Synchronous Generator Excitation control using Fuzzy Logic Controller

By: Abdurahman Kedir Dekamo

A Thesis Submitted to

The Department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

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

Office of Graduate Studies

Adama Science and Technology University

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DECLARATION

I hereby declare that this master thesis entitled "Synchronous Generator Excitation control using Fuzzy Logic Controller" is my original work. That is, it has not been submitted for the award of any degree, diploma or certificate in any other university.it is my best knowledge. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Abdurahman Kedir Dekamo ____________________ ______________

RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled “Synchronous generator excitation control using fuzzy logic Controller’’ prepared under my guidance by Abdurahman Kedir Dekamo submitted in partial fulfillment of the requirements for the degree of Masters of Science in Electrical Power Engineering. Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

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Advisor	Signature	Date

APPROVAL SHEET

I, the advisors of the thesis entitled "Fuzzy Logic Based Synchronous Generator Excitation System controller "and developed by Abdurahman Kedir Dhekamo, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

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We, the undersigned, members of the Board of Examiners of the thesis by Abdurahman Kedir Dekamo, have read and evaluated the thesis entitled "Synchronous Generator Excitation control using Fuzzy Logic Controller" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Electrical Power Engineering.

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The name of Allah, most gracious, most merciful!

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LIST OF ABBREVIATIONS

Abbreviation	Descriptions
A.C	alternating current
AVR	automatic voltage Regulator
CAVR	Compensated automatic voltage controller
D.C	Direct Current
e.m.f	electromotive force
FIS	Fuzzy inference system
FLC	fuzzy logic controller
FPI-AVR	Fuzzy proportional integral-automatic voltage controller
HVDC	high voltage direct current
LFC	load frequency control
Mat lab	Matrix laboratory
MPC	Model Predictive Control
P	Real(active) power
PID	Proportional Integral Derivative
PI	Potential integral
PT	potential transformer
PSS	power system stabilization
Q	Reactive power
SGE	synchronous generator Excitation
t	instantaneous time in sec

LIST OF ACRONYMS

$Dout$	Derivative term of output
E	error = set value – actual value
$Iout$	Integral term of output
Kd	Derivative gain, a tuning parameter
KA	Amplifier gain constant
KE	Exciter gain constant
KF	stabilizer gain constant
KG	Generator gain constant
Ki	Integral gain, a tuning parameter
K_P	Proportional gain, a tuning parameter
P_{out}	Proportional term of output
V_e	error signal
$Ve(S)$	Error voltage signal
$VRef(S)$	Reference input voltage
$VR(S)$	Amplifier Voltage
$VF(S)$	Exciter Voltage
$Vt(S)$	Output Voltage
$Vs(S)$	sensor voltage
τA	Amplifier time constant
τE	Exciter time constant
τG	Generator time constant
τF	Stabilizer time constant

ABSTRACT

As the development of the national economy increasing, the needs of electric power become increasing day to day. The stability and reliability of power system is one of the important national economic securities. So that Reliability of generator excitation system is one of the important elements to improve the stability of the power system. The demands towards the generator's excitation control system have been constantly increasing, due to the complexity of the electric power system. It is a trend of development that the integration of the intelligent control theory and synchronous generator excitation control can achieve a better effective control. Conventional control methods like, PID cannot meet the requirements of the increasingly complex power system due to some defects. The first step of controls system analysis and design is the mathematical modeling of the system. The work discussed in this thesis has used transfer function method to develop mathematical model of generator exciting for stability analysis, state space model with linear differential equations is used for system description. In the next step, in this thesis it is developed the actual mathematical and Simulink models to check the controllability input voltage of excitation system. From this thesis it was obtained that, FLC controller model gave shorter settling time and almost negligible overshoot after specific load variation (perturbation) when we compared with the conventional PID controller. Fuzzy logic controller has many advantages. Simple in structure, it is relatively easy to be realized and mathematical model of the controlled system is not required. So this makes FLC better to use. This thesis is focused only on generator's excitation control using FLC comparing with the output result of PID controller. The result of the output of FLC is control comparing with AVR control only and with addition of PID control and recommend on the result using MATLAB2020a software that we analyze the curve.

Keywords: - Excitation System Control, PID Control, FLC, overshoot voltage, settling time, steady state error, steady state response.

CHAPTER- ONE

1.INTRODUCTION

1.1. Background

The first step of electric power system is generation. Transmission, distribution and utilization are the other parts of conventional electrical power networks. Each one of these four stages: - generation, transmission, distribution and utilization has its own problems and control approaches in order to keep them in service. The main objectives of the control in power system is to generate and deliver in interconnected system as economically and reliable as much as possible while maintaining the voltage and frequency in steady state within permissible limit [1]. In electric power systems there are three different control levels [2]: Level 1-Generating Unit Control -It consists of prime mover control and excitation control with AVR and PSS. The prime mover controls generator speed deviation and energy supply system variable like boiler pressure or water flow and also excitation control level is maintaining the generator terminal voltage and reactive power output within its machine-dependent limits. Here is that, this thesis is focused on the study only on excitation system control level areas. Level 2- System Generation Control-which determines real power output such that the overall system generation meets the system load. It further controls the frequency and the tie line flows between different power system areas. Level-3-Transmission control monitors- means controlling power and voltage control devices (like tap-changing transformers, synchronous condensers and static AVR compensators). From the view point of system automation [3], generating Unit Controls a complete closed-loop system and in the past a lot of effort has been dedicated to improve the performance of the controllers. Typical, generator’s excitation control is a non-linear time-variant control system. Due to the complexity of the electric power system, the demands towards the generator’s excitation control system have been constantly enhancing. Generator excitation is one of the most important elements of electric power system since, it is the source of electrical energy. In generator, mechanical energy (usually from a turbine) is converted into electrical energy. So that, energy conversion is possible only if generator excitation exists. The output values of generator excitation are voltage and reactive power. This means that regulation of generator excitation means actually regulation of generator output energy and also has impacts the stability of entire electric power system. A reliable, continuous supply of electric energy is crucial issue for the functioning of today's many complex needs in societies. Due to a combination of increasing energy consumption and impediments of various kinds concerning the extension of existing electric transmission networks, these power systems are operated closer and closer to their limits. In case of a large disturbance, the system conditions will change in a highly non-linear manner and the controller parameters are no longer valid. In this case the controller may even add a destabilizing effect to the disturbance by for example adding negative damping. These problems provide an important motivation to explore other modern control techniques like fuzzy logic control. With the development of control theory, it is a trend of development that, the integration of the intelligent control theory and generator's excitation control can achieve a better effect of control. The traditional PID control is also its structure is simple, has certain robustness, and can achieve better control effect, but it needs to manually adjust the parameters, so that the generator excitation adjustment process is more complicated and inconvenient. FLC is characterized by the independent control objects from mathematical model, and the design method is simple and has strong adaptability, and is easy to implement [4].

After the theoretical and mathematical analysis is completed, MATLAB2020a simulation software is used in simulation, in which a satisfying effect has been observed. The synchronous generator driven by either a hydraulic or a steam turbine is the main unit in electrical power generation and the control of power systems mean the control of synchronous generator. However, the concept of power system control has been changed since the adoption or introduction of micro grids. In conventional power networks, the generation is usually away from the urban areas or customers center and the distribution is either done by radial or ring networks. Due to the impedances of transformers, distribution and transmission lines, the power network is considered as an infinite bus compared to the distribution networks and power dissipation units. Changes in small load and fault currents in distribution feeders do not affect the rest part of the power networks due to the high impedances between the generator and distribution. Therefore, large power networks are represented by infinite bus and power management is done in some specified locations in power transmission networks, not everywhere in distribution systems. As a result of the network structure, the equilibrium between generation and dissipation is obtained by controlling the generating units, which are the synchronous generators. An exhaustive investigation is carried out in this thesis research is the control of generator excitation for enhancement of the power system stability. The basic function of an excitation system is to provide direct current to the synchronous generator field winding. Excitation controls have used for both adjusting voltage and damping oscillation by controlling the field voltage. The power system generator terminal voltage could drop substantially during a large disturbance such as a three-phase fault occurring on near the generator bus. During the fault, the flow of the electrical power to the power system is interrupted, and the generator rotor speed is accelerated by the input mechanical power. The protection circuit in the power system will normally operate to clear the fault. The generator is then reconnected to the power system and recovers the power supply to the system. This recovery often results in some post-fault oscillations caused by the energy stored in the generator rotor during the period of the fault. The damper windings on the generator rotors can be used to control these oscillations. However, increasing the damper windings is costive when designing and making the generator. The generator excitation control provides, in general, a better control in terms of cost and control effectiveness. One typical generator excitation control is the AVR that controls the terminal voltage of generator. This type of regulator normally increases the field voltage to quickly recover the terminal voltage to its pre-fault level. Such a fast recovery of the generator terminal voltage will impose a negative effect on the damping of the post-fault oscillation. Because the oscillating torque that causes the oscillation increases relatively with the terminal voltage. The regulator and the stabilizer are usually designed separately. The regulator is designed to achieve the best voltage regulation performance and the stabilizer is designed to damp the oscillations. The coordination of two goals may have some problems when operating conditions has changes.

The control of electrical power systems is done in two steps; - LFC and excitation control. In order to generate the required power, steam or water input to the turbine is controlled by LFC which is called governor control. The power factor and magnitude of the generated current are adjusted by excitation control.

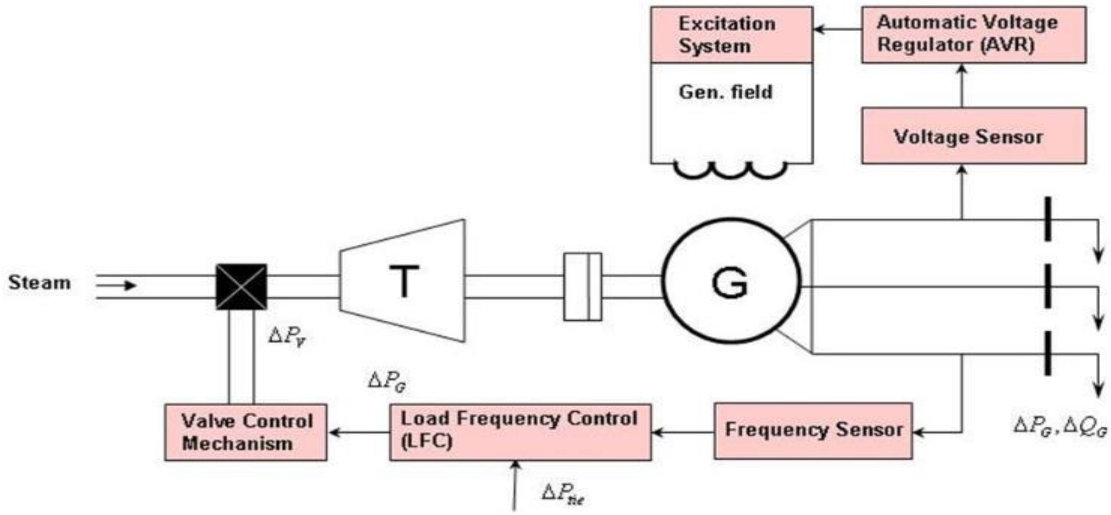

Figure 1. 1 Schematic diagram of LFC and AVR of a synchronous generator [6]

Where: P is active power energy, Q is reactive power energy and Δ is represent changes.

1.2 Statement of the Problem

The traditional PID cannot meet the requirements of the increasingly complex power system due to some defects. The traditional PID control structure is simple, has certain robustness, and can achieve better control effect. However, the traditional PID controller needs to manually adjust the parameters. So that the generator excitation adjustment process is more complicated and inconvenient. On the other hand, PID controllers do not work efficiently and satisfactorily in non-linear systems. It is more difficult to account for changes measured values of the voltage magnitude and it has a longer rise and settling time which affects excitation system control performance.

1.3. Objectives

1.3.1. General objective

- The objective of this thesis is to improve synchronous generator excitation system control performance using FLC and compare PID controller with FLC controller.

1.3.2 Specific Objectives

- To enhance the excitation system control performance using FLC other than PID.
- To have a better control effective of the synchronous generator excitation system.
- To investigate the effectiveness of the fuzzy logic based synchronous excitation controller.

- ❖ Compare and contrast significances of PID controller and FLC and suggest better excitation system control strategy by using MATLAB/Simulink.

1.4. Scope the study

The scope of this thesis is to design and simulate excitation system controller using FLC by comparing conventional PID controller. All the work is checked by using MATLAB/Simulink software. The effectiveness between conventional PID controller and fuzzy logic(FLC) maximum overshoot, rise time, settling time and under/ input voltage and voltage variations.

1.5 Limitation of the Study

- ➢ The thesis is restricted to simulate the system using MATLAB/Simulink and demonstrating how the various system components communicate with one another. This is due to the difficulty to obtain the necessary material components for the implementation of a real system.

1.6. Motivation

The electric power system is frequently subjected to various disturbances, caused by for example, capacitor switching, fault activating, large load changing, transmission line switching and others. These disturbances, if not properly handled, can cause stability problems on the power system. With appropriate operations on power system controls such as correct circuit breaker operations and proper generator excitation controls the disturbed power system can either re-again the pre-disturbance operating state or reach a new stable operating state after the disturbances. So that one of an element needs to be control is generator excitation system for power system stability.

1.7. Thesis layout (organization)

This thesis consists of five chapters

Chapter-1-This chapter discussed a general background of excitation system, problem Statement, objective, specific objective, limitation of the study and scope of the work are discussed

Chapter-2: Discussed the literature reviews, excitation system, the functions of an excitation system, excitation system requirements, elements of an excitation system, types of excitation systems, reactive power and voltage control, power system consideration, power system stability AVR**,** PID and fuzzy logic controller are studied well.

Chapter-3: Discussed material and methodology, AVR excitation control modeling and conventional control approach, state space representation of excitation and test for stability and controllability, PID with AVR and FLC with AVR.

Chapter -4: presented results, discussions, and comparison without controller, AVR with PID, AVR with FLC for each controlling process using MATLAB /Simulink and finally presented the conclusion and the recommendations of the research based on the analysis.

CHAPTER-TWO

2.LITERATURE REVIEW

2.1 Related Work

Excitation system control is a great role to provide D.C to the generator field winding. Excitation controls have functions of both adjusting voltage and damping oscillation by controlling the field voltage. Therefore, more analysis, control and stabilization of power system control are the main factors that need to be considered to perform best control system. Many control methods are used for control of excitation system has its own drawbacks. The simple and low-cost controller structure is always in demand for most power generation and high-performance applications. Every control method has some advantages and limitation due to particular control method considers as a suitable control method under specific conditions, compared to other control methods. The control method that gives the best performances under any conditions is always in demand. The following description are the basic reasons power system oscillation and the requirements for generator excitation control. The AVR, power system stabilizer, PID control, modem digital control techniques, adaptive control, fuzzy logic control, and artificial neural network control are some of controlling methods. Basic requirements of power system oscillation for generator excitation control. The terminal voltage of the power system generator could be very low during a large disturbance such as a three-phase fault occurring on or near the generator bus. During the fault, the flow of the electrical power to the power system is interrupted, and the generator rotor speed is advanced by the input mechanical power. After the protection circuit has cleared the fault, the generator is reconnected to the power system and recovers the power supply to the system. Very often this recovery results in some kind of post-fault oscillations caused by the energy stored in the advancement of the generator rotor during the period of the fault. The damper windings on the generator rotors can be used to control the oscillation. But this method is very expensive. Compared with damper windings, the generator excitation control provides in general, a better alternative in terms of cost and control effectiveness. One typical generator excitation control is the AVR, that regulates the terminal voltage of the generator based on the terminal voltage feedback. The AVR normally increases the field voltage to quickly recover the terminal voltage to its pre-fault level. Such a fast recovery of the generator terminal voltage will impose a negative effect on the damping of the post-fault oscillation, due to the oscillating torque that causes and maintains the oscillation increases relatively with the terminal voltage.

Power System Stabilizer (PSS)-An addition of a PSS with AVR as a supplementary controller and with this combined generator excitation control, if proper designed, could eliminate any negative effects on the damping of the post-fault oscillation. The gain determines the amount of damping introduced by the PSS. The stabilizer can produce a component of electrical torque in phase with the rotor speed deviation. Therefore, those oscillations relative to the rotor speed can be detected and damped by the PSS. The power system dynamic performance is improved by the damping of post-fault oscillations. The PSS is designed based on the model of a single machine to an infinite bus system under a specific operating condition. This method is commonly used by industry till today for damping the oscillations. However, it has the following drawbacks: [4]

- The AVR and PSS are usually designed separately. The AVR is designed to meet the required voltage regulation performance and the PSS is designed to damp the oscillations.
- The coordination of two goals has some problems when operation conditions change.
- The PSS, which is designed for a narrow band of oscillating frequencies, cannot provide a total satisfactory damping when the oscillation frequency changes.

Modern digital control techniques for generator excitation control-As the modem digital control techniques are replacing the classical analog control techniques, increasing number of controllers are designed and implemented based on new digital signal processing (DSP) technology, such DSP-based controllers with high precision sensors. Comparing with difficulty for maintaining the accuracy of analog controllers, the DSP-based technology has outstanding performance in terms of reliability, accuracy, and implementation. For overcoming the drawbacks in the conventional excitation control, various modern control techniques have been proposed for the design of the excitation controllers such as the optimal control, adaptive control, artificial intelligent control, etc. A linear optimal excitation controller was designed to minimize the system state variation, so that it worked for both voltage and speed deviations. The design focus was on formulating the performance index. The optimal design procedure was to minimize the performance index to get the optimal control. Comparing with the PSS, the compensation blocks was not needed and a wider band of frequencies was obtained. However, because of based on linearization at a specific operating point, this controller cannot provide a good response when the operating condition changed widely. Conventional PSS versus Predictive control -QINGXIANG JIN (19961) has designed and developed an optimal predictive excitation control, named the Model Predictive Excitation Control (MPC). The conventional PSS mainly depends on the feedback control theory such as PI or lead-lag control. These feedback controllers act on the past states of the controlled system. However, the predictive control considers both the past situation and the changing of the system in a finite future time horizon. Predictive control is one of only some advanced control methods used successfully in industrial control applications.

Adaptive control, fuzzy logic control, and artificial neural network control-The adaptive controller can modify performance of the controller in response to changes in the dynamics of the process and in the characteristics of disturbances. Normally the parameters of the conventional controllers such as fixed gain, lead lag and PID, are determined off-line at a nominal operating point to give good performance. However, the controller dynamic response may be unsatisfied when the operating point changes. Adaptive controller can change its parameters to the new operating condition according pre-designed rules, so that adaptive controllers can work well over a large operating range, but it is time consumption for real-time system identification. These controllers cannot be used for fast online control. New methods such as fuzzy logic and artificial neural networks have been used in power system applications. Some new excitation controllers based on artificial neural networks were claimed to be effective for different operating points, but they required complex algorithms and a long time for training neural nets. Fuzzy logic controllers have been used in design power system stabilizers. This type of controllers does not require any kind of computational complexity, but it always needs a right off-line design. In this thesis also tried to investigate methods to control output terminal voltage of generator excitation system using FLC methods.

2.2. Overview of Synchronous Generator

One of the essential components of power system is the three phase ac generator known as synchronous generator or alternator.Synchronous generator have two synchronous rotating fields:one field is produced by the rotor drived at synchronous speed and excited by dc current. The other field is produced in the stator windings by the three phase armature currents. The dc current for the rotor windings is provided excitation currents. In the order units, the exciters are dc generators mounted on the same shaft, providing excitation through slip rings.Today’s system use ac generator using rectifiers known as brushless excitation systems.

2.3. The Function of an Excitation System.

Excitation system means the system which is used for the production of the flux by passing current in the field winding.

The objective of an excitation system depends on the application; -

- For synchronous generator, it is responsible for maintaining a constant terminal voltage.
- For synchronous motor, it is responsible for maintaining a constant power factor. The fundamental function of an excitation system is to provide direct current to the synchronous machine field winding. In addition, the excitation system performs control and protective functions essential to the satisfactory performance of the power system by controlling the field current. Means, that Excitation controls have functions of both adjusting voltage and damping oscillation by controlling the field voltage. The control functions include the control of voltage and reactive power flow and enhancement of power system stability. The protective functions ensure that the capability limits of the synchronous generator, excitation system, and other equipment are not exceeded [21].

