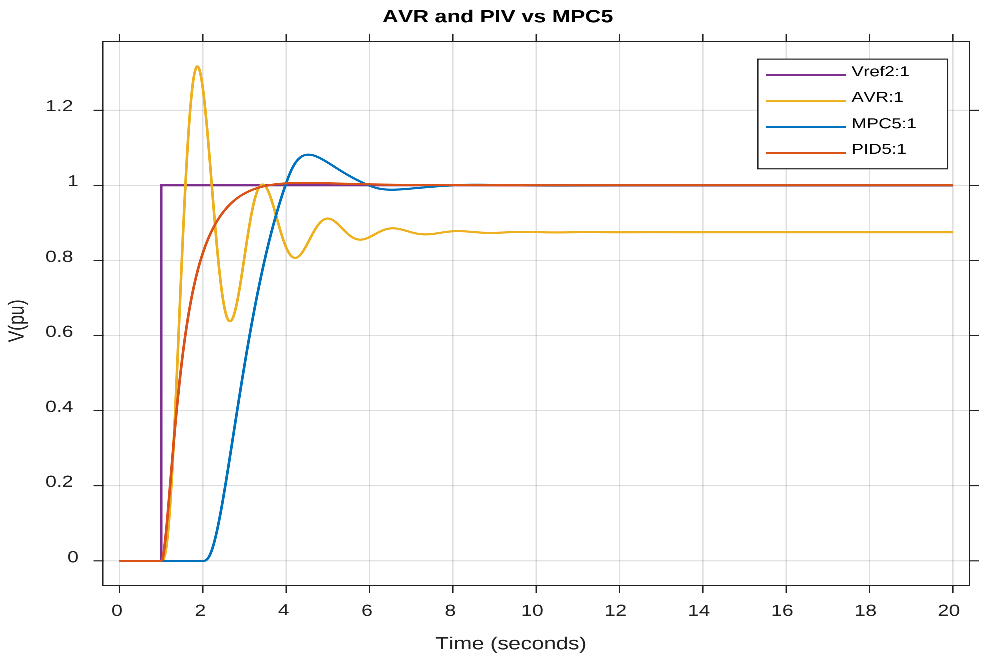



*Figure 5. 4* A comparison of PID controller and MPC5 step response

*Table5. 1 Numerical results for MPC5*

| | beta | alpha | gamma | % OS | $T_R$ (S) | $T_S$ (S) | P (PU) | IAE | ISE |
|---|---|---|---|---|---|---|---|---|---|
| AVR | - | - | - | 50.52 | 0.318 | 4.91 | 1.32 | 9 | 9 |
| PID5 | - | - | - | 0.645 | 1.18 | 2.04 | 1.01 | 0.6336 | 0.3629 |
| MPC5 | 2.833 | 7.3891 | 10 | 20 | 2.043 | 7.584 | 1.12 | 0.3196 | 0.1669 |

The performance of the MPC controller is further improved by manipulating the equation to obtain the best optimal weighting factors (gamma). The second model classified as MPC4, The weighting factor gamma is 2.8277. Graphical and numerical results are shown in figure 5.5 and table 5.2 respectively. It is observed that there is a minor improvement in the step response and the voltage overshot has been decreased to 1.01pu and settled within 7.1 seconds. The performance indicators (IAE and ISE) used to determine the efficacy of the error signal are lowered by nearly half.

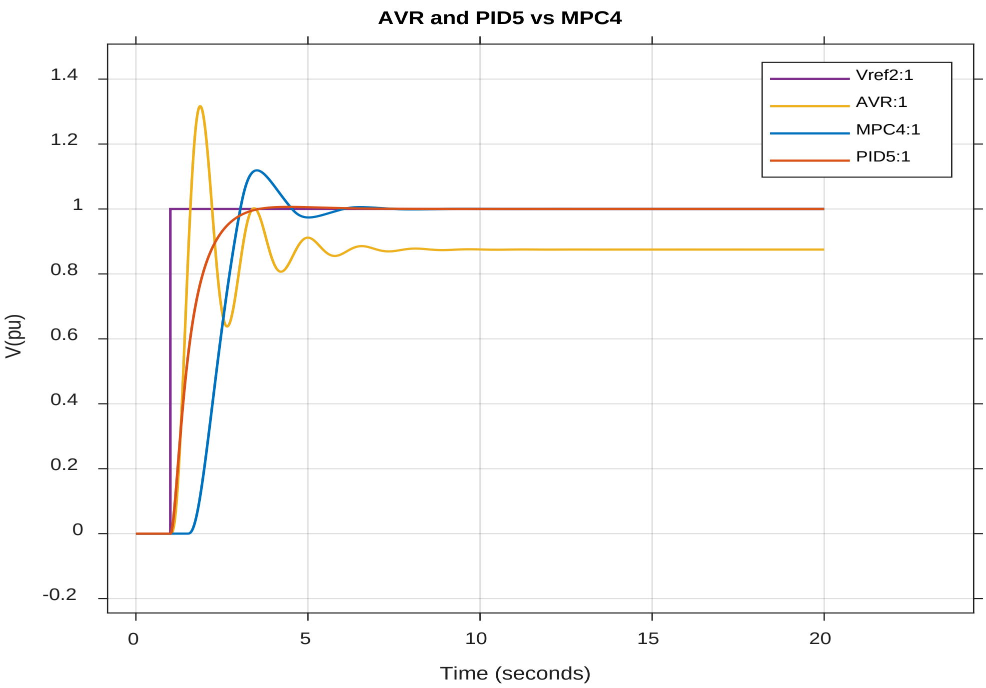



*Figure 5. 5* A comparison of PID controller and MPC4

Table5. 2 Numerical results for MPC4

| | beta | alpha | gamma | % OS | $T_R$ (S) | $T_S$ (S) | P (PU) | IAE | ISE |
|---|---|---|---|---|---|---|---|---|---|
| AVR | - | - | - | 50.52 | 0.318 | 4.91 | 1.32 | 9 | 9 |
| PID5 | - | - | - | 0.645 | 1.18 | 2.04 | 1.01 | 0.6336 | 0.3629 |
| MPC4 | 2.833 | 2.8277 | 10 | | 1.713 | 7.007 | 1.05 | 0.3388 | 0.1733 |

To acquire the optimum results for an MPC-based AVR, the weighted factor is feather adjusted and the controller is classified as MPC3 Corresponding numerical and graphical results is shown in figure 5.6 and table 5.3 respectively.

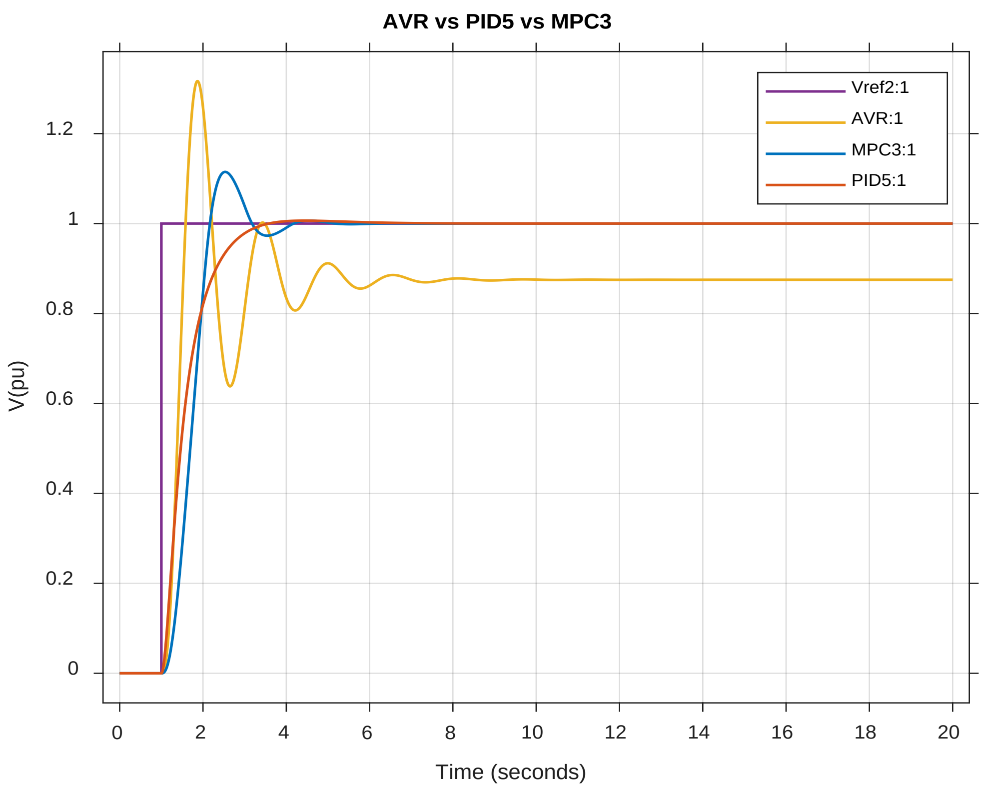



*Figure 5. 6* A Comparison of PID controller and MPC3

Table5. 3 Numerical results for MPC3

| | beta | alpha | gamma | % OS | $T_R$ (S) | $T_S$ (S) | P (PU) | IAE | ISE |
|---|---|---|---|---|---|---|---|---|---|
| AVR | - | - | - | 50.52 | 0.318 | 4.91 | 1.32 | 9 | 9 |
| PID5 | - | - | - | 0.645 | 1.18 | 2.04 | 1.01 | 0.6336 | 0.3629 |
| MPC3 | 2.883 | 2.8872 | 10 | | 1.231 | 4.937 | 1.008 | 0.342 | 0.1744 |

MPC2 showed a significant reduction in response time, as shown in figure (5.7), however the overshoot is significantly higher than 1pu. MPC1 accomplished further enhancements to decrease the percentage overshot to zero and obtain the shortest response time, as illustrated in figure (5.8). Figures 5.7 and 5.8 demonstrate this. The percentage overshoot attained is 0%, and the voltage is returned to 1pu in 2 seconds, indicating that MPC1 is the best performing MPC controller for the AVR system.

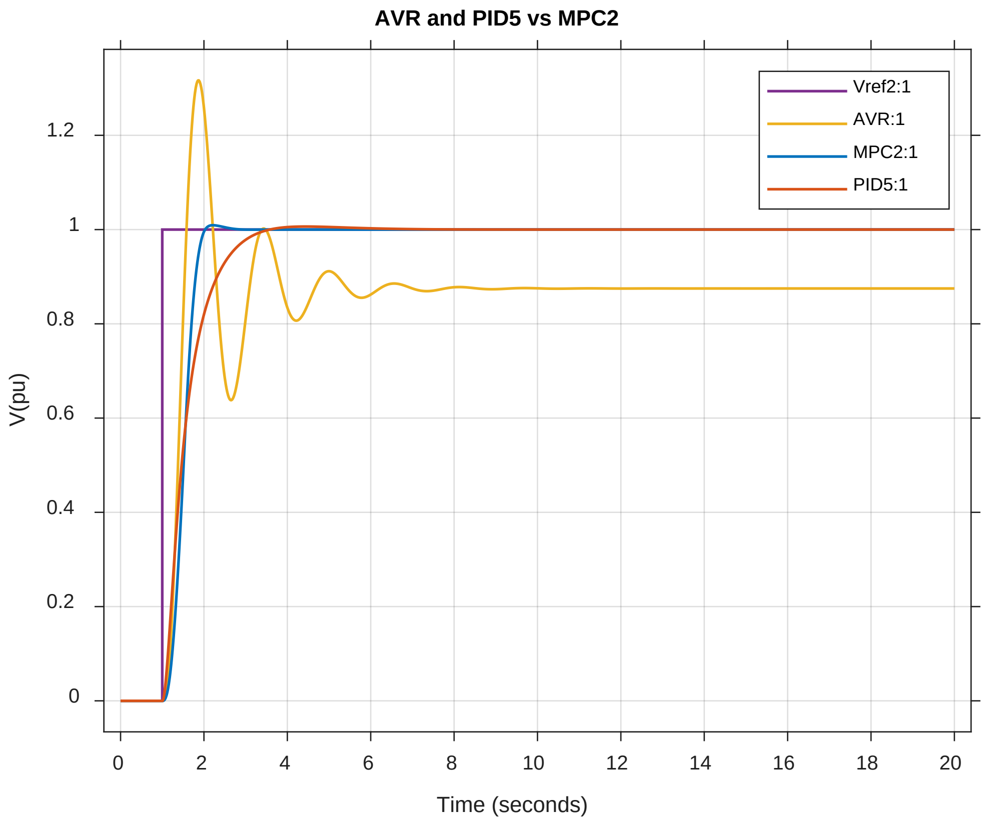



Figure 5. 7 A comparison of PID controller and MPC2

Table5. 4 Numerical results for MPC2

| | beta | alpha | gamma | % OS | $T_R$ (S) | $T_S$ (S) | P (PU) | IAE | ISE |
|---|---|---|---|---|---|---|---|---|---|
| AVR | - | - | - | 50.52 | 0.318 | 4.91 | 1.32 | 9 | 9 |
| PID5 | - | - | - | 0.645 | 1.18 | 2.04 | 1.01 | 0.6336 | 0.3629 |
| MPC2 | 2.883 | 0.13543 | 10 | 0 | 0.892 | 2.574 | 1 | 02989 | 0.1603 |

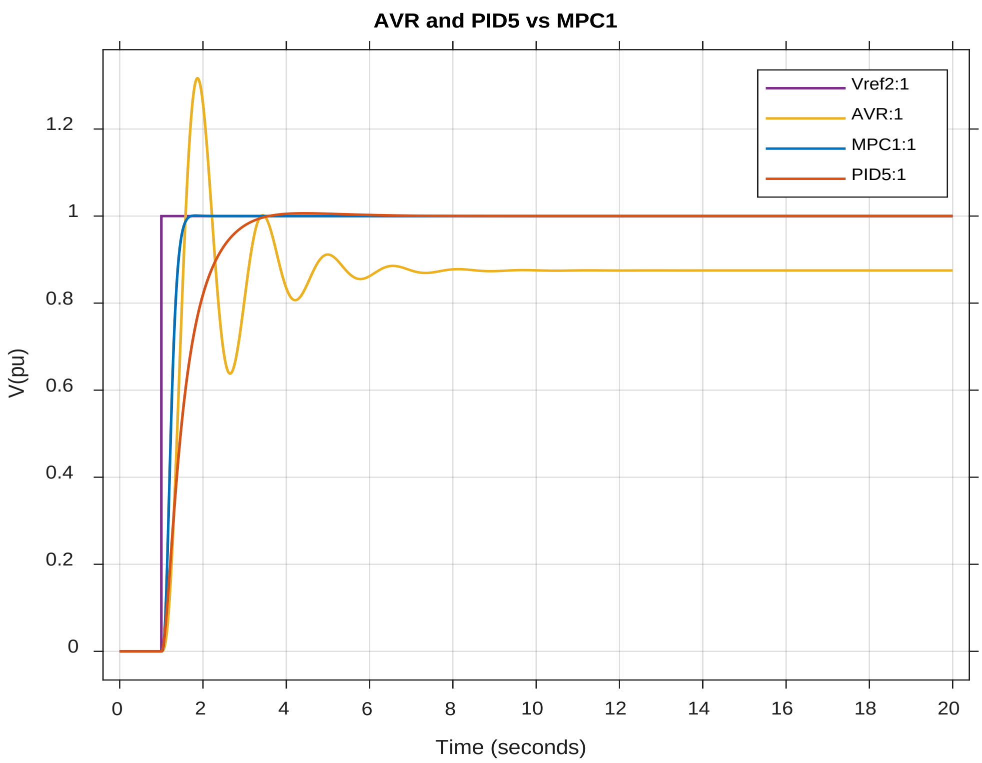



*Figure 5. 8* Comparison of PID controller and MPC1

Table5. 5 Numerical results for MPC1

| | beta | alpha | gamma | % OS | $T_R$ (S) | $T_S$ (S) | P (PU) | IAE | ISE |
|---|---|---|---|---|---|---|---|---|---|
| AVR | - | - | - | 50.52 | 0.318 | 4.91 | 1.32 | 9 | 9 |
| PID5 | - | - | - | 0.645 | 1.18 | 2.04 | 1.01 | 0.6336 | 0.3629 |
| MPC1 | 2.883 | 1.0833 | 10 | 0 | 0.606 | 1.646 | 1 | 0.3494 | 0.1767 |

## 5.5 Conclusion

This chapter has developed and constructed an MPC-based AVR, as well as conducted a comparative study between the MPC and PID5. According to the data, PID5 is the best of all PIDs for the AVR system. The study is expanded to match the output of PID5 with MPC action, and the graphical and numerical results show that MPC can perform significantly quicker than PID5 for AVR systems. Finally, it is discovered that weighting variables play an essential role in MPC and can increase MPC performance. MPC1 has shown to be the best performing controller for this AVR system out of the five MPC controllers.

# CHAPTER SIX

## FUZZY BASED AVR

## 6.1 Introduction

This chapter discusses the use of a fuzzy logic controller in an AVR system. A FLC model is built and implemented in MATLAB Simulink, and the results are reviewed and compared to PID and MPC controllers.Fuzzy logic controllers are quickly gaining traction as a potential alternative to traditional controllers [131]. Fuzzy controllers were designed to mimic the performance of human experts by storing their knowledge in language rules. In addition to being non-linear and adaptive, fuzzy control show a resilient performance under parameter changes [6].The application of fuzzy logic technology in the design of an embedded system allows for the utilization of engineering experience and experimental results. Another benefit of using a fuzzy logic control technique is that it allows for model-free system estimation, which removes the need for the designer to explain how the outputs mathematically depend on the inputs [7].

## 6.2 The concept of a fuzzy logic controller

The fuzzy controller has two input variables: error (e) and error variation (de/dt), as well as an output variable. The difference between the reference model and the plant model to be controlled yields the inaccuracy of the input variable (transfer function of an AVR in this case). The membership function of the determination of input and output variables is determined based on system error experiments [7].

Five steps are believed to explain the FLC process [92], and these steps are as illustrated in table 6.1;

Table 6. 1 the Description of an FLC prosess

| step | Description |
|---|---|
| Fuzzification | Measures the input variable and convert them into linguistic variable. |

| | |
|---|---|
| Data base | offers the data needed to create the fuzzy control rules for the linguistic variables |
| Rule base | gives precise control rules in terms of language factors in order to achieve control goals |
| Defuzzification | In this procedure, scale mapping is used to determine the range of output variables, and these linguistic output variables are translated into numerical values |

FLC is advantageous because it enables outcome based on fuzzy ideas and fuzzy logic interference rules. The fuzzy control is also dynamic and adaptive in nature, which allows it to work consistently even when the parameters change [6]. Fuzzy controllers were created to mimic the performance of human expert operators by encoding their knowledge in language rules [132]. Figure 6.1 depicts the fuzzy logic concept.

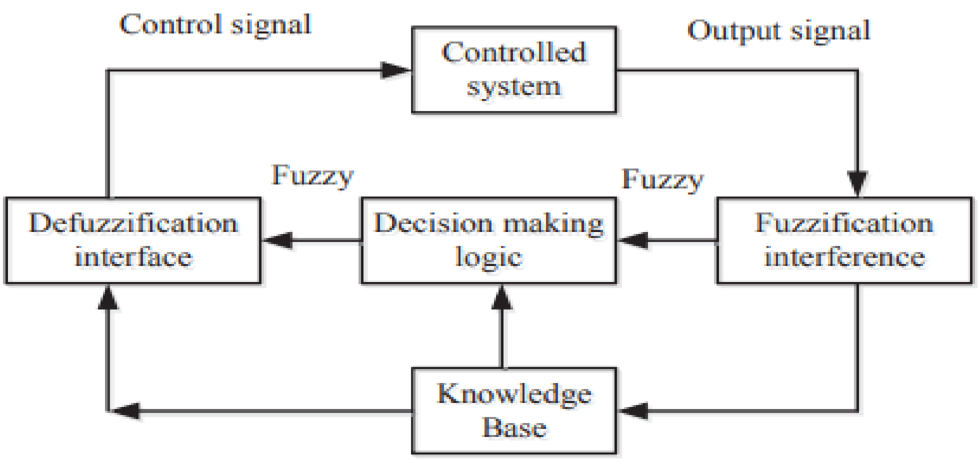



*Figure6. 1* The logic concept of fuzzy logic controlle r[133]

There has been some existing research on fuzzy logic-based controllers for the application on synchronous generator voltage regulation. In [110] a single-machine infinite bus (SMIB) framework, based on the fuzzy set and type-2 fuzzy logic, as well as the proportional–integral (PI) is developed. In [111] the design, implementation, and operation performance of fuzzy controller as part of the combined loop of AGC & AVR for single area power system is described, the fuzzy controller is implemented in the control of ACE calculation in the case of AGC & excitation in case of AVR, which determines the shortfall or surplus generation that has to be corrected.