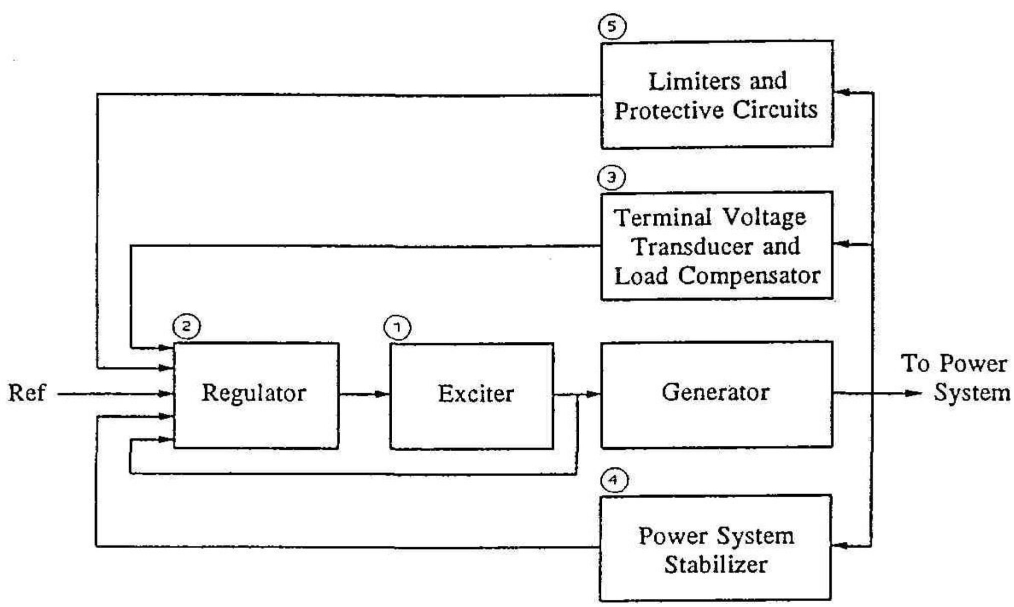

Figure 2. 1The function block diagram of the excitation control system for a large synchronous Generator

The following is a short description of the various subsystems identified in the above figure.

***1.** Exciter:* It is a source of DC power that feeds the field winding of the synchronous generator and is called the field current source, where it controls the amount of magnetic flux and control the voltage.

2. Regulator: it compares the required field current with the existing excitation current and amplifies input control signals to a level and form appropriate for control of the exciter.

3. Load Compensator and Terminal Voltage Transducer: by sensing generator terminal voltage, rectifies and filters it to DC voltage quantity and compares with desired terminal voltage. In additional, load (or line drop or reactive) compensation may be provided if it is desired to hold constant voltage at some point electrically remote from the generator terminal.

4. *Power system stabilizer:* it provides an additional input signal to the regulator to damp power system oscillations of the network in transient time and stabilize the voltage at a given value. Some commonly used input signals are rotor speed deviation, accelerating power, and frequency deviation.

5. *Limiters and protective circuits***:** it ensures that the capability limits of exciter and synchronous generator are not exceeded at some level. Field-current limiter, maximum excitation limiter, terminal voltage limiter, volt-per-Hertz regulator and protection, and under excitation limiter are some of the commonly functions used.

2.4. Types of Excitation System

The excitation system is a variable source of constant current that provides DC current field to the generator. Excitation Systems have taken many forms over the years of their evolution. Based on the power source used, the excitation may be classified into the following three broad categories [21, 24, and 25]: Static excitation system, D.C excitation system and AC excitation system and

2.4.1. Static Excitation System

In this system, the supply is taken from the alternator itself through a 3-phase star/delta connected step-down transformer. The primary of the transformer is connected to the alternator bus and their secondary supplies power to the rectifier and also feed power to the grid control circuit and other electrical equipment This system has a very small response time and provides excellent dynamic performance. This system reduced the operating cost by eliminating the exciter wind-age loss and winding maintenance. This system has a very small response time and provides excellent dynamic performance.

2.4.2. Dc Excitation System

The DC excitation system has two exciters; - a pilot exciter and the main exciter. For controlling the output terminal voltage, the exciter output is adjusted by AVR. When the field breaker is open, the field discharge resistor is connected across the field winding. So as to dissipate the stored energy in the field winding it is highly inductive. The main and the pilot exciters can be driven either by the main shaft or separately driven by the motor. Direct driven exciters are usually preferred as these preserve the unit system of operation, and the excitation is not excited by external disturbances.

2.4.3. AC Excitation system

The AC excitation system consists of an alternator and thyrister rectifier bridge directly connected to the main alternator shaft. The AC excitation system may be classified into two categories; -

a) Rotating thyristor Excitation system. The rotating part is being enclosed by the dashed line. This system consists; - an AC exciter, stationary field and a rotating armature. The output of the exciter is rectified by a full wave thyristor bridge rectifier circuit and is supplied to the main alternator field winding. The alternator field winding is also supplied through another rectifier circuit. The exciter voltage can be built up by using it residual flux. The power supply and rectifier control generate the controlled triggering signal. The alternator voltage signal is averaged and compare directly with the operator voltage adjustment in the auto mode of operation. In the manual mode of operation, the excitation current of the alternator is compared with a separate manual voltage adjustment.

b. Brushless Excitation System. The rotating portion is being enclosed by a dashed line rectangle. The excitation system consists an alternator, rectifier, main exciter and a permanent magnet generator alternator. The main and the pilot exciter are driven by the main shaft. The main exciter has a stationary field and a rotating armature directly connected, through the silicon rectifiers to the field of the main alternators. The pilot exciter is the shaft driven permanent magnet generator having rotating permanent magnets attached to the shaft and a three phase stationary armature, which feeds the main exciter field through silicon rectifiers, in the field of the main alternator. The pilot exciter is a shaft driven permanent magnetic generator having rotating permanent magnets attached to the shaft and a 3-phase stationary armature, which feeds the main's exciter through 3-phase full wave phase controlled thyristor bridges. The system eliminates the use of a commutator, collector and brushes have a short time constant and a response time of fewer than 0. 1seconds.The short time constant has the advantage in improved small signal dynamic performance and facilitates the application of supplementary power system stabilizing signals

2.5 Excitation System Methods

Well-designed excitation system provides reliability of operation, stability and fast transient response. Since it provides field current to rotor winding of the generator. The four common excitation methods include; -

a) shunt or self-excited
b) excitation boost system(EBS)
c) Permanent magnet generator(PMG)
d) Auxiliary winding(AUX)

Each method has its own merits. All methods use an AVR to supply DC output to the exciter stator. But, their construction style of the AVR is differ with each other. The exciter rotor AC output is rectified to a DC input for the main generator rotor. The more advanced systems use an additional input to the AVR. AVRs with the capability of receiving a second input to reduce or eliminate internal harmonics caused by load feedback signals are used for non-linear load applications. The two types commonly advanced systems used are:

Silicon controlled rectifier (SCR)-It senses power level from the stator and determines its firing for the exciter voltage. It can cause trouble when used with non-linear loads.

Field Effective Transistor (FET)-It senses power level from the stator and converts in to a pulse width modulation (PWM) signal to the exciter. In this case, style of AVR can be used for excitation methods. Nonlinear loads don't cause feedback resulting excitation breakdowns.

A) Shunt or Self-Excited.

The self-excited method is a simple features and effective design cost to provide input power to the AVR. This method requires no additional components or wiring. When problems arise troubleshooting is simplified with less components and wiring to validate. As the generator is rotated, the stator supplies input voltage to the AVR. In addition, the AVR has sensors that monitor the output of the stator. The AVR supplies power to the exciter and is rectified to DC current. The current is induced onto the stator for load output. The biggest drawback to this system is the AVR is impacted by the load the generator is powering. When the load increases the voltage begins to decrease and the AVR must provide more current to the exciter to support the demand. This pushes the AVR to its limits. If the AVR is pushed beyond its limits the excitation field collapses. The output voltage is reduced to a small amount. If a short circuit occurs in the supply to the AVR, the generator will not have an excitation source. This causes a loss of generator power output. Generators with shunt or self-excited methods can be used on linear loads (constant load). Applications that have non-linear loads (varying load) are not advised to use for generators with this excitation method. Harmonics associated with non-linear loads can cause excitation field breakdowns.

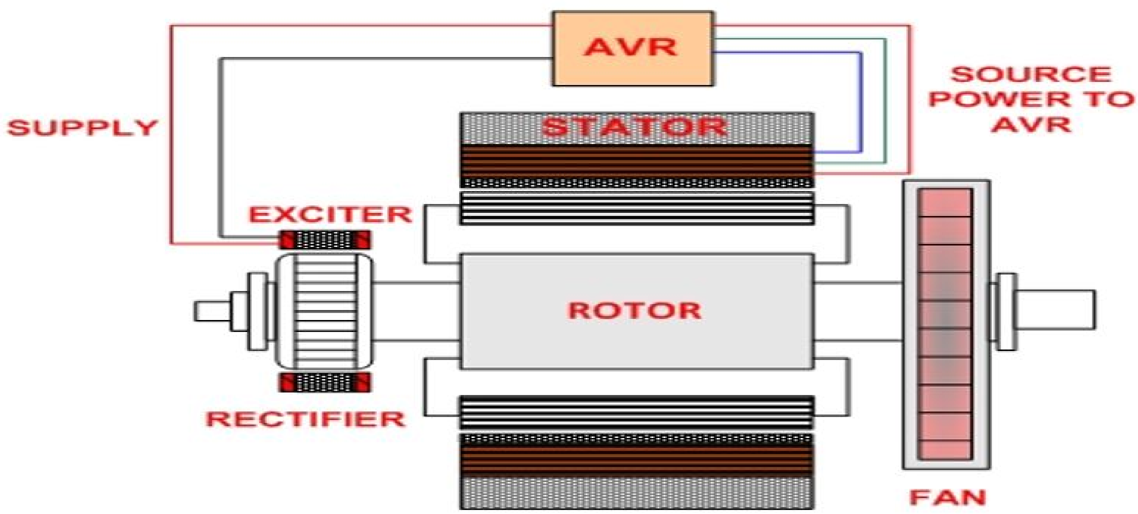

Figure 2. 2 Shunt or self-excited [29]

b) Excitation Boost System (EBS)

The EBS system is comprised of the same basic components supplying inputs to and receiving outputs from the AVR. The additional components in this system are:

- Excitation Boost Control (EBC) Module
- Excitation Boost Generator (EBG).

The EBG is mounted on the driven end of the alternator. Physical appearance is the same as a permanent magnet. The EBG supplies power to the controller as the generator shaft rotates.

The EBC control module is connected in parallel to the AVR and the exciter. The EBC receives signal from the AVR. When needed the controller supplies varying levels of excitation current to the exciter at levels that depend on the needs of the system. The additional power feed to the excitation system supports load requirements. This allows the generator to start and recover the excitation voltage. This excitation system is not recommended for continuous power applications. It is intended for emergency or back-up power applications. When the generator starts the EBS system is disengaged until operating speed is reached. The EBG is still generating power but the controller does not route it. System allows for dynamic response, is less expensive and meets requirements for providing 300% short circuit current. Non-linear loads such as motor starting, are improved when compared to the Shunt or Self Excited method. The EBC control module is connected in parallel to the AVR and the exciter. It receives signal from the AVR. The additional power feed to the excitation system supports load requirements. This allows the generator to start and recover the excitation voltage. This excitation system is not recommended for continuous power applications.

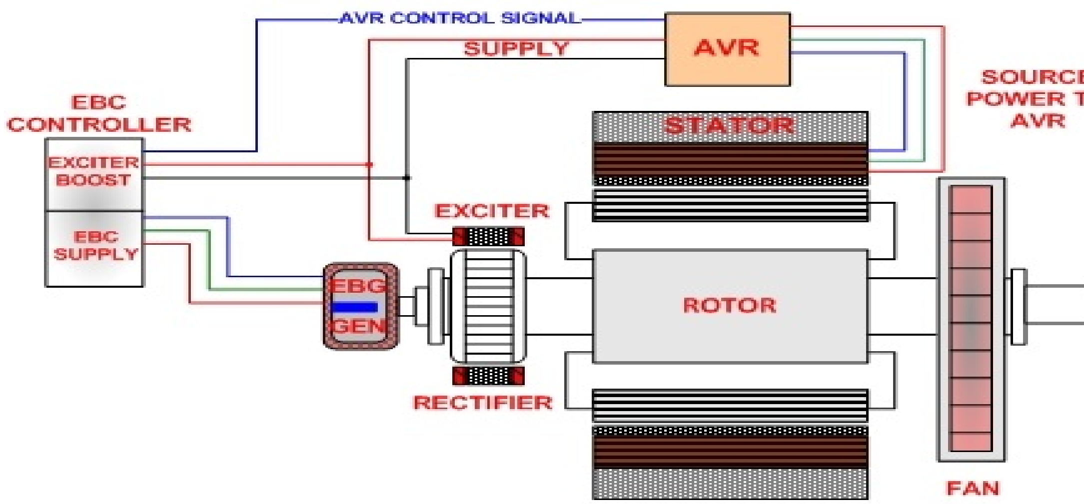

Figure 2. 3 Excitation Boost System (EBS) [29]

c) Permanent Magnetic (PM) Generator

Generators equipped with permanent magnets are among the most well-known separately excited methods. A PM is mounted on the driven end of the generator shaft. PMG supplies isolated power to the AVR when the generator shaft rotates. The AVR uses the extra power when supplying non-linear loads. Some of the benefits of using generators equipped with the PMG excitation method are:

-Excitation field does not collapse allowing for sustained short circuit faults to clear.

- Changing load does not impact on excitation field.

-Voltage is created on initial startup and does not depend on remaining magnetism in the field.

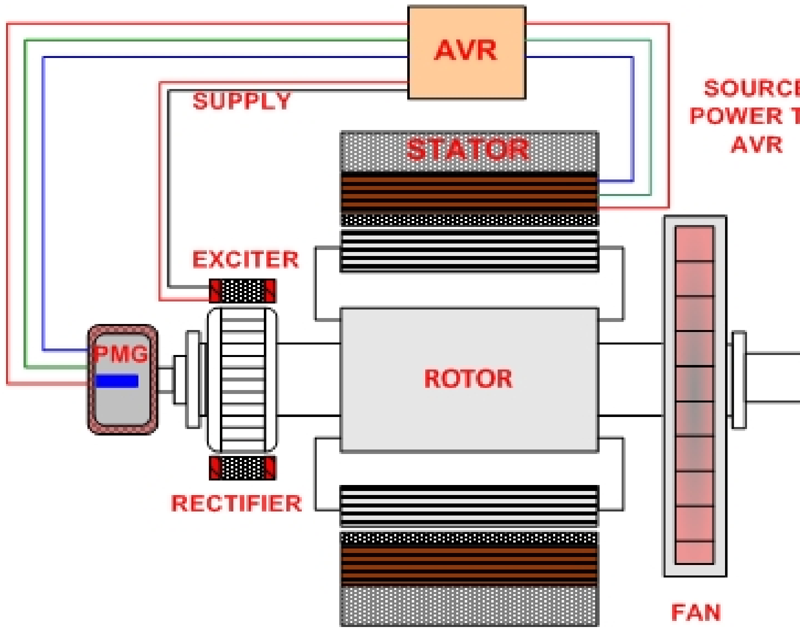

Figure 2. 4 Permanent Magnetic Generator [29]

d) Auxiliary winding (AUX)

The auxiliary winding method has been in use for years. It uses range from marine to industrial applications and is more practical in larger installations. It has a separate excitation field; however, it does not use a component attached to the driven end of the shaft of the generator. These methods use shaft rotation and a permanent magnet or generator to supply the additional excitation. An additional single phase winding is installed into the stator. As the generator shaft rotates the stator main windings supply voltage to the AVR as all methods. The additional single phase windings supply voltage to the AVR. Shunt excitation is the most cost effective method. For non-linear load applications, EBS, PMG and AUX excitation methods can be used. However, PMG excitation is the most common and widely used.

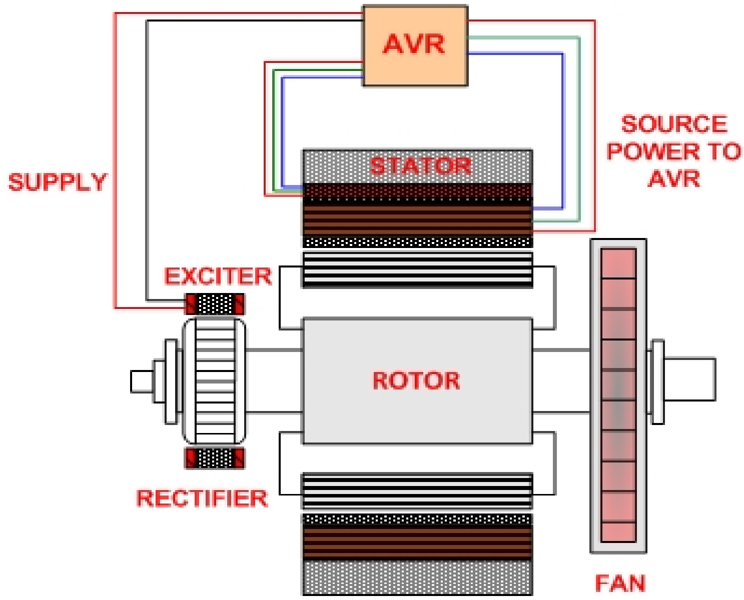

Figure 2.5 Auxiliary winding (AUX) [29]

2.6. Power system considerations

From viewpoint of the power system, the excitation system should contribute to effective control of system voltage and improvement of system stability. It should be capable of responding rapidly to a disturbance so as to increase transient stability. Historically, the role of excitation system in enhancing power system performance has been growing continually. Early excitation systems were controlled manually to maintain desired generator terminal voltage and reactive power loading. When the voltage control was first automated, it was very slow. Greater interest in the design of excitation system developed, and exciter and voltage regulators with faster response were soon introduced to the industry. Modern excitation systems are capable of providing practically instantaneous response with high voltage. Excitation systems must satisfy the following requirements to satisfy above roles;

1. Provide, limiting and protective functions as required to prevent damage to itself, the generator, and other equipment.
2. To meet specified response criteria
3. To meet specified requirements for operating flexibility.
4. To meet the desired reliability and stability by incorporating the necessary level of redundancy and internal fault reduction and isolation capability.

2.7. Power System Stability

The ability of power system to move from one steady-state operating point to another steady-state operating point, with the generators synchronism that having acceptable voltage magnitude and frequency deviation is known as Power system [5].

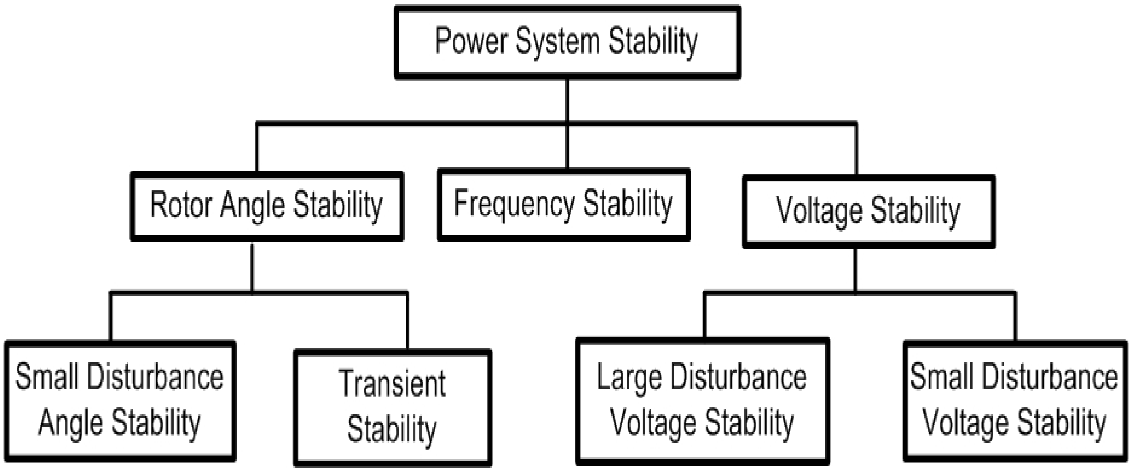

Figure 2. 6 Power system stability classification

Depending on the time scale the voltage instabilities are classified as short-term, a couple of seconds, or long-term, tens of seconds to minutes. The short term voltage instability involves dynamic of fast acting components such as induction motors, electronically controlled loads, and HVDC converters, while the long-term voltage instability involves slower acting equipment such as tap-changing transformers, thermostatically controlled loads, and generator current limiters. To a good modeling on stability studies of the generator, excitation system, and speed governor is therefore very important. The modeling of equipment that does not generally operate under normal conditions, such as over-and under excitation limiters, can also be important. Governor modeling must consider whether the machine is operated in an isochronous or droop control mode.