Aliabadi et. al in [112] implemented a Fuzzy-FOPID to improve dynamic performance of an AVR system. Al Gizi in [95] proposed a particle swarm optimization (PSO) and fuzzy logic control (FLC) integrated in a novel controller to find the best PID values for the generator parameters in the AVR system; this controller was implemented in MATLAB with a set point voltage and frequency. Kumar et. al in [114] proposed a novel concept of an interval type-2 fractional order fuzzy PID (IT2FO-FPID) controller, which requires fractional order integrator and fractional order differentiator, the incorporation of Takagi-Sugeno-Kang (TSK) type interval type-2 fuzzy logic controller (IT2FLC) with fractional controller of PID-type is investigated for time response measure due to both unit step response and unit load disturbance and resulting IT2FO-FPID controller is examined on different delayed linear and nonlinear benchmark plants followed by robustness analysis.

Falahati et. al in [134] Implemented a fuzzy-PID controller because of its high speed and accuracy, this controller has four parameters whose values were determined through optimization and an imperialist competitive method. Dang et.al in [116] analysed an automated voltage regulator (AVR) system using the Interactive Adaptive Fuzzy Algorithm (IAFA) to alter the field excitation of a synchronous generator while maintaining a constant terminal voltage in the face of unknown disturbances.

## 6.3 Modelling of a Fuzzy logic controller

The idea of fuzzy sets is similar to the concept of crisp sets (0 or 1). The crisp set is thought to have a limited quantity of MF. As a result, crisp sets are classified as a subset of fuzzy sets [92]. The MF is an essential concept in fuzzy sets since it is the distinctive representation of fuzzy sets. they are presented in a form of a curve that represents the input-output fuzzy variables [135].

Controller inputs, the output error (e) and the rate or derivative of the output (de) are commonly utilized. In practice, the universe of discourse is restricted to a comparatively small interval [Xmin, Xmax].

The universe of discourse of each fuzzy variables can be quantized into a number of overlapping fuzzy sets (linguistic variables).Definition of a fuzzy set: Assuming that X is a collection of objects, a fuzzy set A in X is defined to be a set of ordered pairs as shown in equation 6.1

$$A = \left\{ (x, \mu_A(x)) \uparrow x \in X \right\} \quad 6.1$$

Where UA (x) is called the membership function of x in A. The numerical interval X is called Universe of Discourse [136]. The membership function $\mu_A(x)$ denotes the degree to which x belongs to A and is usually limited to values between 0 and 1. Fuzzy set operators are defined based on the corresponding membership function like in this research AND and OR operators are used. It is assumed that A and B are 2 fuzzy sets with membership function $\mu_A(x)$ and $\mu_B(x)$ respectively the following operators are described

- AND operator as an intersection of two fuzzy sets (C = A ∩ B) is defined by equation 6.2

  $$\mu_c(x) = \min\left\{ \mu_A(x), \mu_B(x) \right\}, x \in X \quad 6.2$$

- OR operator as a union of two fuzzy sets ( D = A ∪ B) is defined by equation 6.3

  $$\mu_D = \max\left\{ \mu_A(x), \mu_B(x) \right\}, x \in X \quad 6.3$$

- Fuzzy relations R from A to B considered as fuzzy graph characterized by membership function $\mu_R(x,y)$ which satisfy the composition of the rules shown in equation 6.4

  $$\mu_B(y) = \max_{x \in X}\left\{ \min[\mu_R(x,y), \mu_B(x)] \right\} \quad 6.4$$

The MIN operator returns the output membership function of each rule, while MAX – operator provides the combined fuzzy output [137]. Equation 6.5 expresses the composing operation.

$$\mu_B(u) = SUP_x[\min(\mu_A(x), \mu_B(x,u))] \quad 6.5$$

A represents fuzzy set for the input  and B is the inferred fuzzy set for the output. In figure 6.2, there is only one input fuzzy subset (A) for each rule. µ1 is the minimal membership degree for the input fuzzy subsets (A) of the Rule 1; µ2 is the minimal membership degree for the input fuzzy subset (A) of the find Rule 2. B1 and B2 are the inferred fuzzy subset given by the MIN operator; B is the inferred output fuzzy subset given by the MAX operator.

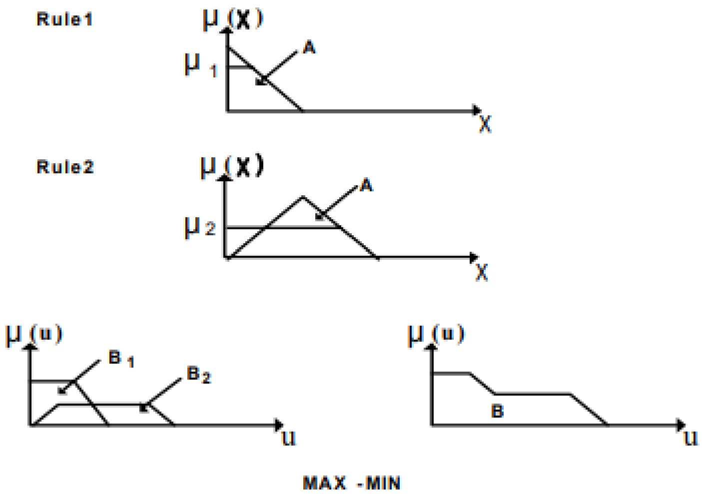



*Figure6. 2* The composition of min-max fuzzy method [138]

The corresponding algorithms of the defuzzification process is illustrated in equation 6.6, w ω is the output fuzzy variable, the corresponding fuzzy subset is C defined in the universe of discourse W.

$$U_O = \frac{\int \omega\mu(\omega)d\omega}{\int \mu(\omega)d\omega} \quad 6.6$$

In this research work, FLC for AVR system is analysed with Triangular membership functions as shown in figure 6.4 error voltage and change in error voltage are fuzzy inputs shown in figure 6.3. The range of each input and outputs is determined based on the information obtained on a transfer function of an AVR without the controller. The interface system used in MAMDANI where a set of rules are implemented to improve a step response of an AVR transfer function. The system was investigated for 5by5 totalling to 25 rules and a 7by7 totaling to 49 rules. The set of rules is represented in table 6.1 and table 6.2 respectively. The range of the output was varied into six different fuzzy interface system (FIS) classified as FLC1 to FLC6. These models were implemented on MATLAB simulink 2021a software and results obtainde are discussed in section 6.4.