2.7.1. Rotor Angular or Synchronous Stability

The total active electrical power fed into the power system by the generators is always equal to the active power consumed by the loads including the losses in the system. On the other hand, there is not always a similar balance between the loads and the power fed into the generators by the prime movers, for example the hydro and steam turbines. If such an imbalance develops the rotating parts of the generators, and other rotating machines, will act as energy buffer(against), and the kinetic energy stored in these will decrease or increase as a result of the imbalance. Rotor angle stability refers to the ability of synchronous machines of a power system to remain in synchronism after a disturbance. If the disturbance is local and substantial, for example an earth fault close to a generator, the generator can fall out of step since it has been accelerated during the fault. As quite big current currents will flow in the generator windings in such a case it must be disconnected to avoid that it is damaged. Typical time scale for such instability to develop is a second to a couple of seconds. This kind of instability is called transient instability and instability is usually in form of aperiodic angular separation due to lack of synchronizing torque. This form of instability is also referred to as large-disturbance rotor angle instability. Small-disturbance (or small-signal) rotor angle stability is concerned with the ability of the power system to maintain synchronism under small disturbances. These disturbances are considered to be sufficiently small that linearization of the system equations is permissible for purposes of analysis. Usually small-disturbance rotor angle stability is associated with insufficient damping of oscillations [7].

2.7.2. Frequency stability

In the cases of the proceeding cases the sum of active power infeed was enough but there was an imbalance locally. But if the total power fed into the system by the prime movers is less than what is consumed by the loads, including losses, this imbalance will influence the frequency of the whole system. As explained above the kinetic energy stored in rotating parts of the synchronous machines and other rotating electrical machines will compensate for the imbalance resulting in a frequency deviation. If the imbalance is not too large the generators participating in the frequency control will regulate the active power input from their prime movers and bring back the frequency deviation to acceptable values. If the imbalance is too large, the frequency deviation will be significant with possible serious consequences. Particularly thermal power plants are sensitive to large frequency drops of long durations, since detrimental oscillations could be excited in the turbines. AS a last resort the generators are disconnected, making the situation even more serious. This type of instability is called frequency instability and the time scale could be from a few seconds up to several minutes. Since the involved mechanisms could be quite different, one often distinguish between short-term and long term frequency instability. In the latter, the control and protections characteristics of turbines, boilers and reactors play important roles.

2.7.3. Voltage Stability and Load Instability

When it comes to reactive power balance the situation is not as clear and simple as concerning active power. There is always a balance between "produced" and "consumed" reactive power in every node of a network. This is in fact a direct consequence of Kirchhoff's first current law. When one talks about imbalance in this context we mean that the injected reactive power is such, normally too small, that the voltage in the node cannot be kept to acceptable values. Reactive power is a more local quantity than active power since it cannot be transported as easily in power system where normally Impedance bigger than resistance. This explains why voltage problems often are local, and often only occur in part of the system. When the imbalances (voltage problems) develop into instabilities these are called voltage instabilities or voltage collapses. The synchronous machines are very important in angular instabilities, and it is sometimes said that these are the driving force in this instability. A more detailed analysis shows that the loads are very often the driving force when it comes to voltage instability, which consequently sometimes is called load instability [7].

2.8. Reactive Power and Voltage Control

As explained earlier, a change in reactive power affective mainly the magnitude of the terminal voltage. The excitation system maintains generator voltage and control reactive power flow. The source of reactive power is generators, capacitors and reactors. The primary means of generator reactive power control is generator excitation control using AVR. The role of automatic voltage regulator (AVR) is to hold the terminal voltage magnitude of synchronous generator at a specified level [25]. An increase in the reactive power load of the generator leads to a drop in the magnitude of the terminal voltage. This drop in the magnitude of the terminal voltage is sensed through a potential transformer (PT**),** this voltage is rectified and compared to a dc set point signal. The compared voltage amplified (error signal) is then amplifier and sent to the exciter which controls the exciter field, and increases the exciter terminal voltage, which results in the increase of the generated e.m.f. The reactive power generation is increasing to anew equilibrium, raising the terminal voltage to the desired value.

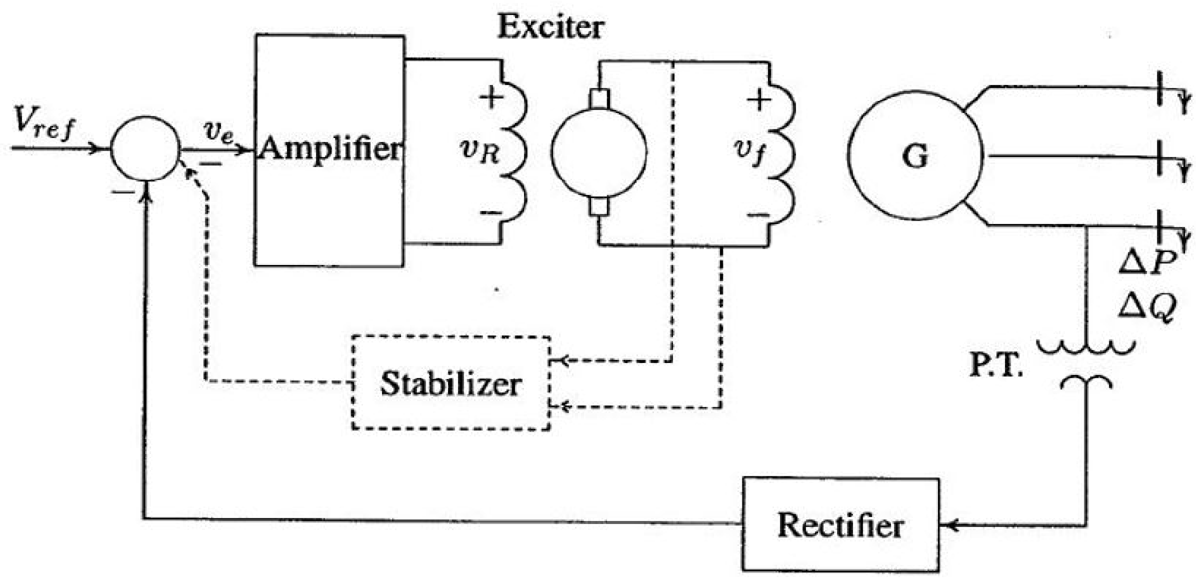

Figure 2. 7 Schematic diagram of AVR system [1]

Where: P is active power energy, Q is reactive power energy and Δ is represent changes.

2.8.1. Automatic Voltage Regulator (AVR)

During power generation process, common problems such as dissimilarity of load, limit deviation in transmission system, and turbine oscillation may produce oscillatory output in synchronous generator. This category of electro-mechanical fluctuation affects the firmness of power system. Hence, in modern power generating stations, in order to improve the dynamic stability and to assure the power quality, most of the synchronous generators are outfitted with an excitation unit, which is supervised by an AVR and a Power System Stabilizer (PSS). The automatic voltage regulator controls generator excitation to maintain the reactive power by hold the terminal voltage magnitude of a synchronous generator at a specified level. When the generator field current is increased, which results in an increase in the generated e.m.f. Then the reactive power generation is increased to a new equilibrium, raising the terminal voltage to the desired value [27].

Figure 2.7 illustrates the block diagram of the AVR system. At the time of closed loop operation, the controller is responsible to maintain stability, robustness and also to support smooth tracking performance based on the set value of terminal voltage. Due to its significant system, AVR is widely considered by most of the researchers. Heuristic algorithm-based approaches are already applied on the AVR system in the literature [9]. Most of the researchers proposed the PID controller design for the AVR system and the performance of the controller is validated for reference tracking response. AVR system is very small and designing a suitable controller requires the following assumptions:

(a) The system is linear.

(b) External disturbance acting on the system is negligible.

(c) The sensor part is free from the measurement noise. In the proposed work, traditional PID controller is considered to regulate AVR system and the controller design process in done using heuristic algorithms.

2.9. PID Controller

Most common controllers available commercially are the proportional integral (PI) and proportional integral derivative (PID) controller. The PI controllers are used to improve the dynamic response as well as to reduce or eliminate the steady state error. PID is made up of three main components proportional, integral and derivative. [15].

a) The proportional term; **-**The proportional term (sometimes called gain) makes a change to the output that is proportional to the current error value.

b) Integral Term; -The contribution from the integral term (sometimes called reset) is proportional to both the magnitude of the error and the duration of the error. Summing the instantaneous error over time (integrating the error) gives the accumulated offset that should have been previously corrected.

c) Derivative Term; **-**The rate of change of the process error is computed by determining the error's slope over time (means its first order derivative with respect to time) and multiplying this rate of change by the derivative gain**.** The proportional part of the PID controller reduces error responses to disturbances. The integral term of the error eliminates the steady state error and the derivative term of the error dampens the dynamic response and thereby improves the stability of the system. [10]

2.10. Fuzzy Logic Controller (FLC)

Fuzzy logic is an artificial intelligence branch that deals with reasoning algorithms that are used to emulate human mind and make computer choices. Fuzzy Logic was introduced in 1965 by Lotfi A. Zadeh, professor for computer science at the University of California in Berkeley. Initially, Fuzzy Logic (FL) is a multivalued logic that makes intermediate values to be defined between conventional evaluations like false/true, no/yes, low/high, big/small etc. word like rather tall or very fast can be formulated mathematically and processed by computers, to apply a more human-similar way of thinking in the programming of computers [27]. The fuzzy logic use has received a lot of attention in today's world because of its merits in reducing the complex models for the problem solution; it employs linguistic terms that deal with the causal relationship between input and output constraints [3]. The development of technology has computerized our life and strengthened the problem of man machine interaction. The fuzzy theory has felt the between 1 and 0, and the degree of any one element is 1or 0. Fuzzy sets will be clearly focused on 0 and 1 of flat boundaries, making it more close to people's thinking expression. The fuzzy rule is defined on the fuzzy set of rules, often using the "If-then" Then... In the form of an expert's experience, knowledge, etc. A fuzzy system consisting of a set of fuzzy shares represents an input and output mapping relationship. In this way, the fuzzy system can approximate any connection function. A power system is highly nonlinear system. For tuning of fuzzy logic stabilizing controller there is no need for exact knowledge of power system mathematical model. The fuzzy controller parameters settings are independent due to nonlinear changes in generator and transmission lines operating conditions. The following advantage of fuzzy controllers:

1. It is simple to know how fuzzy controllers work and how to design and apply it to a concrete application.
2. They are familiar, since it is easier to understand and modify their rules, which not only use a human operator's strategy but also are expressed in natural linguistic terms.
3. Developing a fuzzy controller is cheaper than developing a model based or other controller to do the same thing.
4.Fuzzy controllers are more robust than PID controllers (conventional controllers) because they can cover a much wider range of operating conditions than PID can, and can operate with noise and disturbances of different natures.
5. Fuzzy controllers are more appropriate to control nonlinear processes. Fuzzy control provides a method to construct controller algorithms in a user-friendly way and provides the ability to capture the nonlinear control behavior of humans which has proven to be appropriate for many complex tasks. Having a design method for controllers which is closer to human thinking and perception can reduce development time and requires less skilled personnel to design controllers.

Currently the main areas in which fuzzy control can be applied, are the following:

1. Processes which can be adequately controlled by humans and the controller to be designed has sensors to provide similar information used by humans to control the process. Examples are the application of fuzzy logic in automatic transmission for cars, washing machines, etc. Nowadays, there are many applications of fuzzy logic in consumer products.

2. Processes which are currently controlled by linear control algorithms and need further development resulting in nonlinear control algorithms which are known by operators or process engineers. Mamdani states that: "Fuzzy logic is successful because it replaces the classical PID controller. When tuned, the parameters of a PID controller affect the shape of the entire control surface. Because of fuzzy logic control is a rule-based controller, the shape of the control surface can be individually manipulated for the different regions of the state space, thus limiting possible effects to neighboring regions only." [8]. As a starting point for a fuzzy controller, the linear controller that is currently used to control the process in question can be used, because, under certain conditions, a fuzzy controller can be designed to "emulate" a linear controller. A more or less critical point of view on fuzzy control is given by Elkan, who states that fuzzy controllers are characterized by the following properties:

1. Fuzzy controllers use typically fewer than 100 rules.
2. Often even fewer than 20 rules.
3. The knowledge within a fuzzy controller is usually shallow, both statically and dynamically.
4. The knowledge within a fuzzy controller typically reflects correlations between controller inputs and outputs.
5. The numerical parameters of a fuzzy controller are tuned in a learning process.
6. Fuzzy controllers use fuzzy logic operators.

Elkan (1994) states that the success of fuzzy control is mainly because of the first four properties and that the use of fuzzy logic is not essential. In our opinion these statements about fuzzy controllers are mostly correct, but it should be expressed that these properties do not have to be interpreted as being negative, since it allows user-friendly development of (nonlinear) controllers. Although the rest of Elkan's provocative article does not show a deep understanding of fuzzy logic and related topics in our opinion, it started a discussion on fuzzy logic and fuzzy control which contributes to further discussion of the strengths and limitations of fuzzy logic [11].Stability issues on fuzzy control based on two reasons;-Firstly, fuzzy controllers can be regarded as nonlinear controllers and for this reason it is difficult to obtain general results on the analysis and design of fuzzy controllers[12].The second reason is clearly expressed by Mamdani:"Industry has never put forward a view that the mathematical stability analysis is a necessary and sufficient requirement for the acceptance of a well-designed control system. Moreover, in any practically useful methodology, a stability analysis step would need to be made a desirable but an optional step; it cannot be a necessary step." And "Stability is still an important issue but a different way has to be found to study it. In the final analysis all one may be able to do is to build prototypes for the purpose of approval certification. Zadeh introduced fuzzy sets, although the underlying idea or ideas close to it had already been recognized earlier by others, mainly by philosophers. A comprehensive overview is given in the introduction of the readings in "Fuzzy Sets for Intelligent Systems", edited by Dubois, Prade and Yager, the input space is sometimes referred to as the universe of discourse, fancy name for a simple concept. Conventional control methods cannot provide desired results because power system dynamic characteristics are complex and variable. Advanced controller can be replaced with conventional controller to get fast and good dynamic response in load frequency problems. Fuzzy Logic Controller (FLC) structure. Fuzzy control is a complex system which is difficult to describe. The computer control technology based on natural language and fuzzy reasoning is not dependent on the traditional mathematical model, but is dependent on the fuzzy rules by the operation experience and the expression of knowledge. The fuzzy controller framework contains 5 important parts, that is, the definition of variable, fuzzy, knowledge base, logical reasoning and anti-mode. Defining variables is state of the program is observed and the action to consider. For example, the input variable is CE,e and the output is u, while the control variable is the next state. Where e, CE, u is collectively referred to as fuzzy variables. Fuzzy: the input values are converted to the numerical value of the domain of the input values. The relative membership degree is obtained according to the appropriate language value. Knowledge base: including two parts, including database and rule base, where the database is to provide the relevant definitions of processing fuzzy data, and the rule base is a group of language control rules to describe the purpose and strategy. Logical reasoning: the fuzzy concept of imitating human judgment, fuzzy logic and fuzzy inference, fuzzy control signal. Anti-mode: the fuzzy transformation from the inference to the explicit control signal as the input value of the system. Fuzzy control depends on the "fuzzy rules", which is a scientific and reasonable way to combine the fuzzy control with the excitation control of generator**.**

2.10.1. Fuzzy logic controller structure

Fuzzy logic controller is designed to minimize fluctuation on system outputs. There are three principal elements to a fuzzy logic controller:

(i) Fuzzification module (Fuzzifier).

(ii) Rule base and Inference engine.

(iii) Defuzzification module (Defuzzifier).

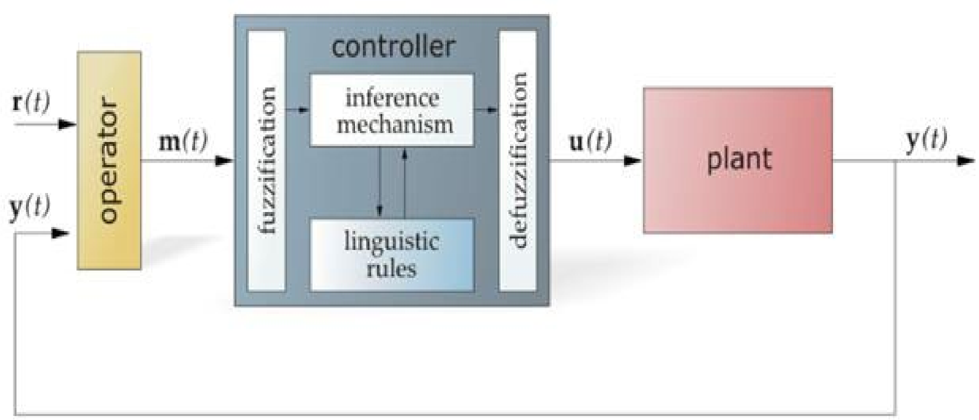

Figure 2. 8 Basic Configuration of FLC

i). Fussification and Membership Functions

The first block inside the controller is fuzzification, which converts each piece of input data to degrees of membership to several membership function. The fuzzification block thus matches the input data with the manner of rulers determine how well the style of each matches the particular input. A membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. There is a degree of membership for each linguistic term that applies to that input variable

[14]. The process of converting a numerical variable (real number) into a linguistic variable (fuzzy number) is called fuzzification. In fuzzy logic, the linguistic variables are used as opposed to numeric variables [14].

ii) Inference Engine

An inference engine (fuzzy inference) is emulates the expert's decision making in interpreting and applying knowledge about how best to control the system. Fuzzy Logic Toolbox software provides a standalone C-code fuzzy inference engine. Fuzzy inference engine can perform the following tasks:

1. It performs fuzzy inference using an FIS structure file and an input data file.
2. Customize the fuzzy inference engine to include your own membership functions.
3. Embed the executable code in other external applications.

iii) Rule Base

Referred to as a knowledge base. It is composed of a database with all of the essential linguistic definitions and a set of control rules. A set of …If-Then… rules, which contains a fuzzy logic quantification of the expert's linguistic description of how to achieve good control. The rules may use many variables both in the condition and the conclusion of the rules. The controllers can therefore be applied to both multi- input-multi-output (MIMO) problems and single-input-single-output (SISO) problems. The typical SISO problem is to regulate a control signal based on an error signal. The controller may actually need both the *error*, the change in error and accumulated error as inputs, but that will call it single-loop control, because in principle all three are formed from the error measurement. To simplify, this section assumes that the control objective is to regulate some process output around a prescribed set point or reference.

iv) Defuzzification

Defuzzification an operation which is the resulting fuzzy set in form of table must be converted to a number that can be sent to the process as a control signal [14].

CHAPTER –THREE

3. METHODOLOGY AND MATERIALS

This work studies the generator excitation control using a conventional controller, PID comparing with FLC to control the synchronous generator excitation system for normal and heavy loading conditions to obtain the input output data of the synchronous generator. The fuzzy logic control FLC and proportional integral derivative PID controller's methods are used with automatic voltage regulator loop (AVR) of the synchronous generator excitation to determine the degree of improvement that could be gained. Finally, the result of this research is approved by MATLAB /2020a Simulink.

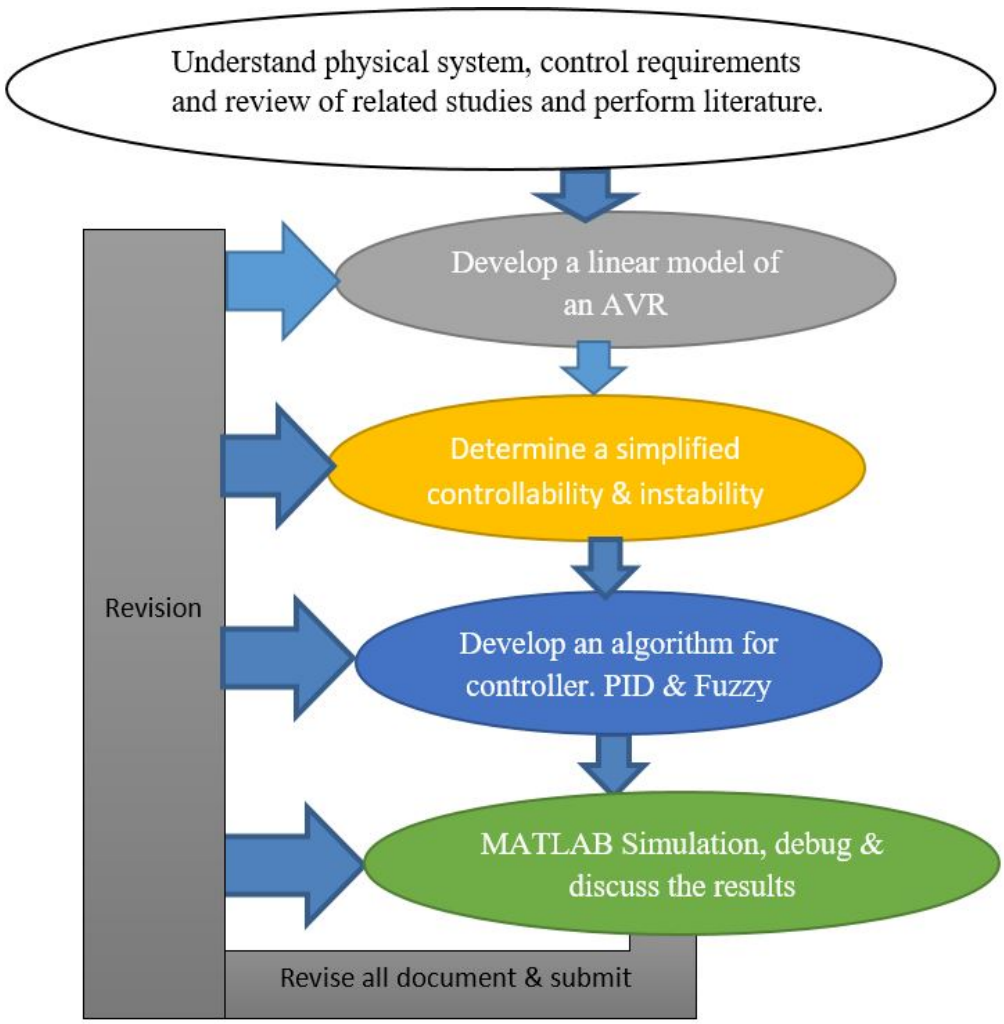

Figure 3. 1 working methods flow chart

Software such as MATLAB/2020a, Microsoft Office 2016, and Math Type 6.0 equation are used in this study. The thesis documentation is edited in Microsoft Office. Math Type 6.0 is a Microsoft Word and PowerPoint presentation tool that allows us to write mathematical formulas and equations.

3.1. Modeling of an Excitation System or AVR Modeling

As mentioned earlier, from figure 2.7 above the AVR model is designed through amplifier model, exciter model, generator model, and sensor model. Assume that for some reason generator terminal voltage |V| has been decreased. This results in an increased error voltage (e) which in turn causes increased values of VR, ie and Vf. The direct axis generator flux increases as a result of increase in i_f thus, raising the magnitude of the terminal voltage to the required level.

3.1.1. Comparator

The comparator compares the measured signal |V| against the reference DC signal (Vref). The difference between these two signals produce an error voltage 've' called error signal. The error signal is;

$$\Delta e = \Delta|Vref| - \Delta|V| \quad \text{......} \quad (3.1)$$

Taking Laplace transform of equation (3.1)

$$\Delta V_{ref}(S) - \Delta V(s) = \Delta e(s)$$

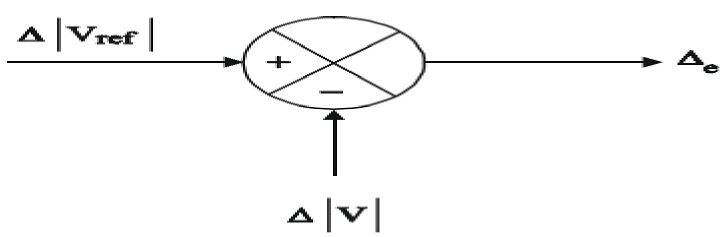

Figure 3. 2 The model of comparator

3.1.2 Amplifier Model

The amplifier amplifies the input error signal depending on the amplification factor. There are various types of amplifiers used in the excitation system. Such as tuned generator, amplidyne and electronic amplifier.

ΔVR ∞ Δe

ΔVR = KAΔe……………………………………………………………..………………3.2

Where, KA = Amplifier gain

ΔVR = Output voltage of an amplifier

Taking Laplace transform of equation (3.2)

ΔVR(s)= KA Δe(s)

Amplifier transfer function

$$\frac{\Delta\ \mathrm{VR(s)}}{\Delta \mathrm{e(s)}} = \mathrm{KA} = \mathrm{GA}$$

where, KA is Instantaneous amplifier gain

GA is Amplifier transfer function

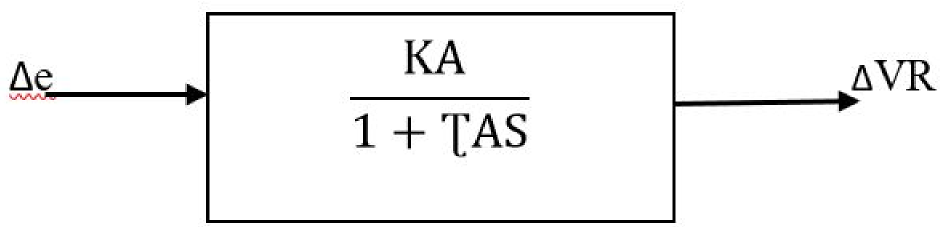

Figure 3. 3 Model of amplifier

When, is VR is amplifier Voltage and Ve is error voltage signal. The typical values of KA are in the range of 10 to 400 and its time constant is in range of 0.02 to 0.1seconds and often is neglected. In this case the values of KA has taken minimum range of 10. Because of it is output signal above the desired value if we take above 10. And also if we take less than 10 the signal is falling under the desired value.

3.1.3. Exciter

There is a variety of different excitation types. However, modern excitation system uses A.C power source through solid-state rectifies such as silicon controlled rectifier (SCR). The output voltage of the exciter is a nonlinear function of the voltage because of the saturation effects in the magnetic circuit. Thus, there is no simple relationship between the terminal voltages and the field voltage of the exciter. Many models with various degrees of sophistication have been developed and are available in the IEEE recommendation publications. A reasonable model of a modern exciter is a linearized model, which takes into account the major time constant and ignores the saturation or other nonlinearities. The linearized exciter model considers the major time constant and ignores the saturation or other nonlinearities [25]:

Let R_e be the exciter field resister and L_e be the exciter field inductance.

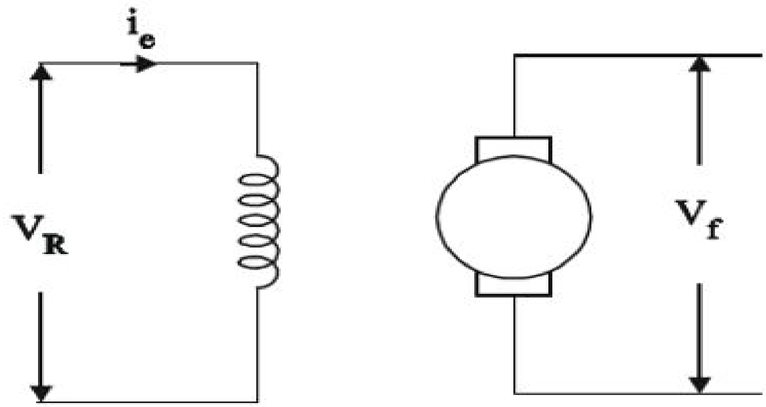

Figure 3. 4 Circuit of an exciter

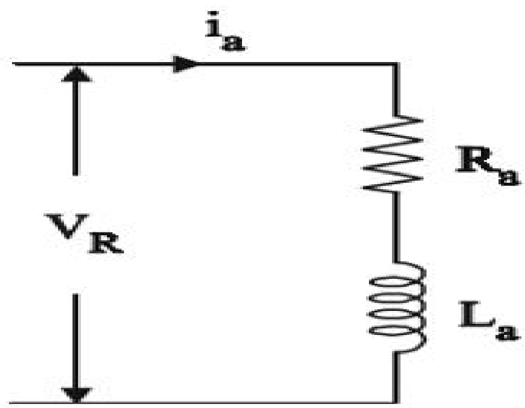

Figure 3. 5 Circuit for field winding of an exciter

From figure 3.5, the input voltage

$$\Delta VR(s)= Re\,\Delta_{ie} + Le + \frac{d}{dt}\,\Delta ie \quad \text{……………………………………………………..3.3}$$

Output voltage of an exciter(or) field voltage of a generator $\Delta v_f \infty\ \Delta_{ie}$

$\Delta v_f = k_1 \Delta_{ie}$……………………………………………………………3.4

Taking Laplace transform of equation (3.2) and (3.4)

$\Delta VR(s) = [R_e + L_{es}]\ \Delta_{ie(S)}$

$\Delta v_f = k_1 \Delta_{ie}$ then,

Transfer function of the exciter, $G_e = \frac{\Delta vf(S)}{\Delta VR(s)} = \frac{K1}{Re + Les} = \frac{K1}{Re\ [1 + Les + \left(\frac{Le}{Re}\right)s]}$

whare ; $G_e = \frac{K1/Re}{1 + Les + \left(\frac{Le}{Re}\right)s} = \frac{Ke}{1 + sTe}$

$Ge = \frac{Ke}{1 + Re} = \frac{KE}{1 + \tau Es}$ and $Te = \frac{Le}{Re}$

When VF is representing exciter voltage, Ke(KE) = gain of the exciter and the time constant Te(τEs) of modern excitation are very small.

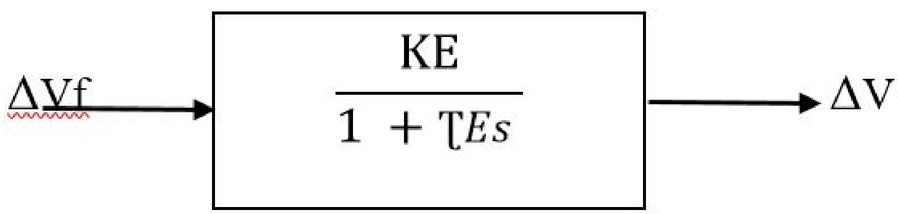

Figure 3. 6 Model of an exciter

3.1.4 Synchronous Generator model

The Synchronous machine generated e.m.f is a function of the machine magnetization curve, and its terminal voltage is dependent on the generator load. It generates three phase AC power at its terminals. It may be derived by steam turbine at a very high speed or by low speed water turbine depending on the energy available at that particular place. The terminal voltage of the generator is maintained constant during its varying load condition, with the help of excitation system. The linearized model transfer function relating the generator terminal voltage to its field voltage can be represented by a gain K_G and a time constant τ_G as follow [25]: The terminal voltage of the generator equals to difference between induced emf (E) and drop across the armature (V_{drop})

$\Delta v = \Delta E - V_{drop}$

at no load the drop can be neglected

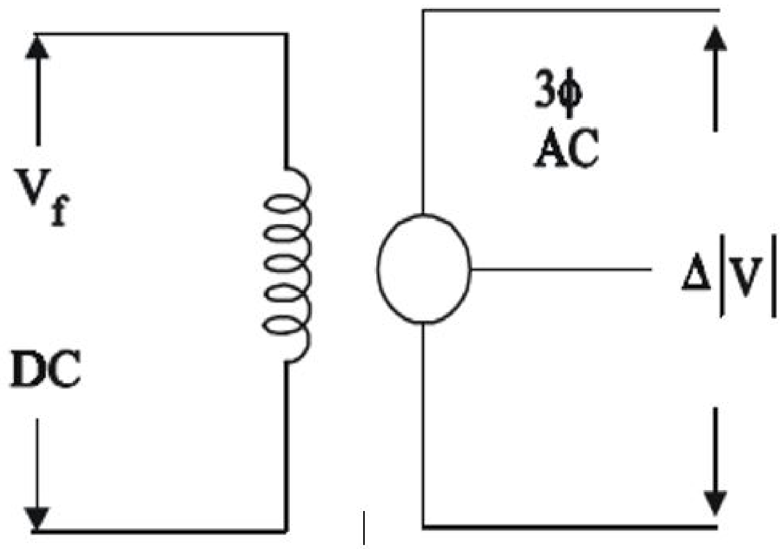

Figure 3. 7 Circuit diagram of a synchronous generator

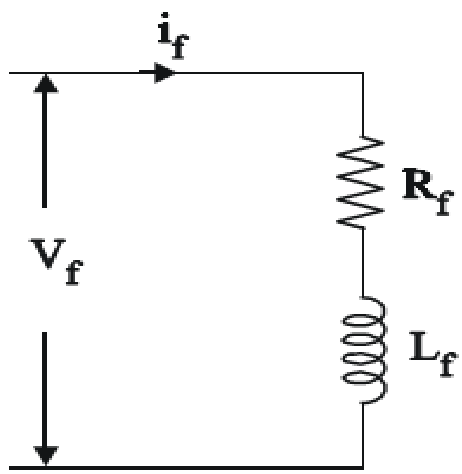

Figure 3. 8 Equivalent circuit for field winding of synchronous generator

$V = E$ (neglected drop)

Taking transform $\Delta V(s) = \Delta E(s)$

Fig 3.14 applying KVL to the field winding

$$\Delta V_f = R_f \Delta i_f + L_f \frac{d}{dt} \Delta i_f \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.5$$

$$E_{max} = I_f X_L = I_f \omega L_{fa}$$

$$E_{rms} = \left(\frac{If}{\sqrt{2}}\right) \omega L_{fa}$$

$$I_f = \frac{\sqrt{2}}{\omega Lfa} E_{rms} = \frac{\sqrt{2}\,E}{\omega Lfa}$$

$$\Delta V_f = \frac{\sqrt{2}\,E}{\omega Lfa} [R_f VE] + Lf\frac{d}{dt} \Delta E$$

Taking Laplace transform

$$\Delta V_f = \frac{\sqrt{2}\,E}{\omega Lfa} [R_f + sL_f] \Delta Vf$$

The transfer function of the generator

$$\frac{\Delta V(s)}{\Delta Vf} = \frac{\Delta E(s)}{\Delta Vf(s)} = \frac{\Delta E(s)}{\frac{\sqrt{2}\,E}{\omega Lfa} [Rf + sLf] \Delta E(s}$$

$$= \frac{\omega Lfa}{\sqrt{2}Rf \left[1 + \frac{Lfs}{Rf}\right]} = \frac{kf}{1+\tau GS} = \frac{KG}{1+\tau GS}$$

$$\frac{Lfs}{Rf} = \tau GS$$

$$k_f = \frac{\omega Lfa}{\sqrt{2}Rf} = KG$$

Where, τ is open circuit direct axis time constant

Lf is self-inductance of field windings and R_f is resistance of field windings

L_{fa} is mutual inductance coefficient between rotor field and stator armature

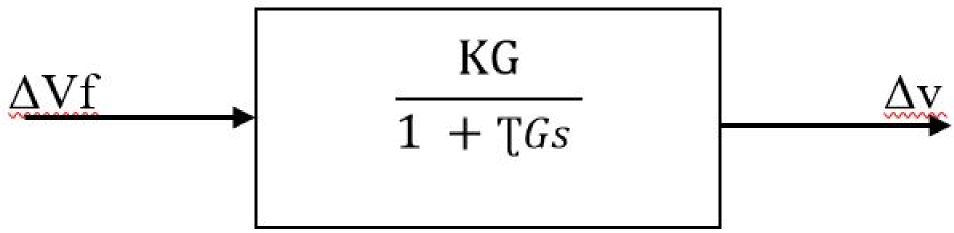

Figure 3. 9 Generator rotor model

Kf values are may varies from 0.7- 1 and Ʈ may vary between 1.0-2.0 seconds from full load to no load.

3.**1.5** Sensor Model

In this model, the potential transformer here senses the terminal voltage k_R of the generator and then rectifies the output at this end through a bridge rectifier. This model has a gain of KR and a time constant ƮR[25]

$$\frac{VS(S)}{Vt(S)} = \frac{KR}{1+ƮRs} \qquad 3.6$$

Where the time constant Ʈ of specified component's and gain K feedback path. $Ʈ_G$ is assumed a range of 0.01 to 0.06 seconds.

Combining all the individual blocks, we get the closed loop model of AVR as shown below

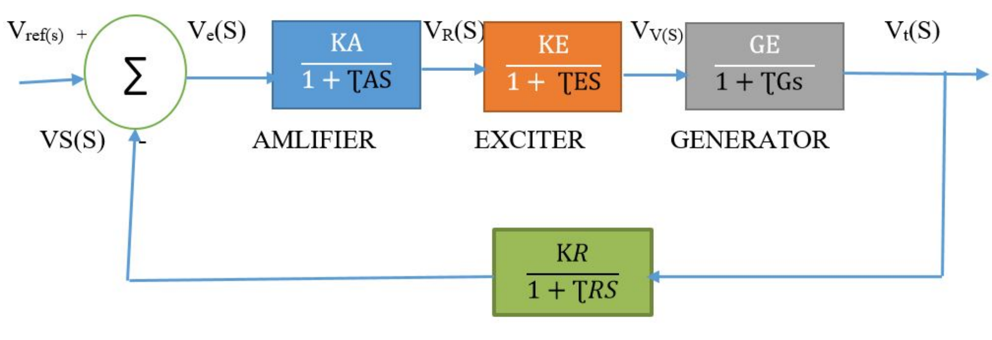

Figure 3. 10 Closed loop block diagram of AVR system [16].

From the above block diagram, the transfer function relating the time constant, the voltage transducer (Sensor) time constant is in the negative DC generator field winding. The first block represents the gain and time constant of an electronic amplifier, the second block is the time constant of the DC generator field winding, and the third block represents the AC generator field time constant.