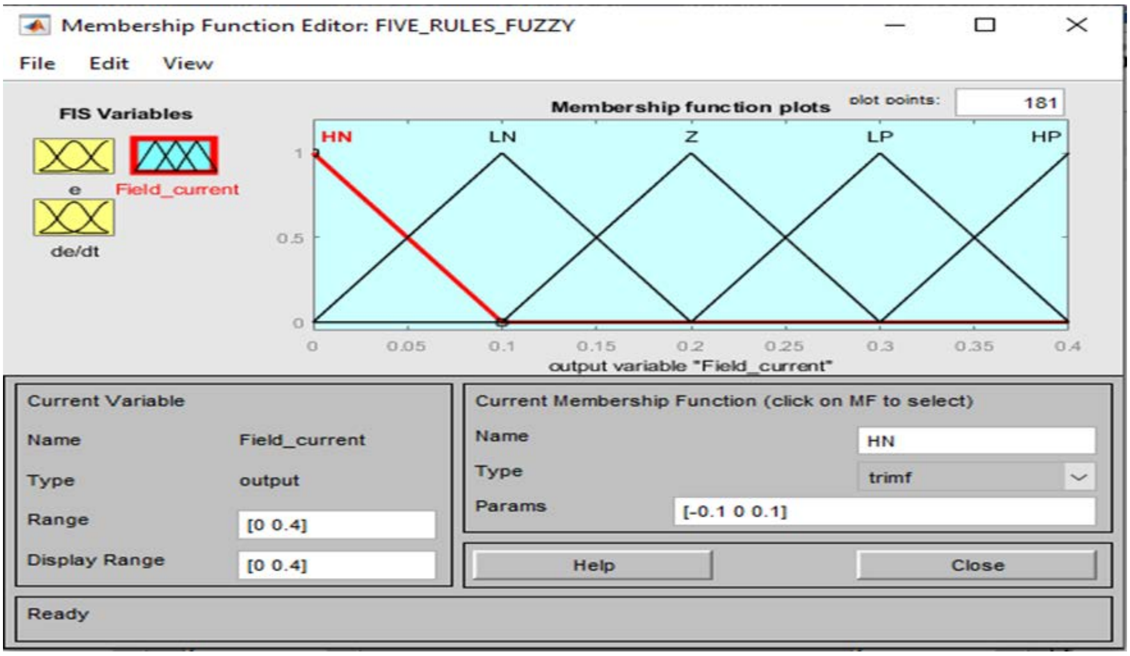



*Figure6. 3* Fuzzy membership functions on MATLAB Simulink

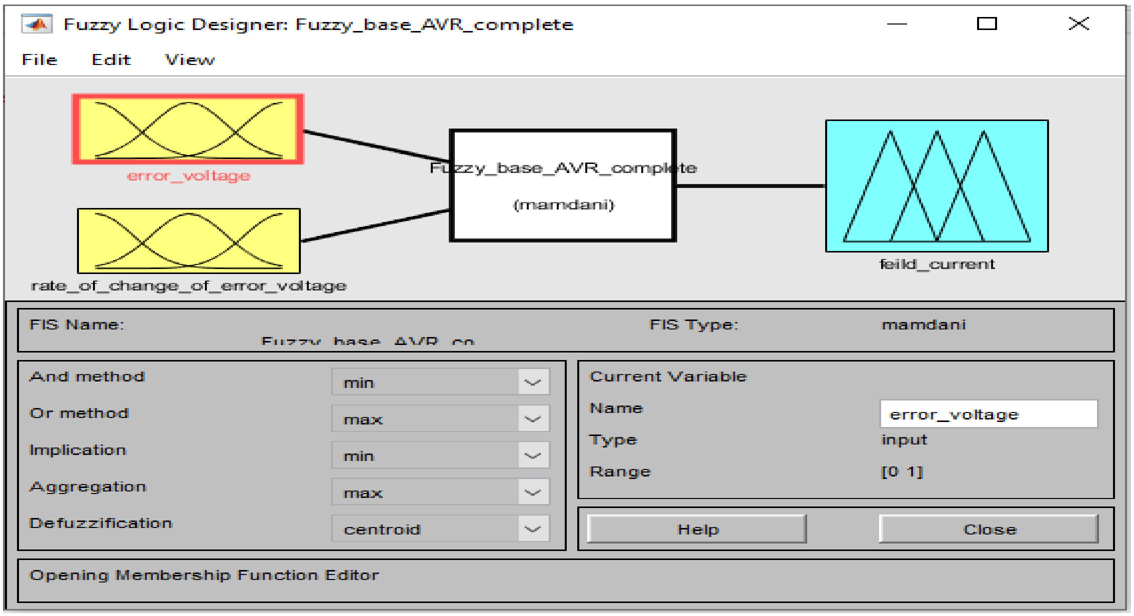



*Figure6. 4* Fuzzy interface system on MATLAB Simulink

*Table 6. 2 Fuzzy rules for a 5 by 5 FIS*

| de(t)/dt<br>e(t) | MN | LN | Z | LP | MP |
|---|---|---|---|---|---|
| MN | MN | MN | LP | Z | MN |
| LN | MN | LN | LN | Z | LP |
| Z | LN | LN | Z | MP | LP |
| LP | LN | Z | LP | MP | MP |
| BP | Z | LP | LP | MP | MP |

*Table 6. 3 Fuzzy rules for a 7 by 7 FIS*

| de(t)/Dt<br>e(t) | BN | MN | LN | Z | LP | MP | BP |
|---|---|---|---|---|---|---|---|
| BN | BP | BP | BP | MP | MP | LP | Z |
| MN | BP | MP | MP | MP | LP | Z | LN |
| LN | BP | MP | LP | LP | Z | LN | MN |
| Z | MP | MP | LP | Z | LN | MN | MN |
| LP | MP | LP | Z | LN | MN | MN | BN |
| MP | LP | Z | LN | MN | MN | MN | BN |
| BP | Z | LN | MN | MN | BN | BN | BN |

The linguistic variables in both Table 6.2 and Table 6.3 represents the following:

BN : Big negative

MN : Medium negative

LN : Low negative

Z : zero

LP : Low positive

MP : Medium Positive

BP : Big positive

Fuzzification may be predicted on a frequent basis in a fuzzy expert system since the input values from withstanding detectors are always deterministic mathematical values. The fuzzy rule base is notable for its structure of "IF-THEN" rules, which includes linguistic variables. The last component of a fuzzy expert system is defuzzification, which is responsible for performing crisp yield operations. Based on the results of this research as discussed below , fuzzy has proven to be the best when observing the percentage overshoot, the MPC has proven to be the best when observing the response time, and the rule base was modelled for a 5 by 5 rule system and a 7 by 7 rule system, as shown in tables 6.1 and 6.2, respectively. The figures below provide more analysis of the results.

FLC1 through FLC3 are the result of a 5 by 5 rule-based FIS. Figure 6.5 depicts the graphical illustration of FLC1's step response, while table 6.3 displays the numerical data. When compared to the PID5 controller, this controller performed better, with a percentage overshoot of 0% and a settling time of 2.0828. The performance indicators, which include the ISE and IAE, have been decreased. This leads to the conclusion that FLC1 outperformed the PID controller. The MPC controller, on the other hand, remained the best performer in all categories when compared to FLC1 and PID5.

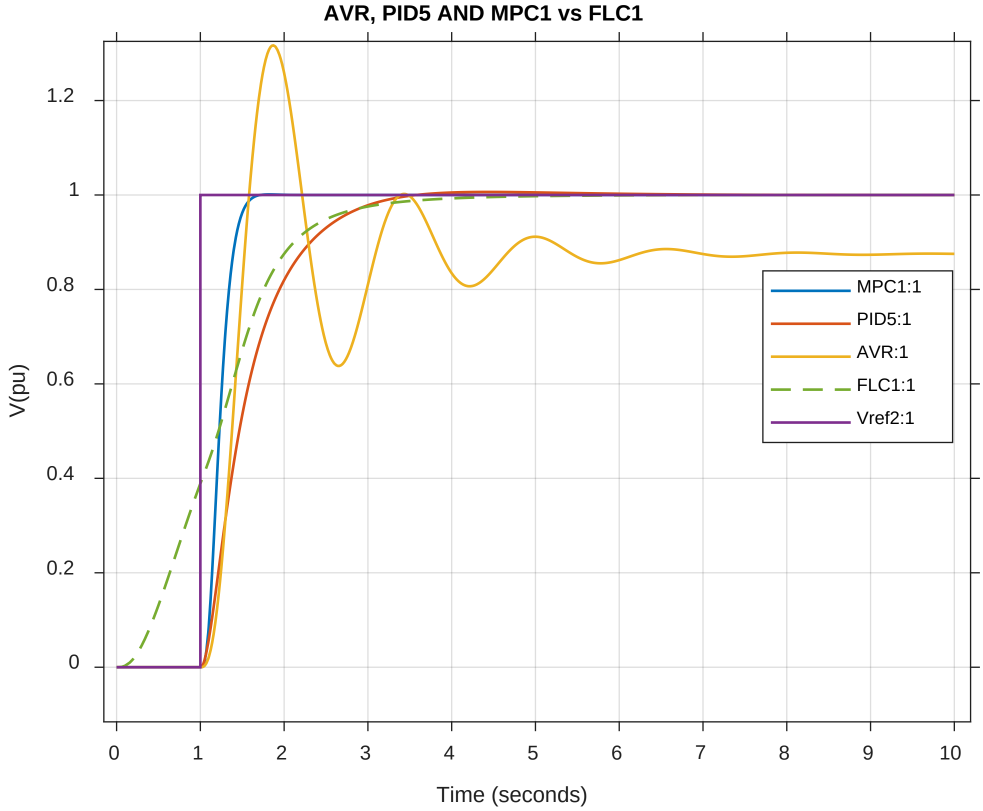



*Figure6. 5* FLC1 vs PID, AVR and MPC step response

Table 6. 4  The numerical results of FLC1

| | u(t) range | E(t) range | De/Dt range | % OS | $T_R$ (S) | $T_S$ (S) | V (PU) | IAE | ISE |
|---|---|---|---|---|---|---|---|---|---|
| AVR | - | - | - | 50.52 | 0.318 | 4.91 | 1.32 | 9 | 9 |
| PID5 | - | - | - | 0.645 | 1.18 | 2.04 | 1.01 | 0.6336 | 0.3629 |
| MPC1 | - | - | - | 0 | 0.606 | 1.646 | 1 | 0.3494 | 0.1767 |
| FLC1 | 0 to 0.4 | -1 to 0.7 | -1 to $1.5 \times 10^{14}$ | 0 | 1.650 | 2.028 | 1 | 0.5947 | 0.183 |

As previously stated, the FLC was categorised into six separate controllers in order to get the greatest performance amongst them; FLC1 outlined above has shown to be the best. The graphical and numerical results of FLC2 are shown in Figure 6.6 and Table 6.4, respectively. According to these data, FLC2 works marginally better than PID in terms of reaction time, however the voltage rises beyond 1 pu before settling. In terms of performance metrics, PID5 has showed a superior reaction. MPC remained the greatest in every aspect.

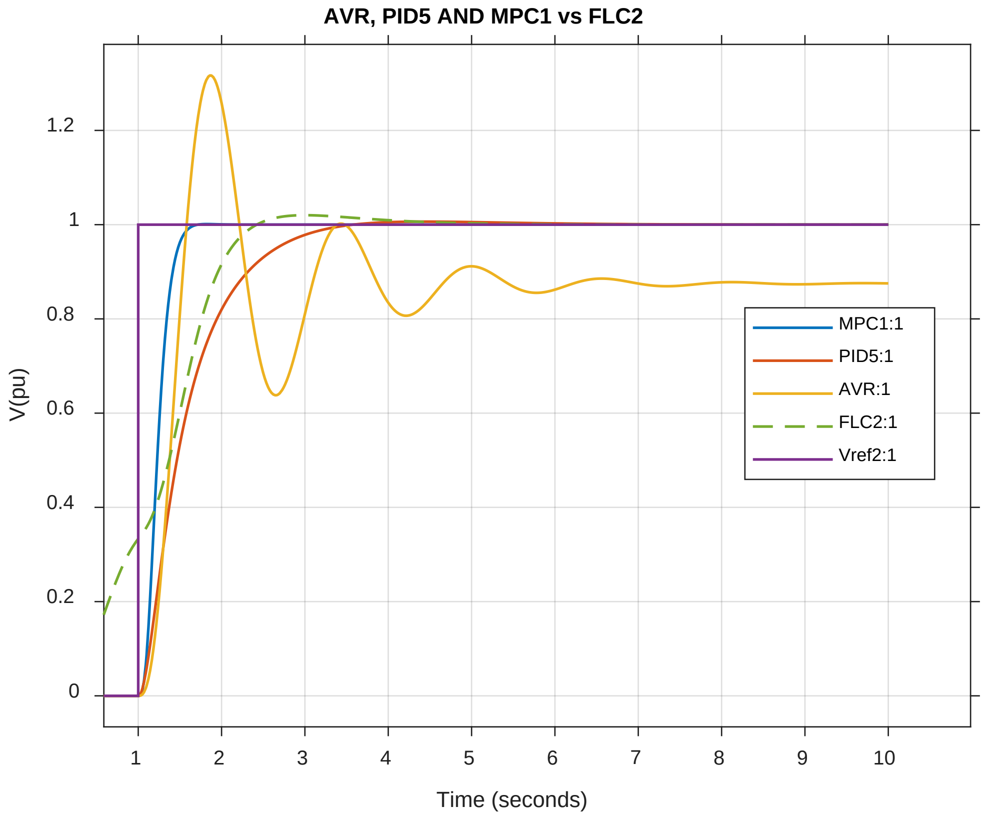



*Figure6. 6* FLC2 vs PID, AVR and MPC step response

Table 6. 5 The Numerical results of FLC2

| | u(t) range | E(t) range | De/Dt range | % OS | $T_R$ (S) | $T_S$ (S) | V (PU) | IAE | ISE |
|---|---|---|---|---|---|---|---|---|---|
| AVR | - | - | - | 50.52 | 0.318 | 4.91 | 1.32 | 9 | 9 |
| PID5 | - | - | - | 0.645 | 1.18 | 2.04 | 1.01 | 0.6336 | 0.3629 |
| MPC1 | - | - | - | 0 | 0.606 | 1.646 | 1 | 0.3494 | 0.1767 |
| FLC2 | 0 to 0.2 | -1 to1 | $0\text{-}1.5\text{x}10^{14}$ | | 1.032 | 1.039 | 1.02 | 3.772 | 1.669 |