3.**2** State Space Representation of an AVR

From figure 3.10. Above State space equations can be written; -

$VR= \frac{KA}{1+\tau AS}(Vref - V(S)$

VR $(1+\tau AS)$ = <u>KA</u> $(Vref-VS)$

$VR + \tau A\frac{dV}{Rdt} = KA(Vref-VS)$

$\frac{dVR}{Rdt} = -\frac{1}{\tau A}VR - \frac{KA}{\tau A}VS + \frac{KA}{\tau A}Vref$ ………………………………………………..…..………..….3.7

$VF= \frac{KE}{1+\tau ES}VR$

$(1+\tau ES) = KEVR$

$VF+ \tau E\frac{dV}{Fdt} = KEVR$

$\frac{dVF}{dt} = \frac{KE}{\tau E}VR - \frac{1}{\tau E}VF$………………………………………………………………….…….. .3.8

$Vs= \frac{KR}{1+\tau RS}VT$

$(1+\tau RS) = KRVt$

$Vs+\tau R\frac{dVS}{dt} = KRVt$

$\frac{dVS}{dt} = \frac{1}{\tau R}VS + \frac{1KR}{\tau R}Vt$……………………………………………………...……...…...3.9

$Vt= \frac{KG}{1+\tau GS}VF$

$Vt(1+\tau GS) = KGVF$

$Vt+\tau G\frac{dVt}{dt} = KGVF$

$\frac{dVt}{dt} = \frac{KG}{\tau G}VF - \frac{1}{\tau G}Vt$…………………………………………………………..............3.10

The voltage transducer (Sensor) time constant is in the negative feedback path. From the above block diagram, the transfer function relating the generator terminal voltage V_t (s) to the reference voltage V_{ref}(s) using Mason's gain rule [8] is; The closed loop of transfer function of the block diagram is written as; -

$$\frac{Vt\,(s)}{Vref(s)} = \frac{K_A K_E K_{AG} K_R (1+\tau_R)}{(1+\tau_A S)(1+\tau_E S)(1+\tau_{AG} S)(1+\tau_R S)+K_A K_E K_{AG} K_R} \quad \text{……………………....…………..3.11}$$

The open-loop transfer function of the block diagram is written as

$$K_G(s)H(s) = \frac{K_A K_E K_{AG} K_R}{(1+\tau_A S)(1+\tau_E S)(1+\tau_{AG} S)(1+\tau_R S)} \quad \ldots\ldots 3.12$$

In the system there is another Feedback loop, the loop of the automatic voltage regulator with the components of the generator stirring, excitation and voltage sensing components, namely the voltage transformer and the amplifier, where it is represented in a closed loop with representation of PID controller. Also using Ackermann's formula [25], the state equations of this excitation system in equation 3.12 are; -

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ V_t \end{bmatrix} = \begin{bmatrix} \frac{-1}{\tau_A} & 0 & \frac{-k}{\tau_A} & 0 \\ \frac{1}{\tau_E} & \frac{-1}{\tau_E} & 0 & 0 \\ 0 & 0 & \frac{1}{\tau_R} & \frac{-1}{\tau_R} \\ 0 & -\frac{1}{\tau_G} & 0 & \frac{1}{\tau_G} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ V_t \end{bmatrix} + \begin{bmatrix} \frac{-k}{\tau_A} \\ 0 \\ 0 \\ 0 \end{bmatrix} \text{Vref(s)}$$

$$[V_t] = \begin{bmatrix} 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ V_t \end{bmatrix} \quad \ldots\ldots 3.13$$

With the AVR system of SGE having the following parameters [25]

KE=KG=KR=1, τA=0.1, τE=0.4, τG=1.0 and τR=0.05, ……… ……………...3.14

Table 3. 1 AVR Parameter

Quality	Transfer Function	Gain	Time Constant
Amplifier	KA / (1 + τ AS)	KA = 10	τ AS = 0.1
Exciter	KE / (1 + τ Es)	KE = 1	τ Es = 0.4
Generator	KG / (1 + τ Gs)	KG = 1	τ Gs = 1
Sensor	KR / (1 + τ Rs)	KR = 1	τ Rs = 0.05

Then, the Open-loop transfer function of the AVR system is

$$K_G(s)H(s) = 1 + \frac{K_{A\,(1)(1)1(1)}}{(1+0.1S)(1+0.4S)(1+S)(1+0.05S)}$$

$$= \mathbf{1} + \frac{\mathbf{500K_A}}{\mathbf{(s+10)(s+2.5)(s+1)(S+20)}}$$

$$= 1 + \frac{500K_A}{s^4+33.5s^3+307.5s^2+775s+500} \quad \ldots\ldots 3.15$$

And again, the steady-state response of the system is

$$V_{tss} = \frac{lim}{s \to 0}\ sVt(s) = \frac{K_A}{1+KA} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.16$$

The characteristic polynomial equation becomes

$$s^4 + 33.5s^3 + 307.5^2 + 775 + 500 + 500k = 0 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.17$$

3.3. Test for Instability

For control stability, the range of KA is found using the Routh-Hurwitz array;

S^4 |	1	307.5	500+500KA
S^3 |	33.5	775	0
S^2 |	284.365	500+500KA	0
S^1 |	58.9KA – 716.1	0	0
S^0 |	500+500KA		

From the S^1 row, we see that for control system stability, KA must be less than 12.16. Also from S^0 KA must be greater than -1 thus with positive values of k, for control system stability the amplifier gain must be K>12.16. For K=12.16, the auxiliary equation from the row S^2 is; - $284.365S^2+6580=0$

Or s=±j4.81. that is for K=12.16, we have a pair of conjugated poles on the jϖ axis, and the control system is marginally stable. to obtain the root locus plot we look on appendix A is

From the table for absolute stability, 58.9KA – 716. 1≤ 0 Therefore KA<12.16

The root-locus plot as K varies from 0 to 12.16

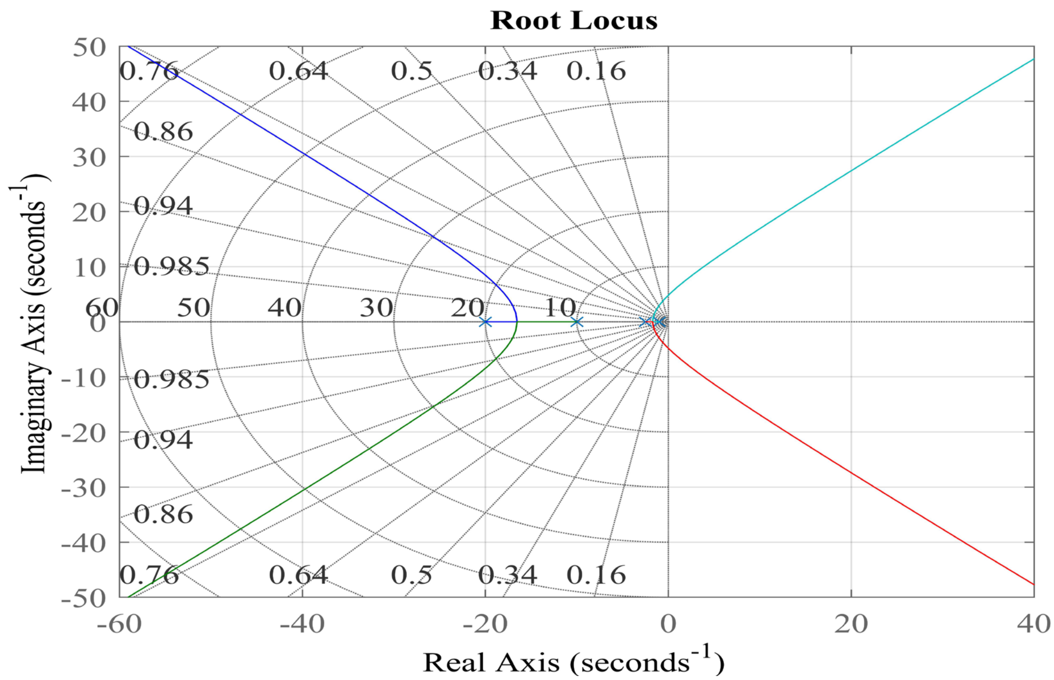

Figure 3. 11 Root locus for controllability checking

In order to minimize steady state error, we have to increase amplifier gain which result is unstable control system.

If the amplifier gain is set at KA=10, the state equation becomes;

$$A = \begin{matrix} -1 & 1 & 0 \\ 0 & -2.5 & 2.5 \\ 0 & 0 & -10 \end{matrix}$$

$$B = \begin{matrix} 0 \\ 0 \\ 0 \end{matrix}$$

3.4 Testing for Controllability

$$PC=[B \quad AB \quad A^2B] = \begin{bmatrix} 0 & 0 & 25 \\ 0 & 25 & -312.5 \\ 0 & 0 & \frac{1}{\tau_R} \\ 100 & -100 & 1000 \end{bmatrix} \qquad 3.18$$

The determinant of Pc = -6250 and ≠ 0. Therefore, the system is controllable.

The steady-state response is $V_{tss} = \frac{10}{1+10} = 0.909$

$V_{ess} = 1.0 - 0.909 = 0.091$

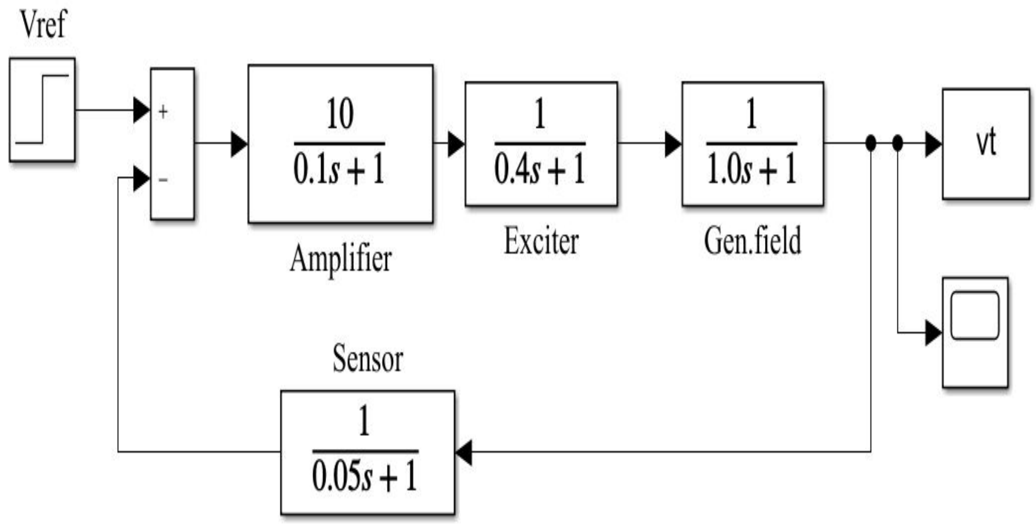

Figure 3. 12 Simulink model for AVR

3.5. AVR Excitation with Stabilizer

The basic function of a power system stabilizer is to add damping to the generator power oscillations by controlling its excitation using an auxiliary stabilizing signal [25]. From the analysis above, the AVR step response was not satisfactory even with a small amplifier gain of KA = 10. It is therefore necessary to increase the relative stability by introducing a controller that can add a zero to the AVR open-loop transfer function. A possible way of doing this is by adding a stabilizer feedback to the control as shown in figure 3.13

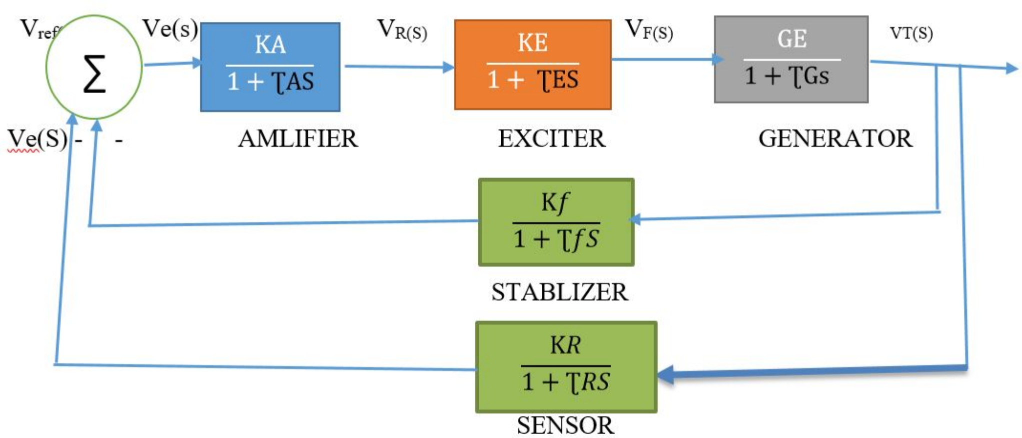

Figure 3. 13 Block diagram of AVR with compensated with a stabilizer

An improved or satisfactory response of the AVR can be obtained by proper adjustment of the stabilizer gain K_F and time constant τ_F or a stabilizer with the derivative gain K_F=2 and time constant τ_F =0.04sec, the closed-loop transfer function becomes.

$$\frac{\text{Vt (s)}}{\text{Vref(s)}} = \frac{250(S^3 + S^2 + 45s + 500)}{S^5 + 58.5S^4 + 13654S^3 + 270962.5S^2 + 274875S + 137500}$$

The steady-state response of the system become

$$V_{tss} = \frac{lim}{s \to 0}\, sVt(s) = \frac{(250)(500)}{137500} = 0.909$$

And the steady-state error becomes, V_{ess}=1-0.909=0.091

By adjusting K_F and τ properly, the terminal voltage step response can be obtained using the MATLAB Simulink.

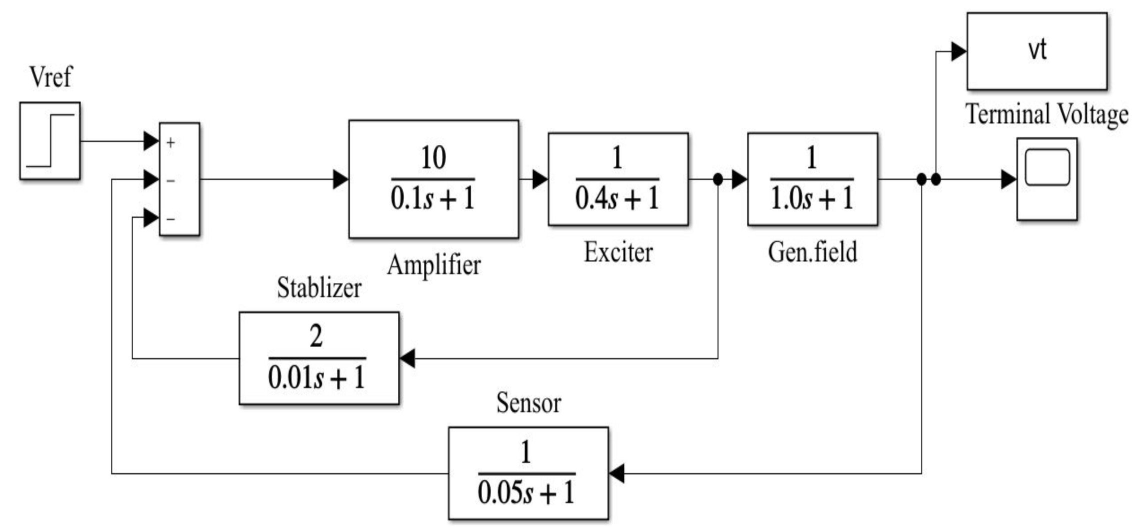

Figure 3. 14 The Simulink model for AVR with stabilizer

3.6. PID Controller with AVR excitation

3.6.1. Proportional term

The proportional response can be adjusted by multiplying the error by a constant K_P, called the proportional gain. The proportional term is given by;

P_{out}=$k_p(t)$……………………………………………………...……..…….3.19

3.6.2. Integral Term

The accumulated error is then multiplied by the integral gain and added to the controller output. The magnitude of the contribution of the integral term to the overall control action is determined by the integral gain Ki. The integral term is given by:

I_{out}=$\frac{1}{T_1}\int_0^t (t)d\tau$ ………………………..……………………………..…3.20

3.6.3. Derivative Term

The magnitude of the contribution of the derivative term (sometimes called rate) to the overall control action is termed the derivative gain Kd. The derivative term is given by:

$D_{term}=Kd\frac{De(t)}{dt}$……………………………………………………………...…….3.21

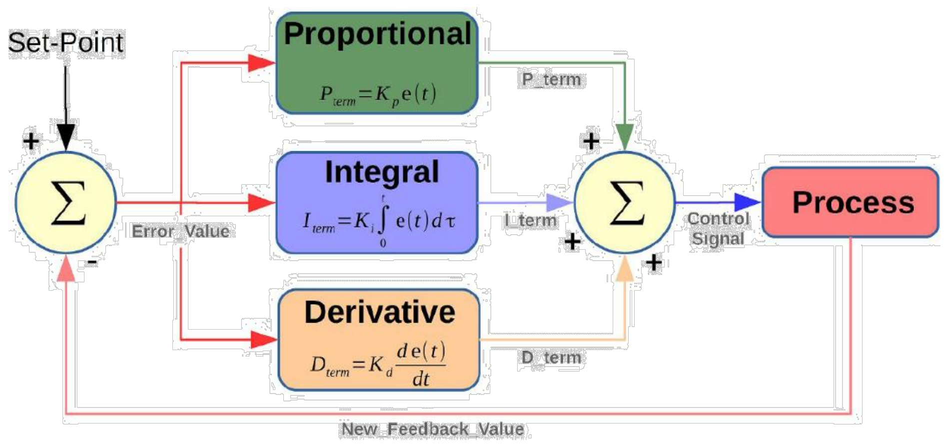

Figure 3. 15 Structural block diagram of PID controller

The ideal version of the PID controller is given by the formula [15]:

$U(t)=K_p\left(e(t)+\frac{1}{T_1}\int_0^t e(t)dt+T_d\frac{de(t)}{dt}\right)$ ……………………………………...…………3.22

Where u(t) is the control signal and e(t) is control error(e=r-y) and the integral time constant and T_d the derivative time constant. The reference value, r is also called the set point. The control signal is thus a sum of three terms: a proportional term that is proportional to the error, an integral term is proportional to the integral of the error, and a derivative term is proportional to the derivative of the error [20]. The controller parameter is proportional gain k_p, integral gain $k_i=k_p/T_i$ and derivative gain $k_d=k_p/T_d$. The controllers can also be parametrized equation 3.22 above. The proportional part acts on the present value of the error, the integral represents an average of past errors and the derivative can be interpreted as a prediction of future errors based on linear extrapolation. Note that the control signal (t) is formed entirely from the error (t), there is no feed forward term. Also, when the implement in mathematical model, will take Laplace transformation to get the transfer function of the controller [16].

$\frac{U(s)}{E(s)}=ki[S^2\ \frac{S^2+\frac{kp}{ki}+\frac{kd}{ki}}{S}]$ ……………………….……………………………………………3.23

which has two zeros plus a pole at the origin. One zero and the pole at the origin can be designed as the ideal integral compensator; the other zero can be designed as the ideal derivative compensator. The design technique consists of the following steps:

step1. Evaluate the performance of the uncompensated system to determine how much improvement in transient response is required.

step 2. Design the PD controller to meet the transient response specifications. The design includes the zero location and the loop gain.

step 3. Simulate the system to be sure all requirements have been met.

step 4. Redesign if the simulation shows that requirements have not been met.

step 5. Design the PI controller to yield the required steady-state error.

step 6. Determine the gains, kp,kd and ki in figure 3.15

step 7. Simulate the system to be sure all requirements have been met.

step 8. Redesign if simulation shows that requirements have not been met.

step 9. The determination methods of gains, kp.kd and ki as known the tuning methods

Tuning methods will use in this research: types of tuning methods; -

1. Automatic tuning in MATLAB simulator tool.
2. Trial and error tuning.
3. In order to reduce the steady-state error and improve the dynamic response, a proportional integral derivative (PID) controller is added.

The transfer function of the PID controller is

$$G_C\,(S)=k_p+\frac{k1}{s}+K_{Ds} \qquad \text{3.24}$$

With the addition of the PID controller, the block diagram of the AVR is then drawn as shown in figure 15

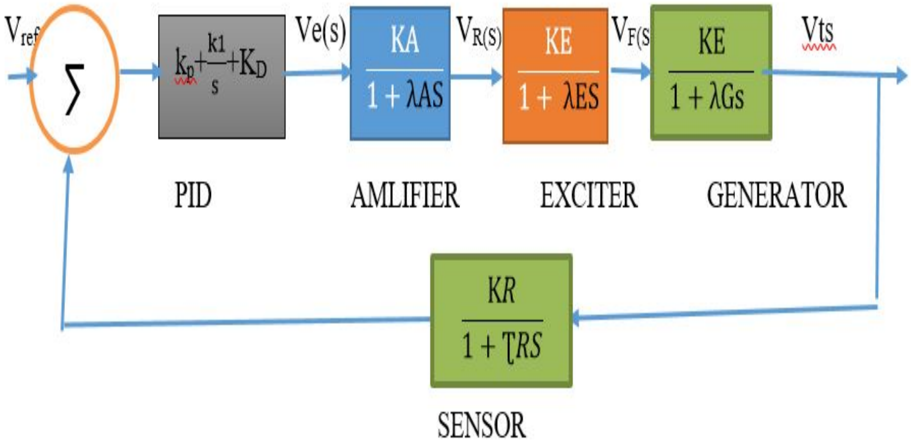

Figure 3. 16 An AVR compensated with PID Controller model

Also applying Mason's gain rule [8], to the block diagram of the figure 3.16, the closed loop transfer function becomes;

$$\frac{\mathrm{Vt\ (s)}}{\mathrm{Vref(s)}} = \frac{(sK_P+K_1+S^2K_D)(K_AK_EK_G)}{S(1+\tau_AS)(1+\tau_ES)(1+\tau_GS)(1+\tau_RS)(sK_P+K_1+S^2K_D)(K_AK_EK_GK_R)} \quad \ldots\ldots 3.25$$

The steady state response is

$$V_{tss} = \lim_{s\to 0} sVt(s) = \frac{(K_1K_AK_EK_G)}{(K_1K_AK_EK_GK_R)} \ldots\ldots 3.26$$

when the parameters of AVR in equation 3.25 with k_p=1.k_1=0.1, k_D=0.063 are substituted in equation 3.7 and 3.8 respectively: -

$$\frac{\mathrm{Vt\ (s)}}{\mathrm{Vref(s)}} = \frac{200(7S^2+25s+625)}{S^5+33.5S^3+307.5S^3+2175S^2+5500s+12500} \ldots\ldots 3.27$$

And the steady- state response becomes

$$V_{tss} = \lim_{s\to 0} sVt(s) = \frac{200(6.25)}{(1250)} = 1$$

The steady state error is 1-$V_{tss=1-1=0}$

The results show that the addition of the PID controller brings the steady-state error to zero. This is common for all integral control. The Simulink model of the block diagram is as Shown in figure 17.