The numerical and graphical results of FLC3, the last controller constructed with the 5 by 5 rule-based scheme, are shown in table 6.5 and figure 6.7 respectively. Among the three FLCs, this has been the poorest performer. This controller behaves similarly to an AVR without the controller. Figure 6.7 shows that the reaction is similar to that of an AVR with a Kg of 0.7.

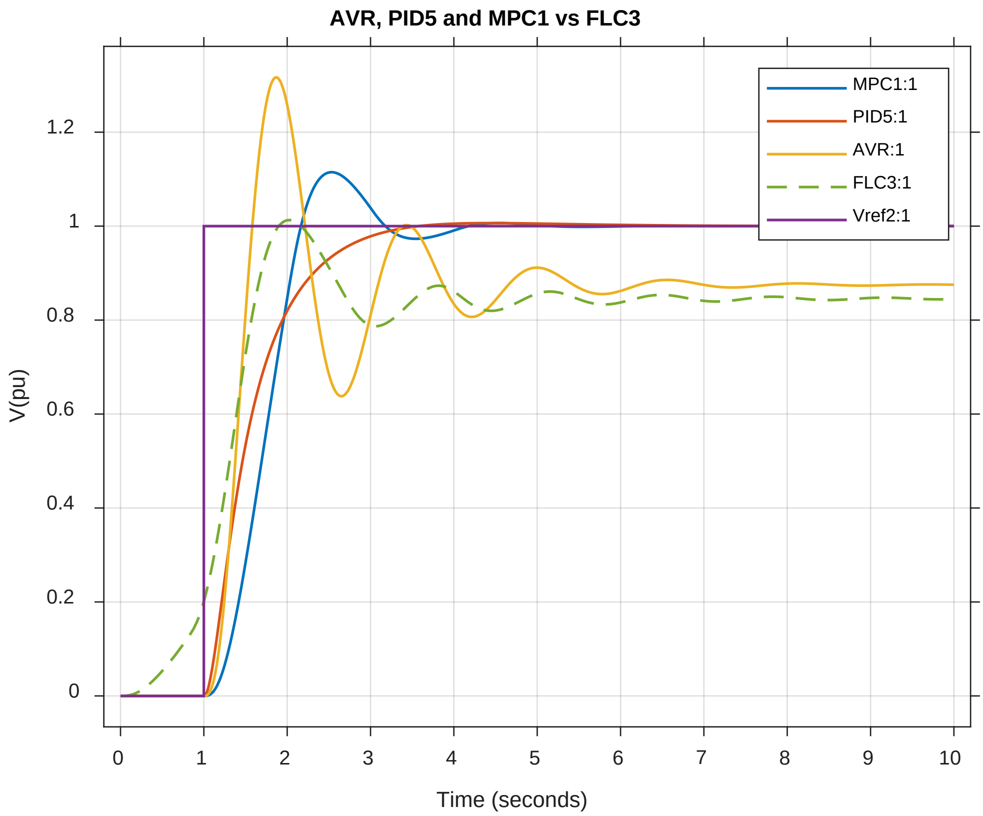



*Figure6. 7* FLC3 vs PID, AVR and MPC step response

Table 6. 6 Numerical Results of FLC3

| | u(t) range | E(t) range | De/Dt range | % OS | $T_R$ (S) | $T_S$ (S) | V (PU) | IAE | ISE |
|---|---|---|---|---|---|---|---|---|---|
| AVR | - | - | - | 50.52 | 0.318 | 4.91 | 1.32 | 9 | 9 |
| PID5 | - | - | - | 0.645 | 1.18 | 2.04 | 1.01 | 0.6336 | 0.3629 |
| MPC1 | - | - | - | 0 | 0.606 | 1.646 | 1 | 0.3494 | 0.1767 |
| FLC3 | 0 to 0.4 | 0 to 0.5 | 0 to 1.5x10 | 0 | 1.695 | 4.061 | 0.938 | 1.969 | 0.5827 |

On MATLAB Simulink 2021a, a 7by7 FSI-based system with FLC4 to FLC6 controllers was simulated. It is observed that their response time is slower than that of the preceding 5by5 FSI system. FLC4 graphical and numerical findings are shown in Figure 6.8 and Table 6.9 respectively. According to these findings, this controller outperformed the PID5 in terms of the IAE and ISE indices, as well as the settling time and percentage overshoot. However, when compared to the MPC controller, it is still the poor performer.

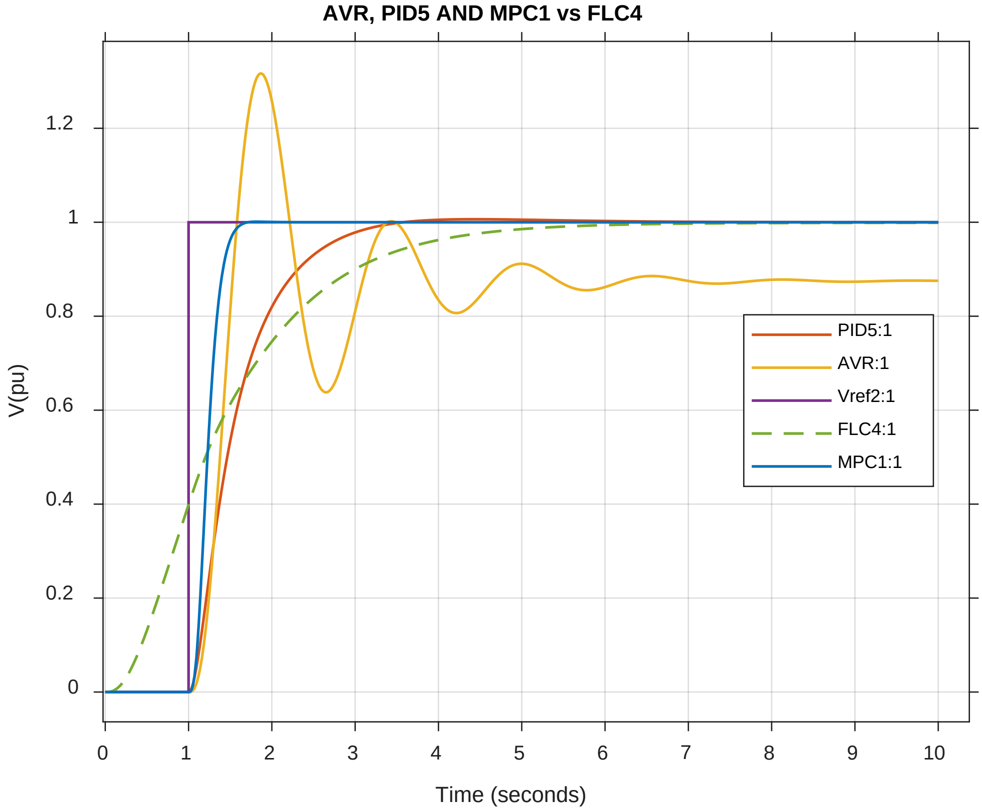



*Figure6. 8* FLC4 vs PID, AVR and MPC step response

Table 6. 7 Numerical results of FLC4

| | u(t) range | E(t) range | De/Dt range | % OS | $T_R$ (S) | $T_S$ (S) | V (PU) | IAE | ISE |
|---|---|---|---|---|---|---|---|---|---|
| AVR | - | - | - | 50.52 | 0.318 | 4.91 | 1.32 | 9 | 9 |
| PID5 | - | - | - | 0.645 | 1.18 | 2.04 | 1.01 | 0.6336 | 0.3629 |
| MPC1 | - | - | - | 0 | 0.606 | 1.646 | 1 | 0.3494 | 0.1767 |
| FLC4 | 0 to 0.1199 | -0.5 to1 | -0.5 to$1.5x10^{14}$ | 0 | 2.346 | 1.998 | 1 | 0.8285 | 0.3562 |

This was tested further on FLC5 and FLC6 and found that the voltage does not return to the rated value of the synchronous generator. This outcome is undesirable for a powersystems network. We may assume that the system was still unstable for FLC5 and FLC6.

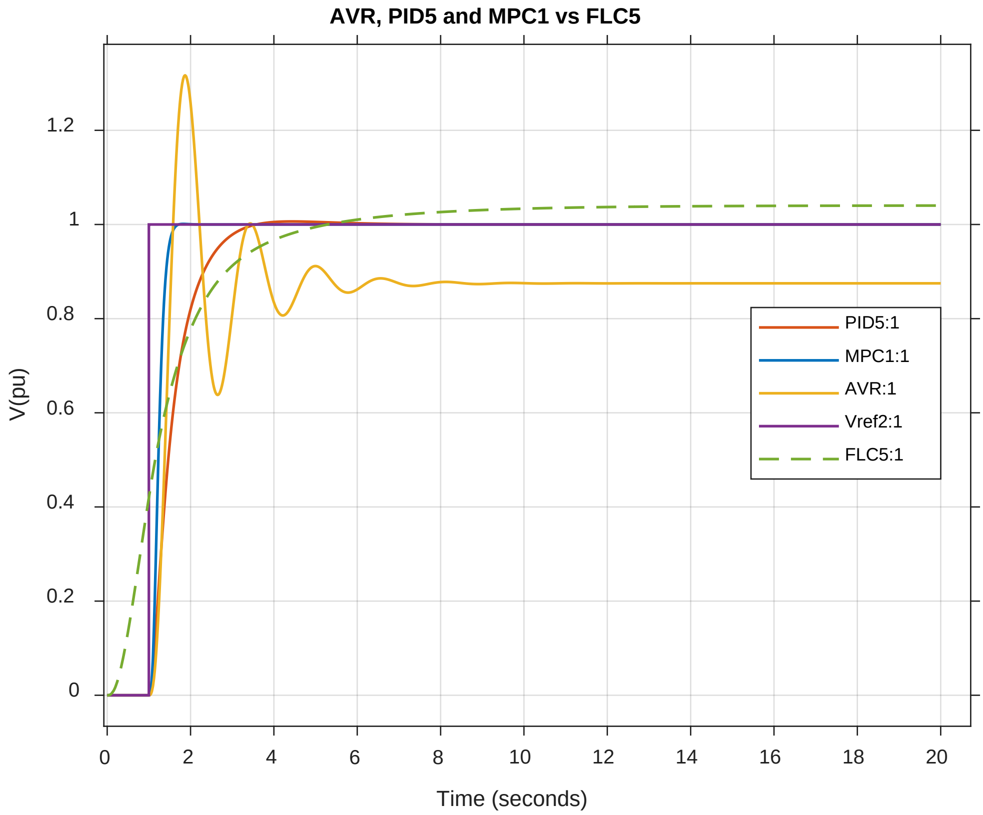



*Figure6. 9* FLC5 vs PID, AVR and MPC step response

Table 6. 8 Numerical results of FLC5

| | u(t) range | E(t) range | De/Dt range | % OS | $T_R$ (S) | $T_S$ (S) | V (PU) | IAE | ISE |
|---|---|---|---|---|---|---|---|---|---|
| AVR | - | - | - | 50.52 | 0.318 | 4.91 | 1.32 | 9 | 9 |
| PID5 | - | - | - | 0.645 | 1.18 | 2.04 | 1.01 | 0.6336 | 0.3629 |
| MPC1 | - | - | - | 0 | 0.606 | 1.646 | 1 | 0.3494 | 0.1767 |
| FLC5 | 0 to 0.119 | -0.5 to1 | -0.5 to $1.5x10^{14}$ | | 3.129 | 6.89 | 1.019 | 3.049 | 0.5482 |

The numerical FLC results are shown in table 6.8, while the graphic results are shown in figure 6.10. It is clear from these findings that the voltage has dropped below 1pu, which may be recognized as an undervoltage by the generator's protective mechanisms. Other controllers' performance indices may be superior, but the system cannot support this sort of response.

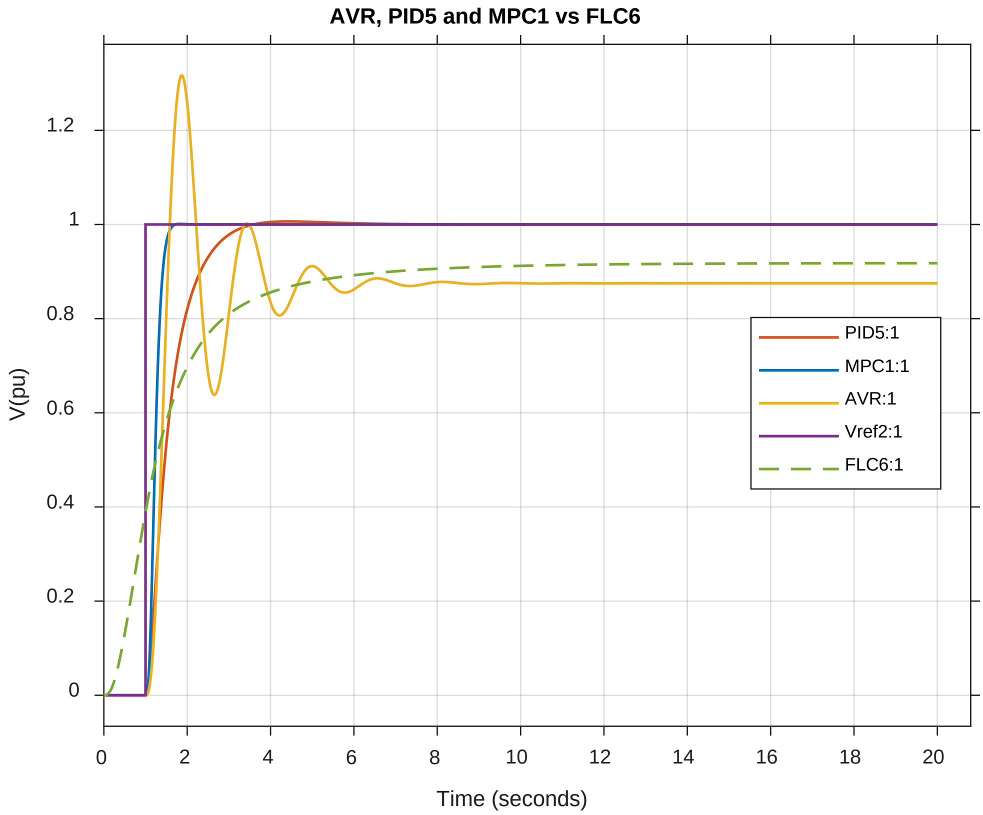



*Figure6. 10* FLC6 vs PID, AVR and MPC step response

Table 6. 9 Numerical results of FLC6

| | u(t) range | E(t) range | De/Dt range | % OS | $T_R$ (S) | $T_S$ (S) | V (PU) | IAE | ISE |
|---|---|---|---|---|---|---|---|---|---|
| AVR | - | - | - | 50.52 | 0.318 | 4.91 | 1.32 | 9 | 9 |
| PID5 | - | - | - | 0.645 | 1.18 | 2.04 | 1.01 | 0.6336 | 0.3629 |
| MPC1 | - | - | - | 0 | 0.606 | 1.646 | 1 | 0.3494 | 0.1767 |
| FLC6 | 0 to 0.105 | -0.5 to1 | -0.5 to $1.5x10^{14}$ | 0 | 2.123 | 6.089 | 0.827 | 3.03 | 0.596 |

## 6.4 Conclusion

This chapter developed and simulated a rudimentary model of an FLC-based-AVR. The model proved that the AVR system performs poorly in the absence of a controller. It is then demonstrated that an effective controlling mechanism is required to enhance an AVR's dynamic responsiveness and hence the voltage stability of the power system however with proper modelling of an FLC the best results are obtained in the third controller (FLC3), hence the dynamic performance of an AVR is improved.

Fuzzy logic provides a straightforward approach for converting perception to reality. However, because fuzzy systems require operator experience, they are frequently hard. Because the rules are established, the decision-making process is based on fuzzy logic if these rules are flawed, the results may not be acceptable at all. With proper modelling of an FLC the best results are obtained in the third controller (FLC1 for a 5by5 FSI system and FLC4 for a 7 by7 FSI system ), hence the dynamic performance of an AVR is improved , howeverThe MPC1 has remain the best performing controller for the AVR. This is illustrated in figure 6.10 and this can also be referred back to table 6.3.

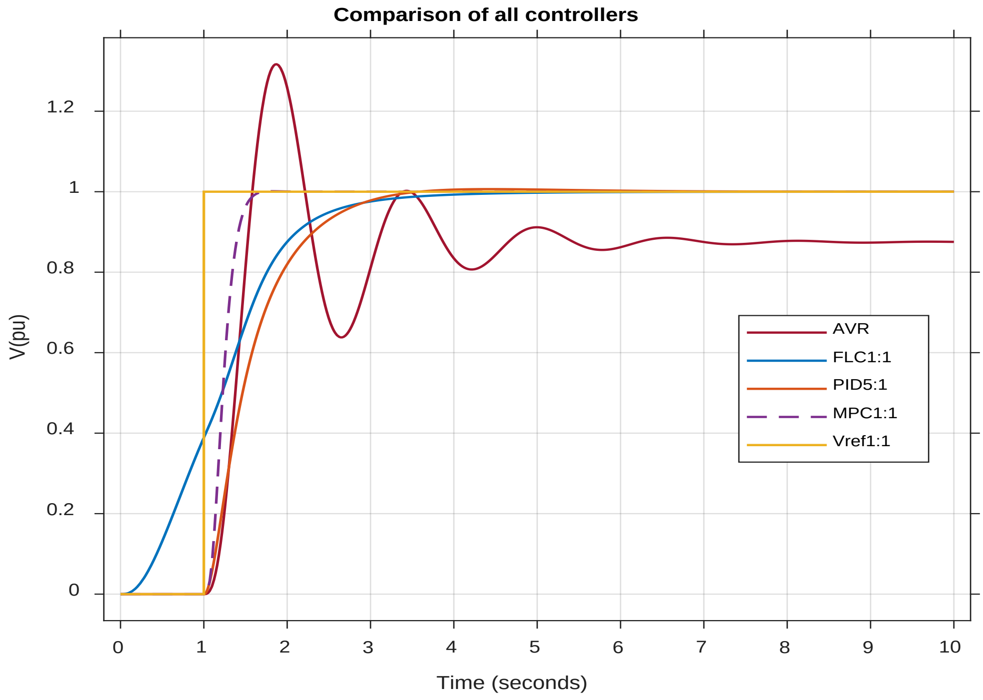



*Figure6. 11* Comparison of all controllers and the reference voltage

# CHAPTER SEVEN

## CONCLUSION AND RECOMMENDATION

### 7.1 CONCLUSION

Improving AVR performance is critical in the context of power system stability. To optimize the performance of an AVR system, a proper controlling mechanism is essential. The employment of PID, MPC, and FLC controllers for an AVR can be utilized as an AVR's controlling mechanism to increase its dynamic performance. An AVR's stable and rapid reaction is obtained through adequate design modelling and performance analysis.