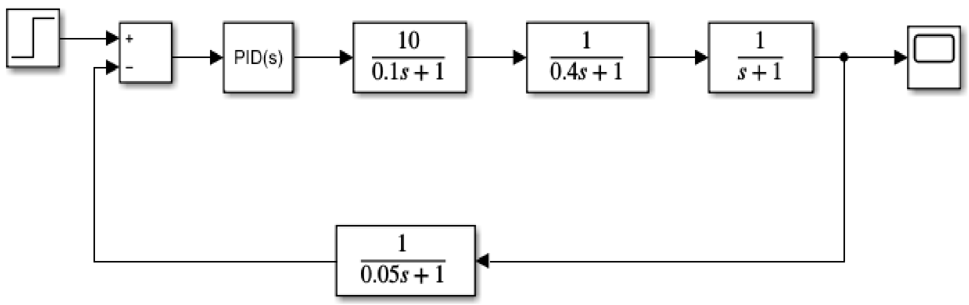

Figure 3. 17 Simulink model for an AVR compensated with PID Controller

3.7. FLC Controller method with AVR excitation

FLC controller was used to control the generator excitation system and improve the dynamic response as well as reduce or eliminate the steady-state error.

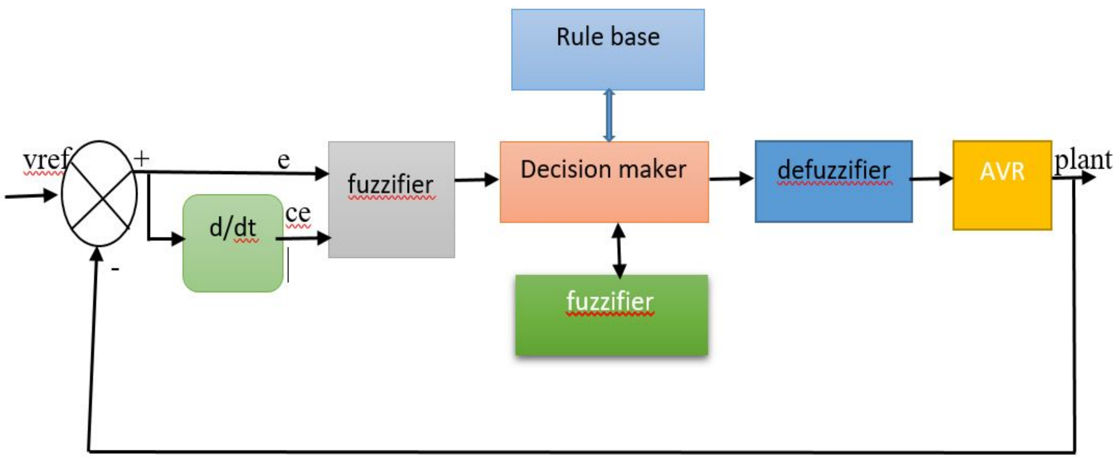

Figure 3. 18 Basic configuration FLC

Where, e is error and ce(Δe) is change of error

3.7.1. Fuzification

The input variables blow is measured based on the expert knowledge or the knowledge of the plant operator and quantified linguistically. The first block inside the controller is fuzzification, which converts each piece of input data to degrees of membership by a lookup or several membership function. The fuzzification block thus matches the input data with the conditions of rulers determine how well the condition of each matches the particular input. In this controller, five fuzzy subsets are selected. Those are; -Negative big (NB), Negative small(NS), Zero(Z), Positive small(PS), and Positive big(PB).

The error e and the change of error Ce are the fuzzy logic controller's inputs, which are defined as:

$$e = v_O - v_{ref} \quad \text{...3.28}$$

$$ce = e_k - v_{k-1} \quad \text{...3.29}$$

Where Vo is the current output voltage, Vref is the reference input voltage, and k denotes the values taken at the starting of voltage.

The Rule Editor is for editing the list of rules that defines the behavior of the system. The 25 rules in the rule table of table 2 are encoded in the fuzzy controller through the Rule Editor.

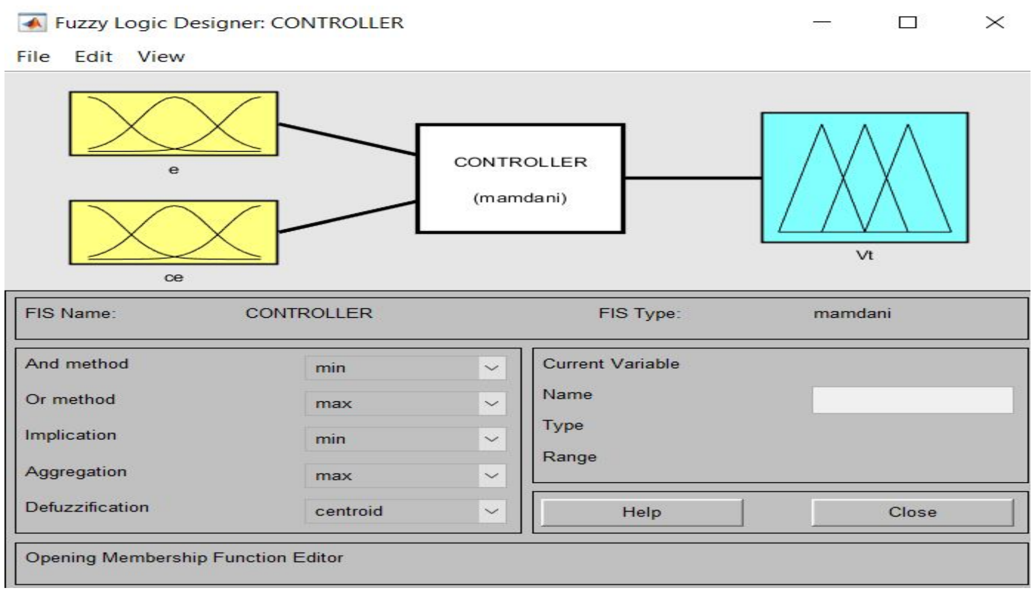

Figure 3. 19 The Editor of Fuzzy Inference System using MAT LAB

As shown in figure 19 the fuzzy logic control excitation system controller is made up of two input variables and one output variable, which are the error(e) and change of error(Ce) as input variables and the change of terminal voltage(Vt) as an output variable. Five partitions have been created for each control variable. These partitions, known as membership functions, are divided into five fuzzily defined subsets: PB (Positive Big), PS (Positive Small), Z (Zero), NS (Negative Small), and NB (Negative Big) are all positive terms (Negative Big). Figure 18 and 19 shows the partitioning of fuzzy subsets and the shape of the membership function, i.e. (error variable) and (change of error variable), and figure 20 shows the shape of the membership function (output variable). The triangular forms of this arrangement's membership function indicate that there is only one dominant fuzzy subset for each given input. Table 2 below lists the rules for the excitation fuzzy controller. The fuzzy rule basis is constructed into 25 rules using the tabulated table

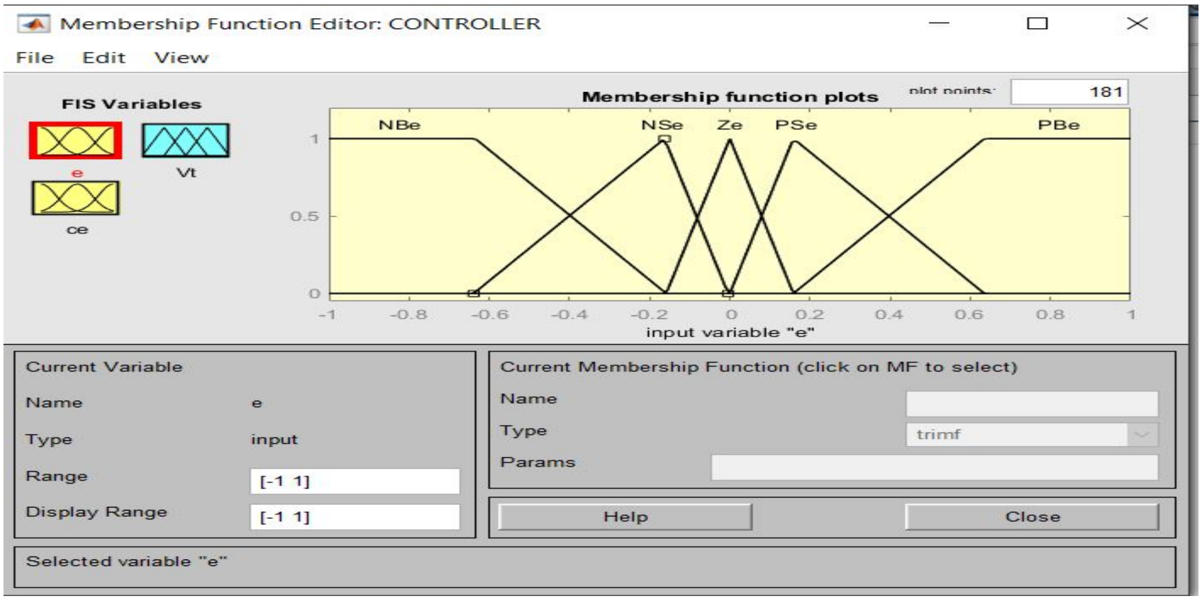

Figure 3. 20 Membership function error

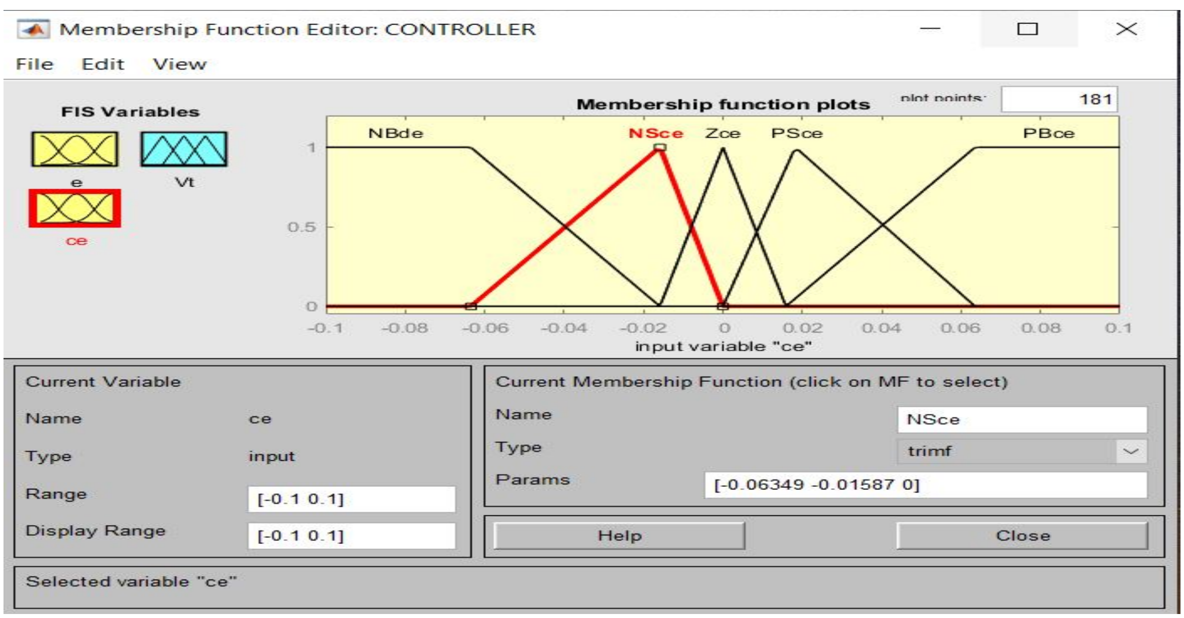

Figure 3. 21 Membership Function of Input Variable ‘change of error

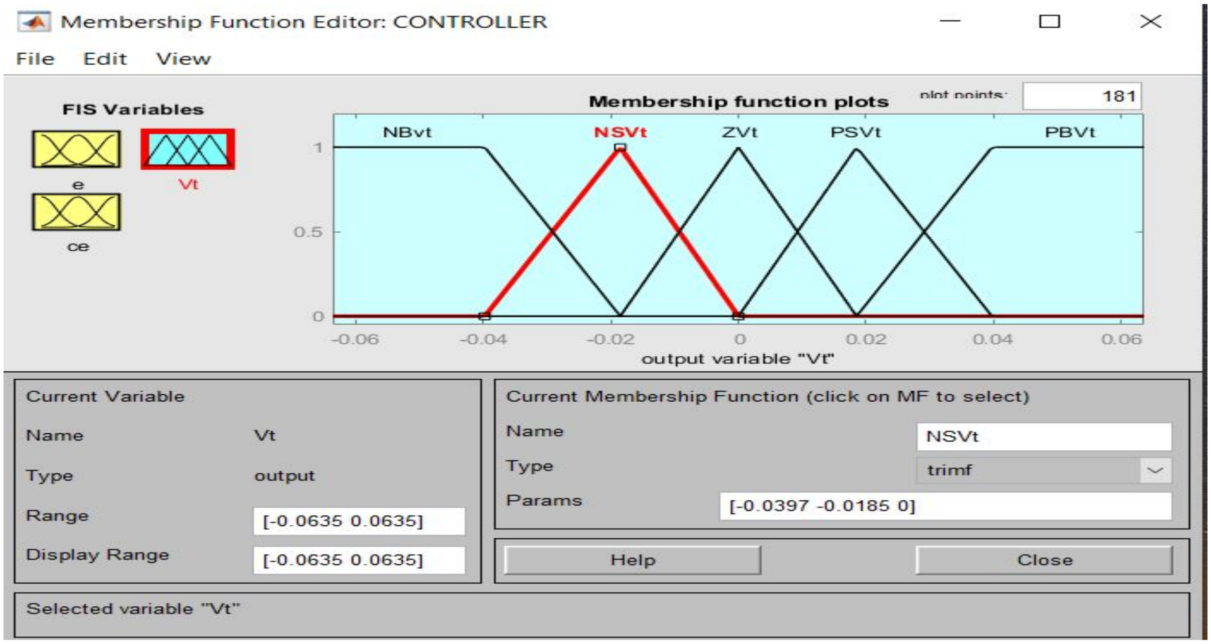

Figure 3. 22 Membership function for output terminal voltage

3.7.1 The Inference Mechanism

There are control laws that govern the operation of the controller in the design of a conventional controller. In the design of fuzzy logic controller, there are linguistic rules that allow the operator to develop a control decision in a more familiar human environment. With the two inputs for this FLC, an (5x5) decision table is constructed as table 3.2. In this table as a sample the first row says that if the *error* is negative big and the *change in error* is negative big then the output should be negative big and so on. The rules reflect the strategy that the control signal should be a combination of the reference error and the change in error.

Table 3. 2 Decision table of 25 rules for fuzzy AVR controller

ERROR \ CHANGE IN ERROR	NB	NS	Z	PS	PB
NB	NB	NB	NS	NS	Z
NS	NB	NS	NS	Z	PS
Z	NS	NS	Z	PS	PS
PS	NS	Z	PS	PS	PS

The inference mechanism evaluates which of the control rules are relevant at the current time and then decides what the input to the plant or the output of the fuzzy should be as [26] puts it, the inference mechanism is a way of determining the applicability of each rule called "matching". Hence, the inference mechanism seeks to determine which rules are on to find out which rules are relevant to the current situation. The inference mechanism will seek to combine the recommendations of all the rules to come up with a single conclusion. There are two types of fuzzy inference systems in the fuzzy MATLAB toolbox: Mamdani-type and Sugeno-type. The most commonly used method for inferring the rule output is the Mamdani method because of its wide acceptance. The processes involved in the Mamdani method includes; Fuzzy Inference System(FIS), Membership Function Editor, Rule Editor, Rule Viewer, Surface Viewer. The FIS handles the high-level issues for the system which includes the number and names of the inputs and outputs. The defuzzification technique is also set at the FIS The membership function editor is used to define the shapes of all the membership functions associated with each variable as shown in figure 3.23.

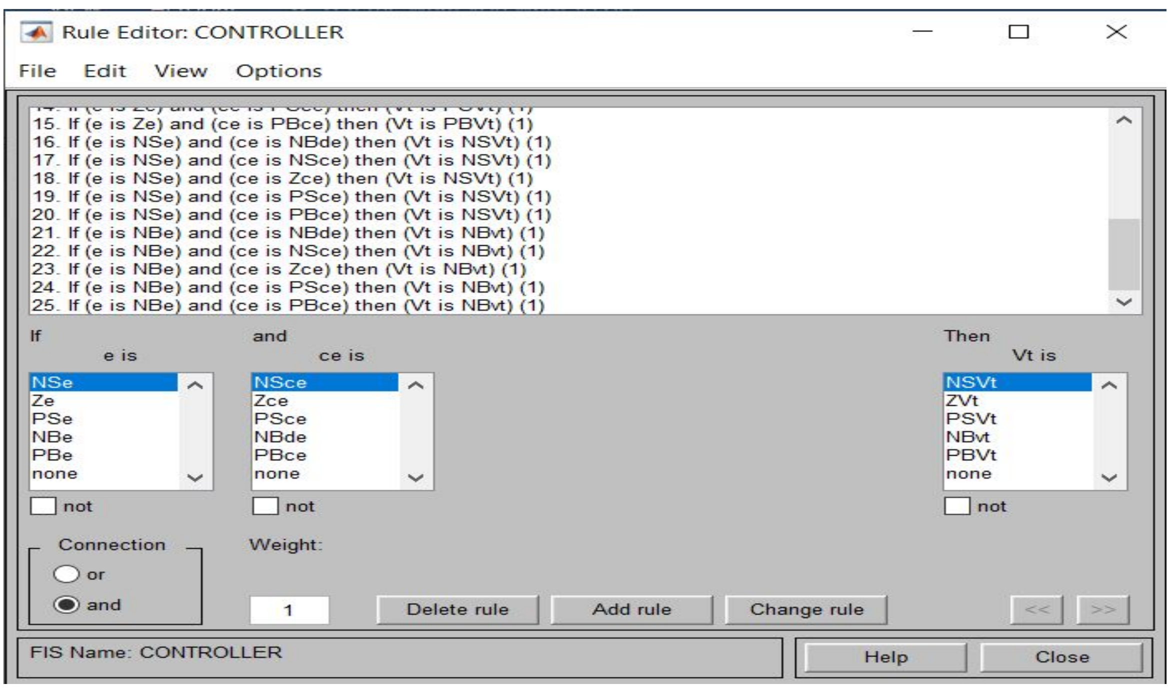

Figure 3. 23 Rule editor

The Rule Viewer and the Surface Viewer are used for looking at, as opposed to editing the FIS. They are strictly read-only tools. The rule viewer is a MATLAB technical computing environment based display of the fuzzy inference diagram as shown in figure 3.24. They are used as a diagnostic.

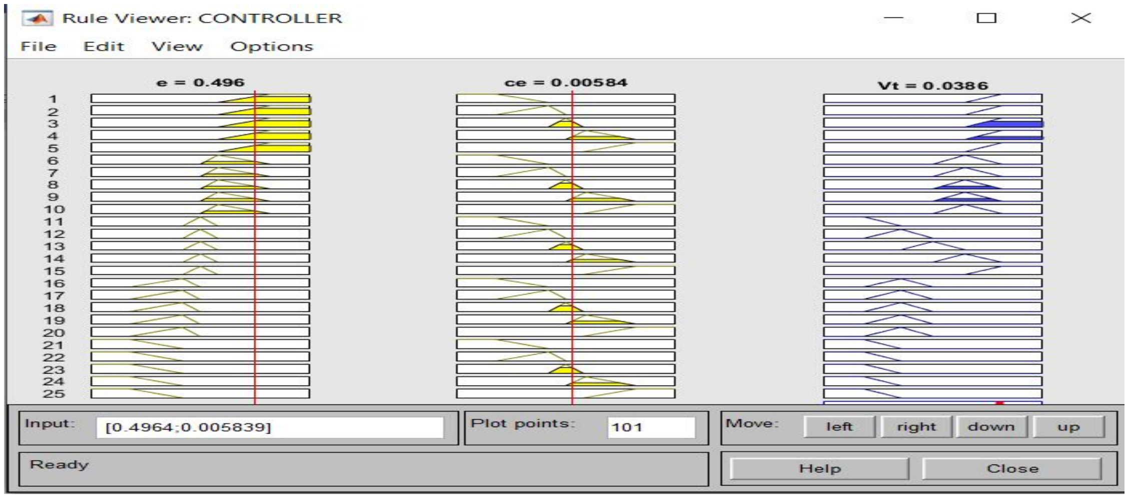

Figure 3. 24 Rule viewer

The Surface Viewer is used to show (for example) which rules are active, or how individual membership function shapes are influencing the results. The Surface Viewer is used to display the dependency of one of the outputs on any one or two of the inputs that is, it generates and plots an output surface map for the system. The surface of a fuzzy controller applying the previous rules is shown in Figure 3.25. Using the Centroid defuzzification, the surface shows the relationship between the inputs and outputs at any point in the intervals [-1 1].

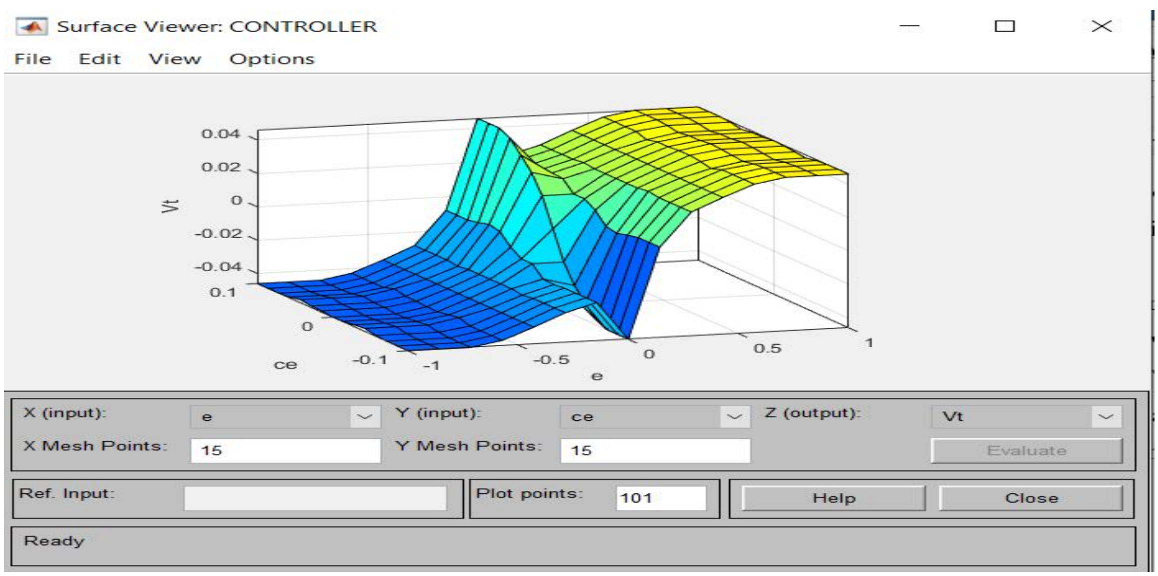

Figure 3. 25 Surface of Fuzzy Controller

The Simulation model of synchronous generator with AVR with FLC control loop is shown in figure 3.26 blow

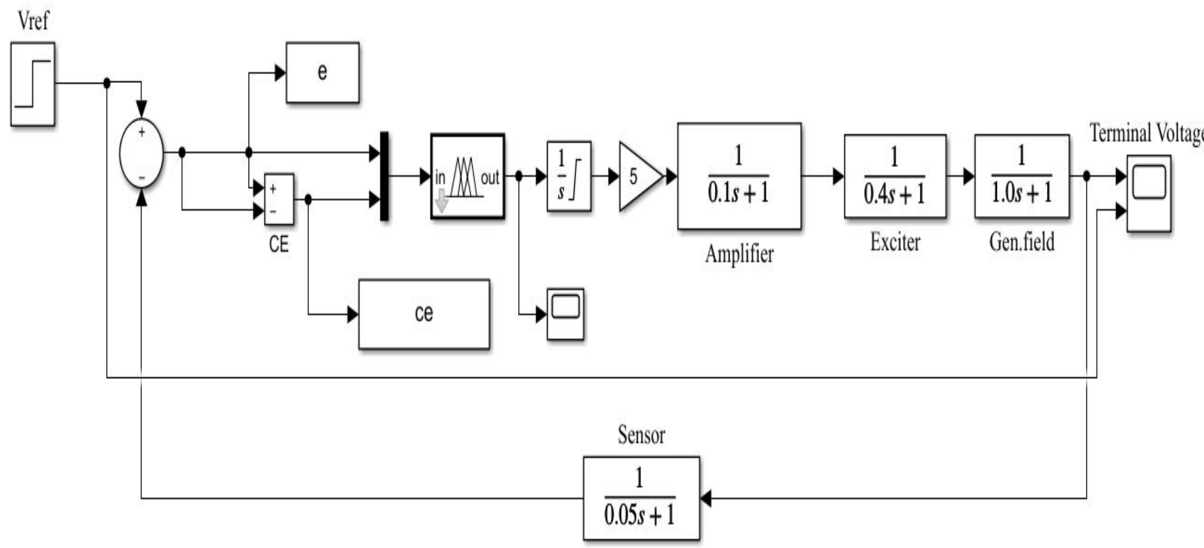

Figure 3. 26 Simulink model for (AVR) with FLC control

CHAPTER FOUR

4. SIMULATION RESULTS AND DISCUSSION

To compare and observe the output result of four different cases were used to simulate synchronous generator.

a) without control loop

b) With a Stabilizer Connected Between the Exciter Output and the Input.

c) With PID controller

d) with fuzzy logic controller

c) Comparison of the output result generator excitation with AVR loops for all cases.

Table 4. 1 Parameters required for the simulation of SGE with AVR.

parameter	K_A	K_E	K_G	K_R	τ_A	τ_E	τ_G	τ_R
Value	10	1	1	1	0.1	0.4	1	0.05

4.1. AVR without Controller

From the table 4.1 Simulation of synchronous generator with automatic voltage regulator (AVR) control loop is shown in figure 4.1 below.

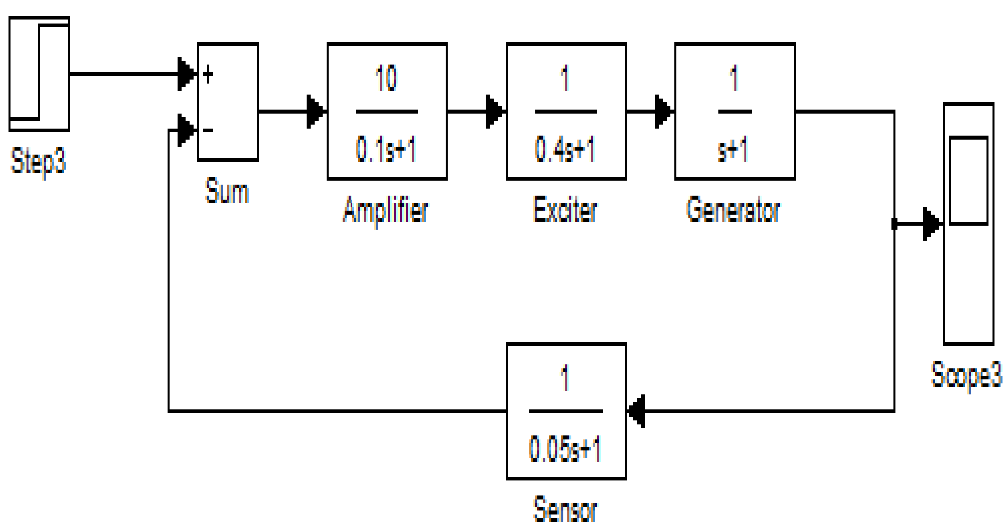

Figure 4. 1 Simulation block diagram of (SGE) with (AVR) loop only

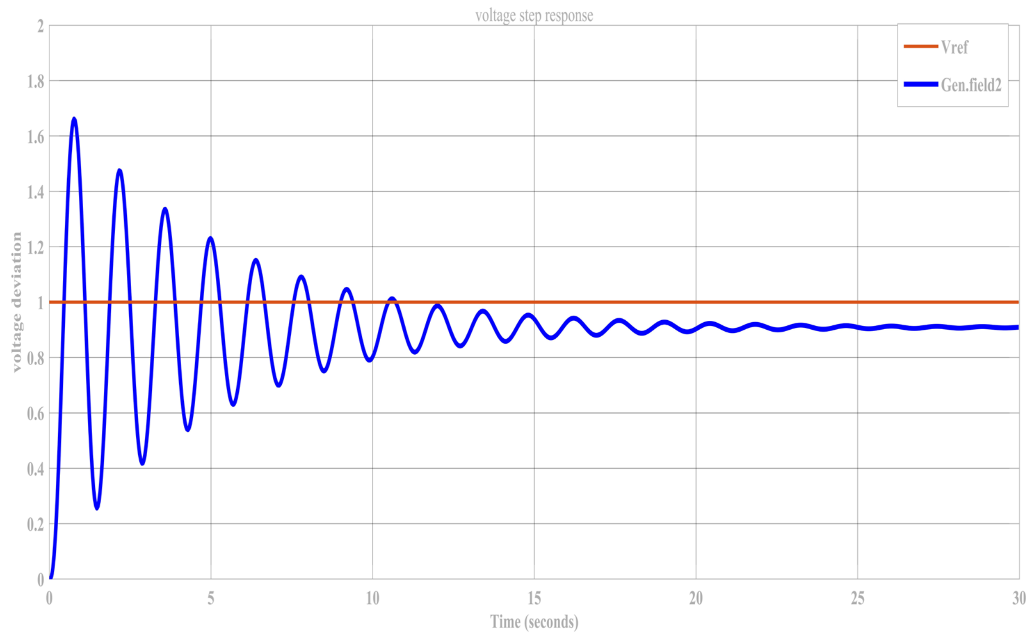

Figure 4. 2 Terminal voltage step response of SGE with (AVR).

From the result we have seen that for an amplifier gain KA= 10, the response is highly oscillatory, with a very large overshoot and long settling time and also we cannot have small steady sate error and a satisfactory transient response at the same time. From the terminal voltage step response of figure 4.2, it is observed that the system has a large percent overshoot and a long settling time with an oscillatory response, and a steady-state error of more than 9%. As we increasing the values of amplifier gain, the a steady-state error also increases. when we decrease the values of amplifier gain, steady-state error also decreases, but we cannot get the nearest desired values of input voltage. Therefore, we cannot have small steady state error and a satisfactory transient response at the same time. In this case the values of KA has taken minimum range of 10. Because of it is output signal (oscillatory response) above the desired value if we take above 10. And also if we take less than 10 the signal is falling under the desired value.so that it needs to find another additional controlling method.

Table 4. 2 Time-domain performances specifications

Rise time	Settling time(sec)		Peak time(sec)	Overshoot (voltage)	Steady state response (voltage)	Steady state error (voltage)	Percent overshoot %
value	29		0.7	0.74	0.091	0.091	77.679

4.2. With a Stabilizer Connected Between the Exciter Output and the Input.

With a stabilizer connected between the exciter output and the input, stabilizer time constant is TF= 0.04 and derivative gain is adjusted to KF is 2 ,the transfer function of the stabilizer is $\frac{2}{0.01s}$ the shown below

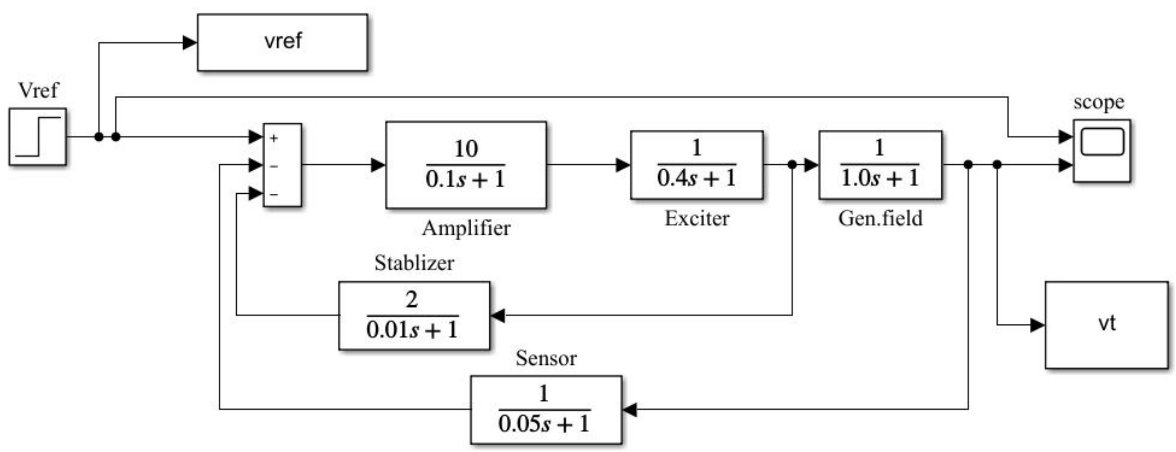

Figure 4. 3 The Simulink model for AVR with stabilizer

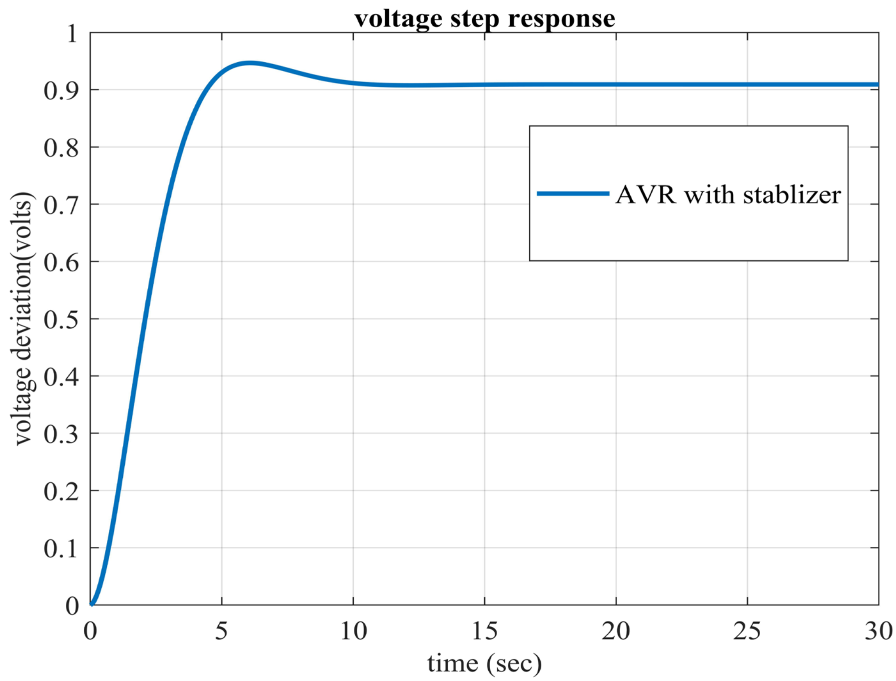

Figure 4. 4 Terminal Voltage Step Response of CAVR with stabilizer

The file is opened in Simulink window. The simulation results in the same response as shown in figure 4.4. The result shows a very satisfactory transient response with an overshoot about 4.13 percent and settling time of approaches to 12 seconds. In this case also, the steady-state error, settling time and percent overshoot is still high, there is need for improvement in the terminal voltage step response hence the use of PID to modify the dynamic response and lower or remove the Steady-State error.

4.3. AVR with PID Controller

Simulation of synchronous generator with automatic voltage regulator (AVR) with connected PID in series with amplifier control loop is shown in figure 4.5. we further going by selecting five values and finally taking the best values of k_{p}=0.6, k_{i}=0.16, kd=0.063

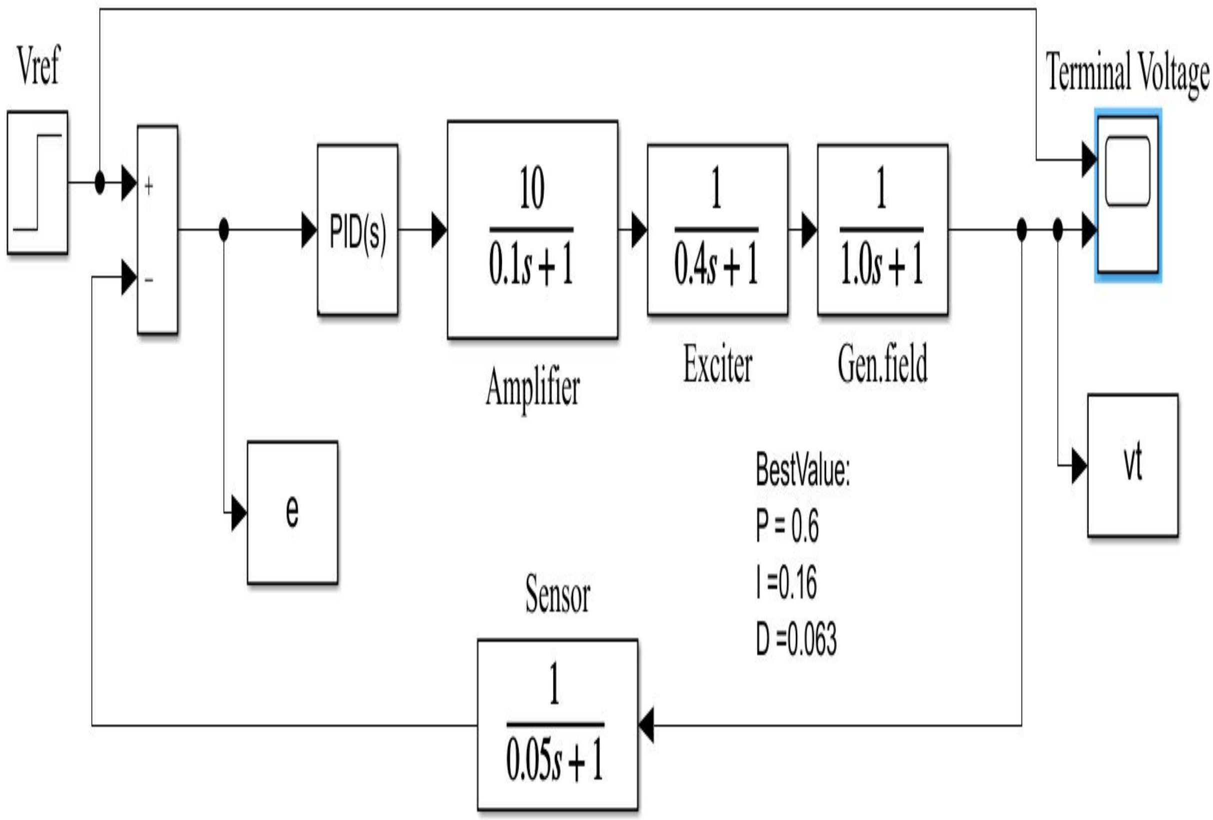

Figure 4. 5 Simulation block diagram of (SGE) with (AVR) with PID controller

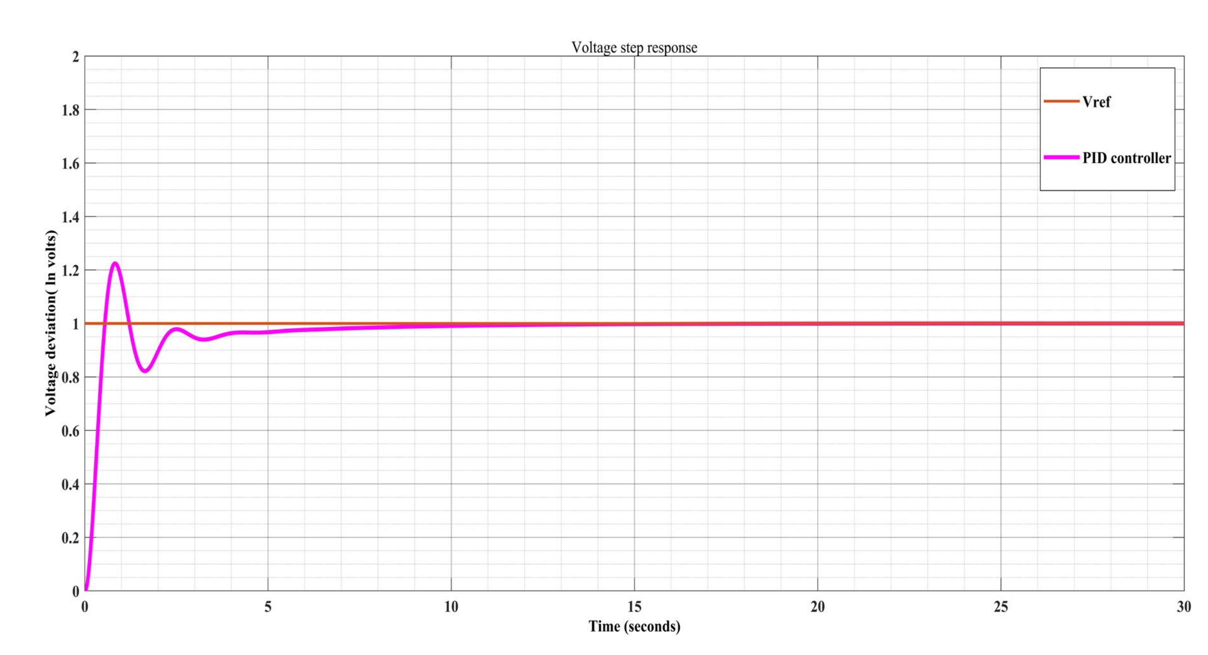

Figure 4. 6 Terminal voltage step response of (SG) with (AVR) with PID controller.