This research work presents the modelling, simulation, and performance analysis of three controllers for use on an AVR system. The major goal was to restore the terminal voltage of a synchronous generator to 1pu (considered the nameplate voltage) in the shortest amount of time, even after it had been subjected to disturbances such as load fluctuation or reactive power demand by the power systems network. Each controller's performance is evaluated by examining its step response when the generator's terminal voltage is disrupted.

To investigate the transient response of an automated voltage regulator without a controller, a transfer function is mathematically modelled and simulated in MATLAB Simulink 2020a. The AVR has performed poorly as the generator's terminal voltage deviates by about 50%. The AVR system has also failed to restore the terminal voltage as it falls below 1pu, which necessitate the addition of a controller for the system. A PID controller is then introduced to enhance the AVR system's transient responsiveness. The PID was divided into five controllers, PID1 to PID5. Tuning of each PID was done by analysing each controller using performance indices such as IAE, ISE, ITAE, and ITSE, as well as transient response of rising time, settling time, percentage overshoot, and peak value. PID5 proved to be very effective and best performing controller amongst the other PIDs.

To analyse, evaluate the dynamic performance of these two controllers, and enhance the step responsiveness of an AVR system, an MPC is mathematically modelled and simulated for the same AVR system. The investigation has been expanded to match the output of PID5 with MPC action and. Based on these findings, the MPC-3 through MPC-5, PID5 controller remains the best performing controller in terms of percentage overshoot response time and fault pickup time. As the value of beta improves, the MPC's reaction time decreases while its ISE and ITE significantly improve. The graphical and numerical findings show that MPC1 has the capacity to perform substantially quicker than PID5 for AVR systems.

Fuzzy logic offers a simple technique for translating this perception into actuality. However, the Fuzzy systems requires expertise from the operator and it is often challenging. Since the rules are based on predetermined rules, the decision-making process is based on fuzzy logic. If these rules are flawed, the results may not be acceptable at all. Choosing a membership function and basic rules is one of the most challenging parts of creating fuzzy systems. A FLC is mathematically modelled and simulated for the same AVR system. The research is extended to compare the FLC with both MPC and PID controller, from the graphical and numerical results; it is proven that MPC1 remained the best performing controller for the application of an AVR system. A major drawback of Fuzzy Logic control systems is that they are completely dependent on human knowledge and expertise.

## 7.2 SCOPE FOR FUTURE WORK

1. The problems of an AVR system can be incorporated with the optimal control of power system stabiliser to provide a positive contribution by damping generator rotor angle swings, which are in a broad range of frequencies in the power system.
2. The MPC controller can be replaced with fractional order model predictive controller (FO-MPC) as the Fractional calculus allows a more compact representation and problem solution for many non-linear systems.
3. The PID controller optimisation technique can be incorporated in this research to further improve the dynamic performance of the controller. An optimisation-

based controller using Particle swarm optimisation technique for a master's level.

4. With the development of virtual synchronous generator (VSG) techniques, parallel operations of synchronous generators (SGs) and VSGs become increasingly common in a micro grid, this research can be extended to consider these types of generators.

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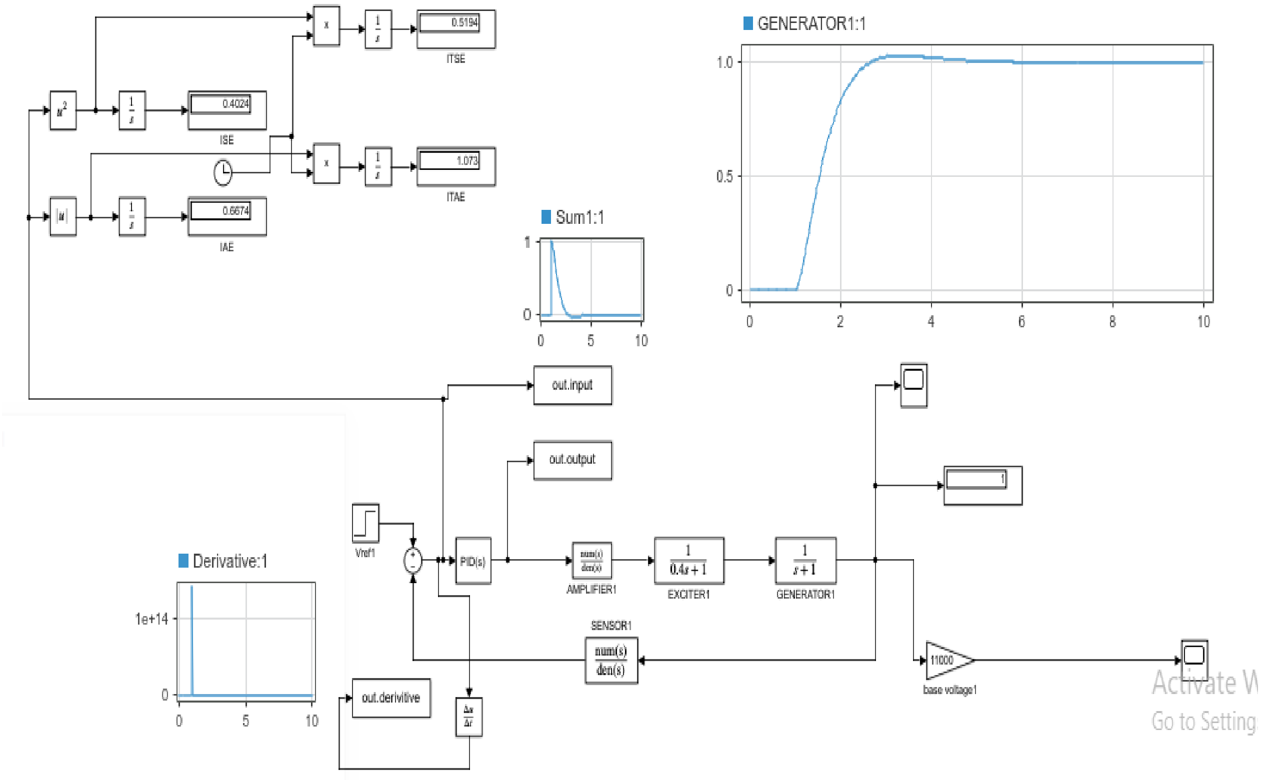
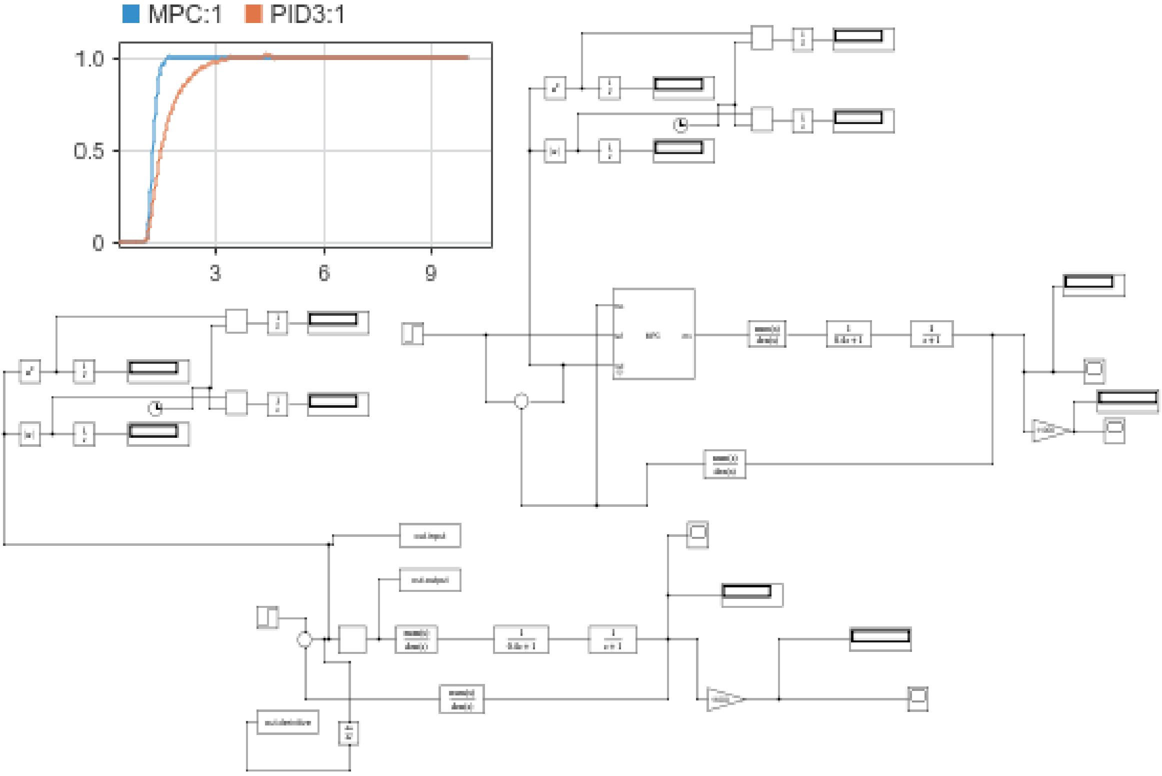
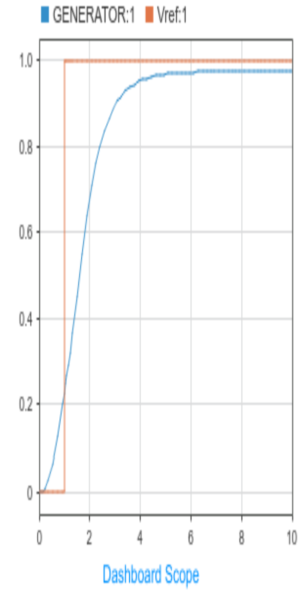
## APPENDIX A: PID-BASED-AVR circuit model on Simulink

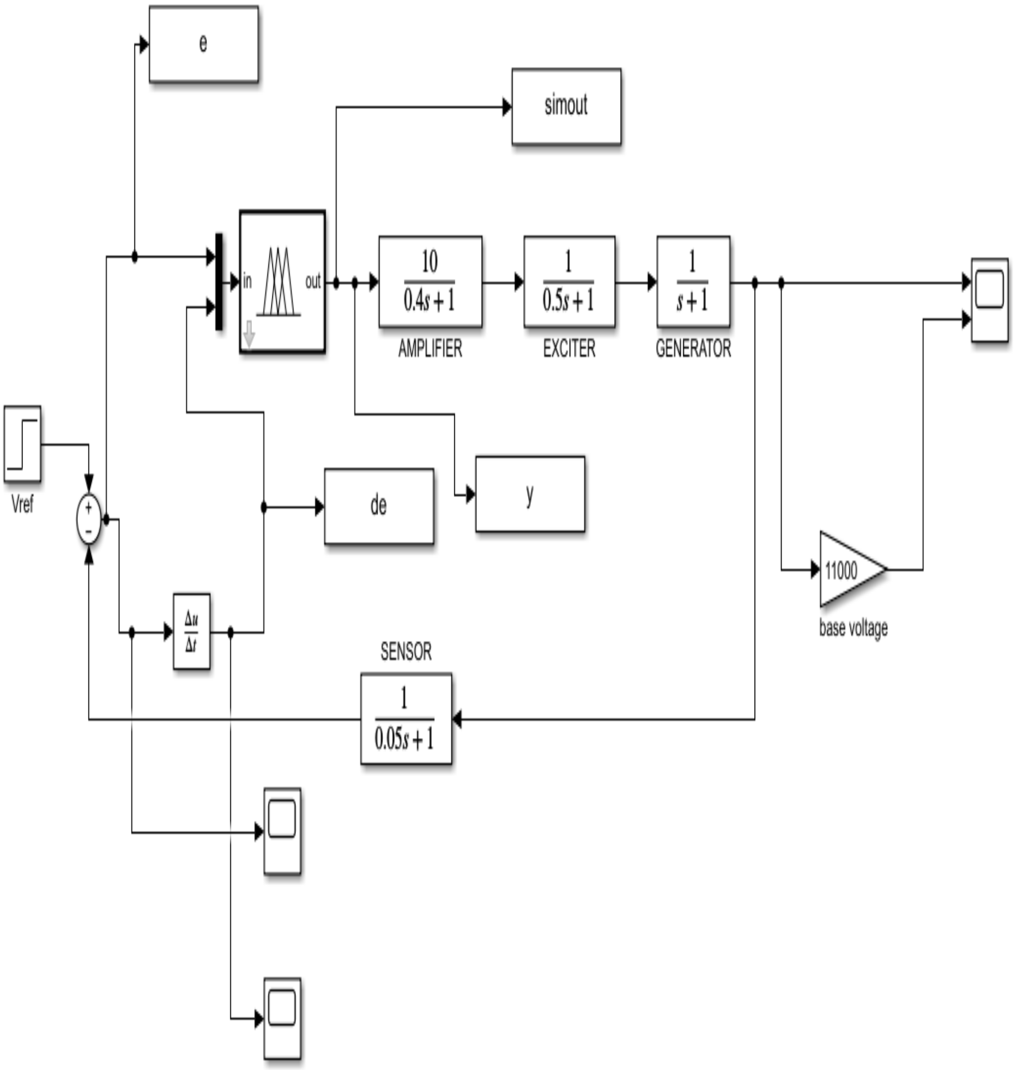


# APPENDIX B: MPC-BASED-AVR circuit model on Simulink

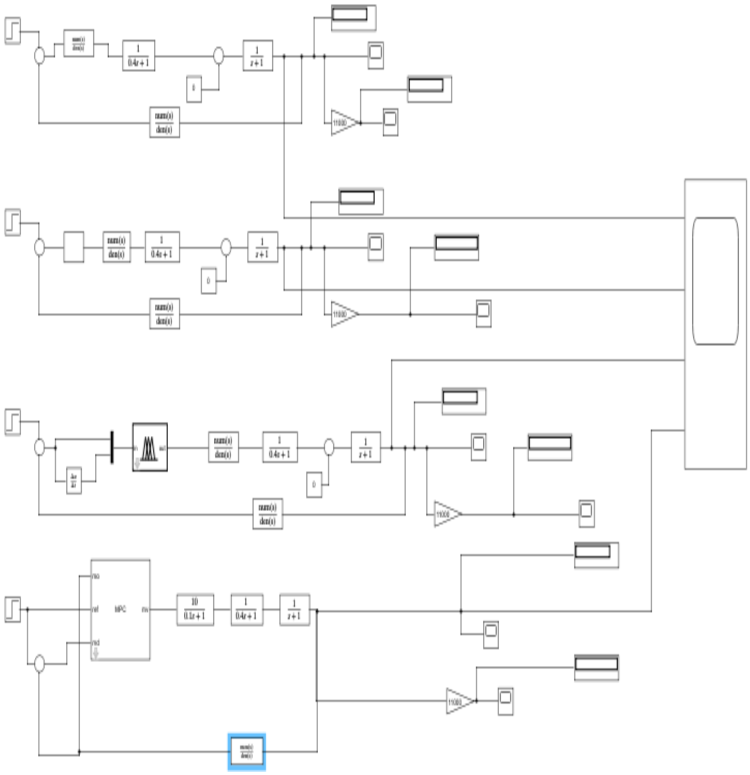


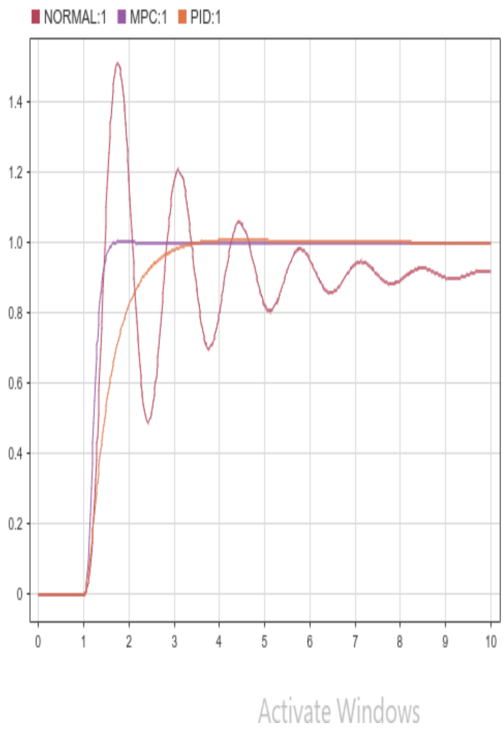
# APPENDIX C: FUZZY-BASED-AVR circuit model on Simulink



# APPENDIX D: FUZZY-PID-MPC BASED AVR SYSTEM (A COMPARISON)





## Appendix E: Comparison of different tuning techniques for a PID, as referred to

| Method number | Method used | Kp | Ki | Kd |
|---|---|---|---|---|
| 1 | GA | 0.886 | 0.7384 | 0.3158 |
| 2 | PSO | 0.6568 | 0.5393 | 0.2458 |
| 3 | BFGA | 0.6728 | 0.4787 | 0.2299 |
| 4 | GA | 0.8282 | 0.7143 | 0.3010 |
| 5 | PSO | 0.6445 | 0.5043 | 0.2348 |
| 6 | GAPSO | 0.6794 | 0.6167 | 0.2681 |
| 7 | CRPSO | 0.3741 | 0.2685 | 0.1000 |
| 8 | GA | 0.5781 | 0.3745 | 0.2502 |
| 9 | ABC | 1.6524 | 0.4083 | 0.3654 |
| 10 | PSO | 1.7774 | 0.3827 | 0.3184 |
| 11 | DEA | 1.9499 | 0.4430 | 0.3427 |
| 12 | GA | 0.8220 | 0.6068 | 0.3838 |
| 13 | PSO | 0.4641 | 0.4370 | 0.1330 |
| 14 | ICA | 0.6830 | 0.6709 | 0.3048 |
| 15 | GA | 0.6785 | 0.4824 | 0.2550 |
| 16 | PSO | 0.6445 | 0.4603 | 0.2002 |
| 17 | GSA | 0.6054 | 0.4148 | 0.2007 |
| 18 | PSO | 0.6254 | 0.4578 | 0.2187 |
| 19 | CAS | 0.6746 | 0.6009 | 0.2617 |
| 20 | RGA | 0.6311 | 0.4615 | 0.2125 |
| 21 | PSO | 0.6443 | 0.4700 | 0.2423 |
| 22 | HEA | 0.6364 | 0.4654 | 0.2349 |
| 23 | PSO | 0.3452 | 0.4778 | 0.1017 |
| 24 | SPSO | 0.5523 | 0.4418 | 0.1572 |
| 25 | APSO | 0.5536 | 0.4369 | 0.1940 |
| 26 | TLBO | 0.5911 | 0.4036 | 0.1943 |
| 27 | PSO | 0.4585 | 0.2894 | 0.1246 |
| 28 | DE | 0.6286 | 0.3829 | 0.2659 |
| 29 | SPSO | 0.5857 | 0.4189 | 0.1772 |
| 30 | DEPSO | 1.8256 | 0.4973 | 0.2366 |
| 31 | TLBOT | 0.5302 | 0.4001 | 0.1787 |
| 32 | COA | 0.6710 | 0.5050 | 0.2640 |
| 33 | LUSA | 1.2012 | 0.9096 | 0.4593 |
| 34 | GWO | 0.6459 | 0.4527 | 0.2128 |
| 35 | IKIA | 1.0426 | 1.0093 | 0.5999 |
| 36 | WOA | 0.7847 | 0.9961 | 0.3061 |
| 37 | ACO-NM1 | 0.6739 | 0.5951 | 0.2622 |
| 38 | ACO-NM2 | 0.6348 | 0.4801 | 0.2276 |
| 39 | SOSA | 0.5693 | 0.4097 | 0.1750 |
| 40 | TLBO | 0.9685 | 1.0000 | 0.8983 |
| 41 | LUS | 0.9519 | 0.9997 | 0.8994 |
| 42 | HAS | 0.8683 | 0.93254 | 0.9419 |
| 43 | PSO | 0.7080 | 0.6560 | 0.2820 |
| 44 | ECSA | 0.5195 | 0.3808 | 0.1625 |