Table 4. 3 Terminal voltage step response of (SGE) with (AVR) with PID controller

case	K_p	K_i	Kd	Settling time (sec)	Overshoot (voltage)	Steady state response (voltage)	Steady state error (voltage)
1	0.18	0.05	0.03	23	0	1	0
2	0.18	0.06	0.4	18	0	1	0
3	0.18	0.8	0.05	13	0	1	0
4	0.18	0.09	0.06	11.5	0	1	0
5	0.6	0.16	0.063	11	0	1	0

From case 5 the best response of the AVR loop occurs when the gain Kp, Ki, $and\ Kd$ are equal 1, 0.1 and 0.06 respectively. This implies that case 5 gives the good trade-off between overshoot/undershoot and settling time. Here we understand that the system has almost negligible overshoot and settling time about 11. Here we understand that PID controller needs to manually adjust the parameters. So that the generator excitation adjustment process is more complicated and inconvenient. On the other hand, PID controllers do not work efficiently and satisfactorily in non-linear systems. It is more difficult to account for changes measured values of the voltage magnitude and it has a longer rise and settling time which affects excitation system control performance.

4.4. CAVR Excitation with FLC Controller

FLC controller was used to control the generator excitation system and improve the dynamic response as well as reduce or eliminate the steady-state error.

Simulation of synchronous generator with automatic voltage regulator (AVR) with FLC control loop is shown in figure 4. 7 below.

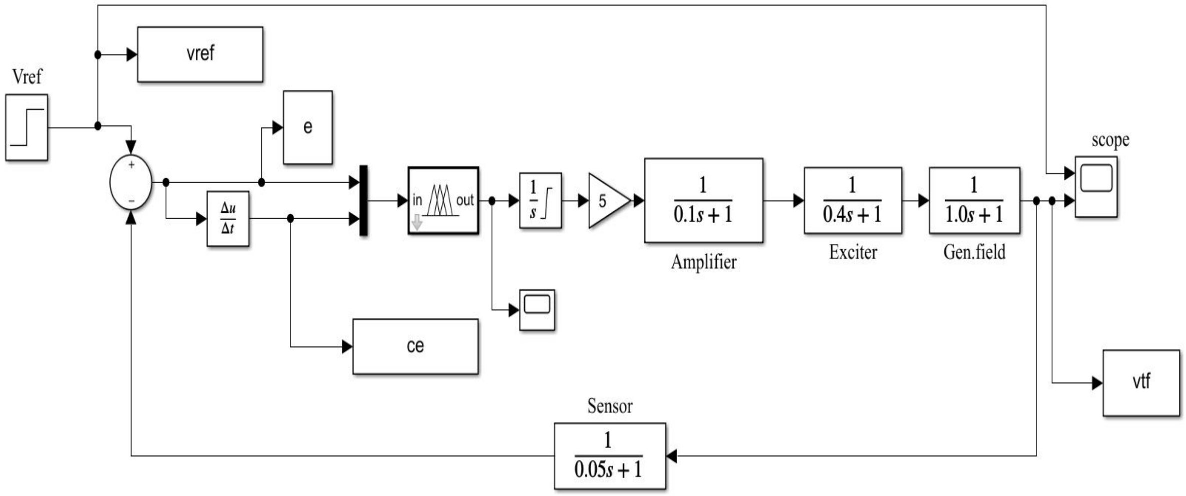

Figure 4. 7 Simulation block diagram of (SGE) with (AVR) with FLC controller

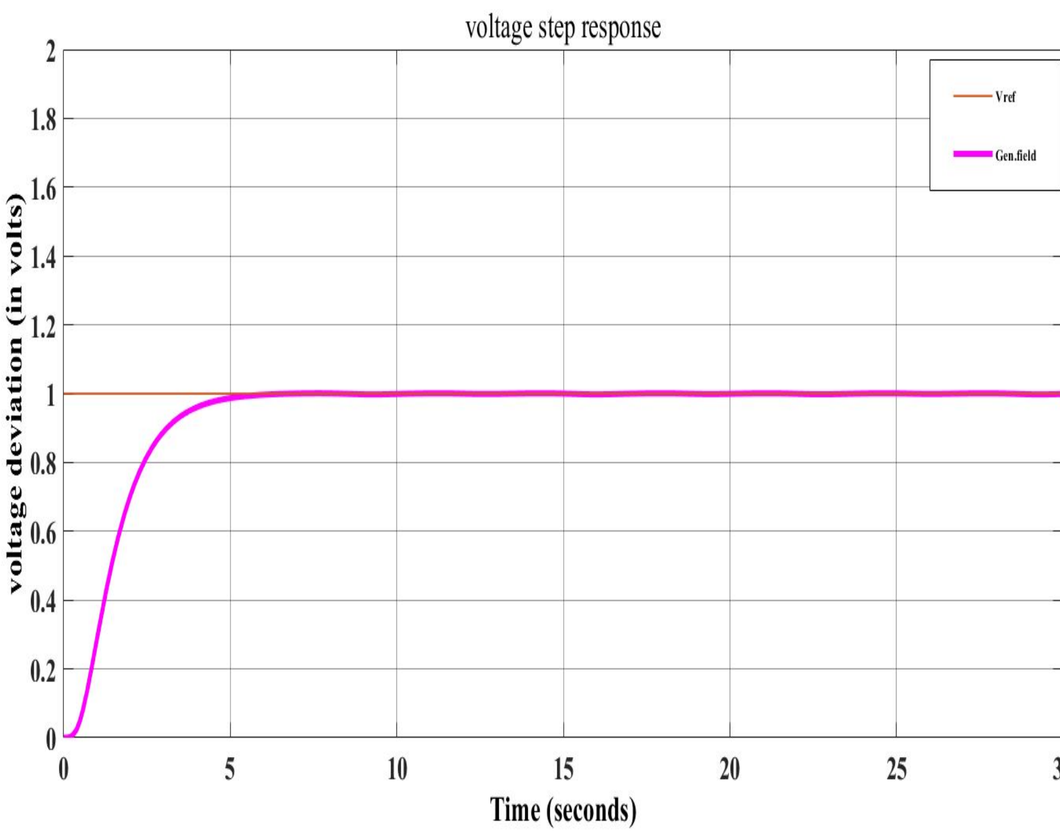

Figure 4. 8 Terminal voltage step response of AVR with FLC controller

Table 4. 4 Terminal voltage response results of (SG) with (AVR) with FLC control loop

Results	Settling time (sec)	Overshoot (voltage)	SteadyState response (voltage)	SteadyState error (voltage)
Value	5.1	0	1	0

The simulation results in the same response as shown in figure 4.4. as we observe figure 4.8 and table 4.4 above shows a very satisfactory transient response with an overshoot about zero percent and settling time of approaches to 5.1 seconds. In this case, the steady-state error, settling time and percent overshoot is almost negligible, hence the use of FLC is suggested as to modify the dynamic response and remove the Steady-State error at small selling time.

4.5. Comparison of the output result generator excitation with AVR loops for all cases.

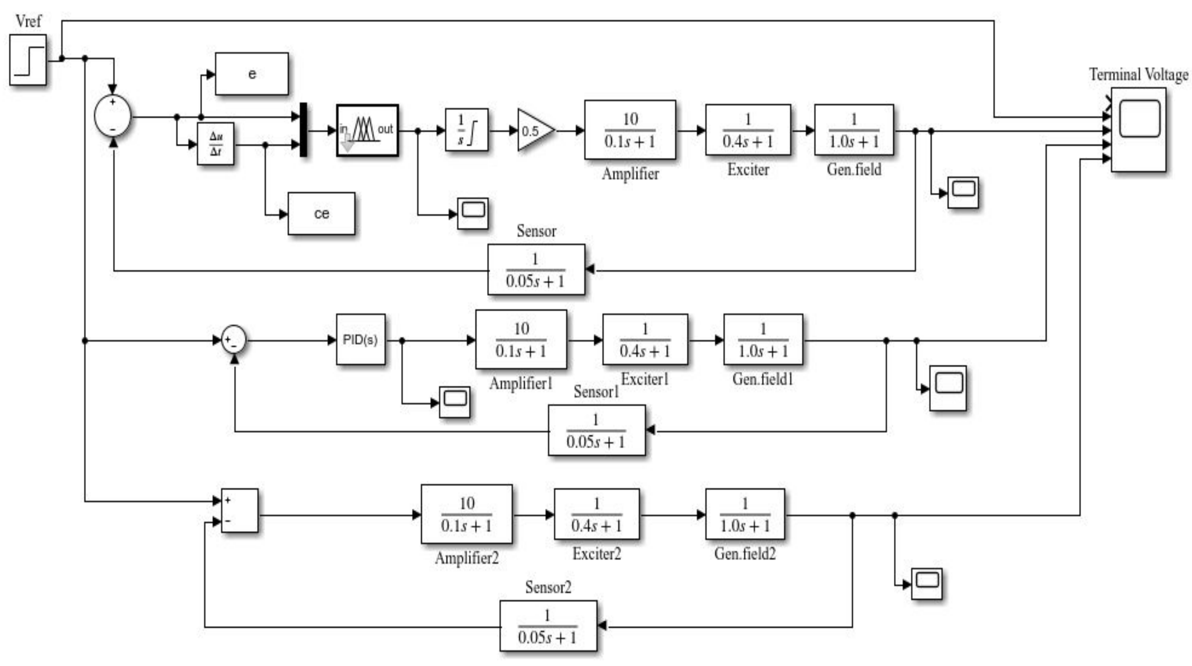

Figure 4. 9 The simulation block diagram the A AVR loop using without controller, PID, and FLC controllers

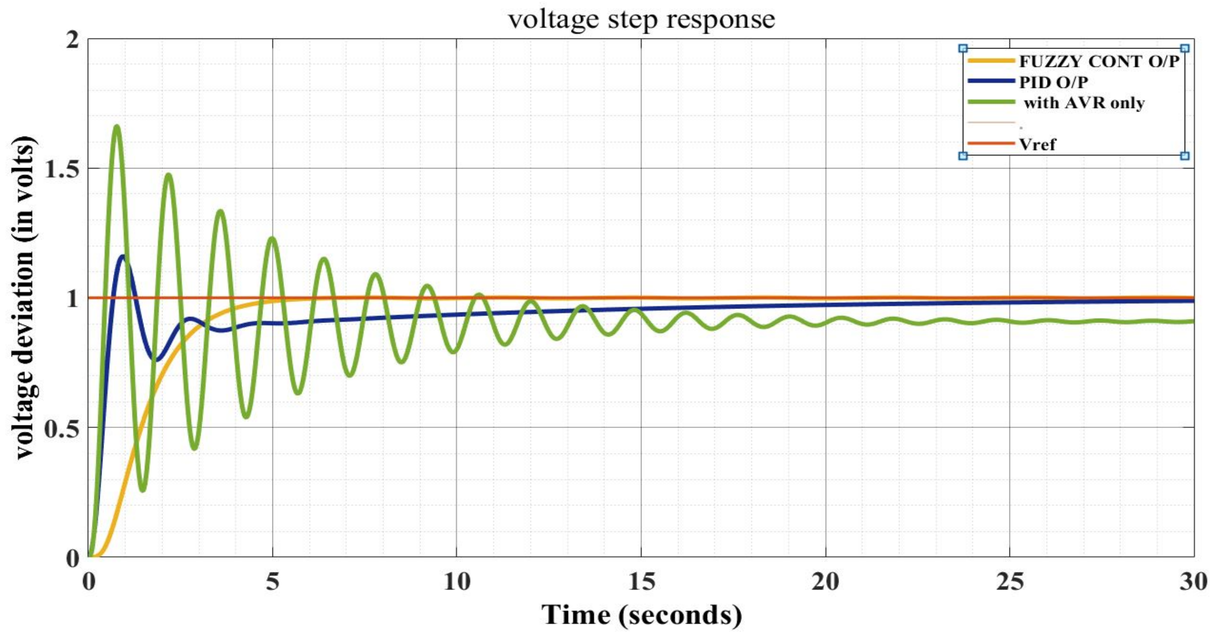

Figure 4. 10 Simulation block diagram of SGE with AVR loop and with both PID and FLC controllers

Table 4. 5 Terminal voltage response results of (SG) comparing (AVR) with PID and FLC control loop

Controller methods	Settling time (sec)	Overshoot (voltage)	SteadyState response (voltage)	SteadyState error (voltage)	present overshoot (%)
Without control	29	0.7	0.909	0.091	82.382
With PID	8	0	1	0	50.758
With FLC	5.1	0	1	0	0.505

Here, as we look from the table 4.5 us comparing the best PID controller result for AVR loop with the result Obtained using FLC controller significant improvement was observed almost the best result is achieved on FLC controller. So that fuzzy based generator excitation control is the best method other than using PID.

5. CONCLUSION AND RECOMMENDATION

5.1. CONCLUSION

This thesis analyzes the generator excitation control based on FLC compared with PID. FLC has a better result compared with traditional PID excitation control. Adding FLC into generator excitation control system with AVR loop is mainly aimed at the feature of generator excitation control system which is nonlinear, time varying, and complex. After adding fuzzy control system, the generator excitation control system can give the best result and do more reasonable measures according to the experience which make the generator excitation control system more reliable and effective. The controller based on FLC is designed with advantages of fuzzy control with that of PID control combined, which is characterized by simplexes, high accuracy rather than PID control, good adaptability and speed ability of fuzzy control. It has been shown that fuzzy logic control can effectively be applied to the regulation of voltage for a synchronous generator. The results show that the FLC-AVR performance is very high when compared to conventional AVR (CAVR) or PID-AVR. The resulting system was computationally efficient and negligible settling time, zero preset overshoot and rise time reduced. The arrangement of the structure results in a computationally less intensive control algorithm. Another significant advantage of fuzzy logic is that it can easily accommodate additional input signals. Therefore, integrating controllers becomes much simpler with resultant performance enhancement. Fuzzy Logic Control provides a convenient means to develop the controller which can accommodate the non-linear nature of the exciter-generator system.

5.2. Recommendation

- FLC developed in this thesis is recommended to be fully tested in the real synchronous generator excitation system.
- *FLC* is recommended to be further investigated to enhance its capability for different types of power system control that could occur in the real power system.
- The optimization procedure for the *FLC* is recommended to be further investigation.
- The other control methods such as Neuro Fuzzy Control (NFLC) are also recommended for the better dynamic response of excitation system.

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APPENDICES

APPENDIX A: root locus plot for convergent check for figure10 kA=10;

>> numc=kA*[25 500];

>> denc=[1 33.5 307.5 775+500 500kA];

denc=[1 33.5 307.5 775500+500kA];

APPENDIX B: (Program for the terminal voltage step response of an AVR

%program for the terminal voltage plot of figure27

denc=[1 33.5 307.5 775 500+500*kA];

t=0: .05:30;

c=step(numc,denc,t);

figure(2),plot(t,c),grid

APENDEIX C (program for terminal voltage response for figure 28)

>> num=250*[1 45 500];

>> denc=[1 58.5 13645 270962.5 274875 137500];

>> t=0:.05:30;

>> c=step(numc,denc,t);plot(t,c),grid timespec(numc,denc)

>> c= step(numc,denc,t);plot(t,c),grid

>> c=step:plot(t,c),grid

Here is an example of how the function step works:

Consider a randomly generated stable Transfer Function Model:

of the form G(s)=num(s)/den(s):

num = 0 0 0 0.4882 0.5881 -1.2102 -0.9761 1.2019 0.3591 -0.3949

den = 1.0000 8.6073 42.0872 126.3624 242.6969 293.1992 213.2203 87.9905 18.7456 1.5927

APPENDIX C: (Program for the terminal voltage response for figure. 29)

%program for the terminal voltage plot of figure

numc=[1400 5000 1250];

denuc= [1 33.5 307.5 2175 5500 1250];

t=0:0.05:30;

c=step(numc, denuc, t);

xlabel ('t [sec]');

```
ylabel('c[volts]');
grid on;
title ('Terminal voltage step response for CAVR with PID');
plot(t, c);
grid on;
end
```

APPENDIX D: (Initializ**e** parameters for the fuzzy controller/ fuzzy matab/Simulink code

```
[System]
Name='DESGHN FUZZY'
Type='mamdani'
Version=2.0
NumInputs=2
NumOutputs=1
NumRules=25
AndMethod='min'
OrMethod='max'
ImpMethod='min'
AggMethod='max'
DefuzzMethod='centroid'
[Input1]
Name='e'
Range=[-1 1]
NumMFs=5
MF1='NB':'trimf',[-1.5 -1 -0.5]
MF2='NS':'trimf',[-1 -0.5 0]
MF3='Z':'trimf',[-0.5 0 0.5]
MF4='PS':'trimf',[0 0.5 1]
MF5='PB':'trimf',[0.5 1 1.5]

[Input2]
Name='ce'
Range=[-1 1]
NumMFs=5
MF1='NB':'trimf',[-1.5 -1 -0.5]
MF2='NS':'trimf',[-1 -0.5 0]
MF3='Z':'trimf',[-0.5 0 0.5]
MF4='PS':'trimf',[0 0.5 1]
MF5='PB':'trimf',[0.5 1 1.5]

[Output1]
Name='Vt'
```

```
Range=[-1 1]
NumMFs=5
MF1='NB':'trimf',[-1.5 -1 -0.5]
MF2='NS':'trimf',[-1 -0.5 0]
MF3='Z':'trimf',[-0.5 0 0.5]
MF4='PS':'trimf',[0 0.5 1]
MF5='PB':'trimf',[0.5 1 1.5]

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