MODELLING AND TIME DOMAIN ANALYSIS OF SYNCHRONOUS MACHINE WITH FUZZY BASED AVR

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ABSTRACT

An Automatic Voltage Regulator (AVR) is crucial for maintaining the output voltage of generators within acceptable limits, ensuring the stability and efficiency of power systems. Traditional AVR systems often rely on linear control methods, which may not perform optimally under varying load conditions and nonlinearities. This paper explores the implementation of a Fuzzy Logic Controller (FLC) in an AVR system to enhance its performance and robustness.

The FLC-based AVR aims to handle non-linearities and provide better transient and steady-state performance compared to conventional controllers. The Fuzzy Logic Controller is expected to demonstrate superior performance in handling nonlinearities and varying load conditions. Key improvements may include reduced overshoot, faster settling time, and improved voltage stability under transient conditions. In this paper, Performance of AVR is enhanced with FLC and compared with PI Controller. It is proven that fuzzy controller based synchronous generator works better than PID based system

Key words: Synchronous machine, Modelling,Time domain analysis, FLC, AVR

1. INTRODUCTION

An AVR is a vital component in power systems that maintains the terminal voltage of a generator at a desired level, regardless of load variations or other disturbances. The components that present in the AVR are generator, exciter, voltage, controller the power system stabilizer that improves system stability by damping power oscillations. [1], [6]. The operation of the AVR is that continuously monitors the generator's terminal voltage and adjusts the excitation to maintain it at the set point.

The structure of an FLC includes fuzzification which changes crisp input values into fuzzy sets, rule base which contains IF-THEN rules that define the control strategy, Inference engine that applies the rules to the fuzzified inputs and finally, the defuzzification which converts the fuzzy output back to a crisp value. Handling nonlinear systems, robust to un certainty and incorporating expert knowledge are the advantages of fuzzy logic controller. [2], [3]

The following are the salient features that motivates for FLC in AVR

- **Nonlinearity:** AVR systems exhibit nonlinear behaviour due to saturation effects and the interaction between components.

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- **Uncertainty:** Load variations, network changes, and disturbances introduce uncertainties.
- **Performance:** FLCs can potentially provide better dynamic response and steady-state performance compared to conventional controllers.
- **Adaptability:** FLCs can be designed to adapt to changing system conditions.

2. AUTOMATIC VOLTAGE REGULATOR

An Automatic Voltage Regulator (AVR) is an electrical device used to maintain a constant voltage level in an electrical system, regardless of disturbances in the load or source voltage which is shown in figure 2.1. The main purpose of an AVR is to provide a stable and consistent voltage supply to electrical equipment, ensuring their proper operation and preventing damage caused by over voltages or under voltages.

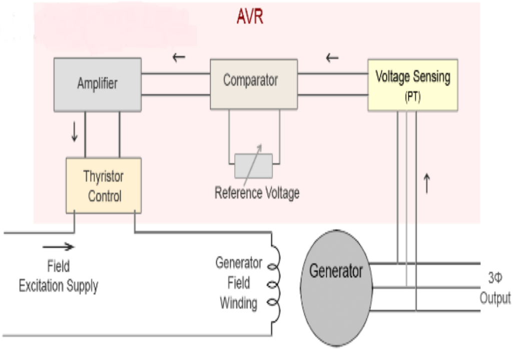

Fig.2.1. Block diagram of Automatic Voltage Regulator

2.1 Operating Principle

The AVR continuously monitors the output voltage of the generator through the sensing circuit. This involves using voltage transformers and rectifiers to convert the AC output voltage to a DC signal that represents the magnitude of the voltage. The sensed voltage is fed to a comparator, where it is compared with a pre-set reference voltage. The reference voltage is set with respect to the desired output voltage level.

2.2. Components of AVR

2.2.1 Voltage Sensing Circuit

The voltage sensing circuit measures the output voltage of the generator and converts it into a form suitable for further processing. Transformers steps down the generator output voltage to a lower level that can be safely handled by the AVR. Rectifiers are converting the AC voltage from the transformers into a DC voltage, which is easier to process and compare with a reference voltage.

2.2.2 Comparator

The comparator compares the sensed voltage with the reference voltage and generates an error signal based on the difference. The Operational Amplifiers are commonly used in comparators to produce a differential voltage.

2.2.3 Error Signal Amplifier

The error signal generated by the comparator is usually small and needs amplification to drive the subsequent control circuitry. The amplifiers are boosting the error signal to a level that can effectively control the exciter circuit. These can be simple transistor amplifiers or more complex operational amplifier circuits.

2.2.4 Control Circuit

The control circuit processes the amplified error signal and generates a control signal for the exciter. In some advanced AVRs, PWM is used to precisely control the output based on the error signal. The Transistors/MOSFETs are used as switches or amplifiers in the control circuit to modulate the exciter's input. The FLC is used for the modulation of the exciter's input.

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2.2.5 Exciter

The exciter controls the field current supplied to the field winding of the generator. Adjusting the field current changes, the strength of the magnetic field, thereby regulating the output voltage. The DC exciters are providing direct current to the rotor winding.

3 MATHEMATICAL MODELLING

Fuzzy Logic Controller is incorporated for an AVR which improves its performance especially in handling nonlinearities and uncertainties in the system. Modelling of AVR includes generator, exciter, amplifier and sensor. All are approximated as first order transfer function.

3.2 MODELLING OF SYNCHRONOUS GENERATOR

The derivation of the first-order approximation of a synchronous generator's dynamic model is produced. This simplified model is valuable for analysing and understanding the generator's behaviour under certain conditions. Understanding the dynamic behaviour of the generator is crucial for the stability and control of power systems. Although the complete dynamic model involves complex differential equations, a first-order approximation provides a simplified yet insightful representation.

The mechanical dynamics of a synchronous generator's rotor are described by the swing equation:

$$J\frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} = T_m - T_e$$

where:

- δ is the rotor angle,
- J is the moment of inertia of the rotor,
- D is the coefficient of damping
- Tm is the mechanical torque input,
- Te is the electrical torque output.

Linearization and Simplification

For small perturbations around an operating point, the swing equation can be linearized:

$$J\frac{d^2\Delta\delta}{dt^2} + D\frac{d\Delta\delta}{dt} + K_d\Delta\delta = \Delta T_m$$

Assuming that the electrical torque Te is proportional to the rotor angle deviation $\Delta\delta$

$$T_e = K_d\Delta\delta$$

where Kd is a damping coefficient.

substituting this into the swing equation:

$$J\frac{d^2\Delta\delta}{dt^2} + D\frac{d\Delta\delta}{dt} = \Delta T_m - \Delta T_e$$

First-Order Approximation

The following assumptions are made to derive the first order transfer function.:

1. The system is heavily damped (large D).
2. The inertia term J is negligible.

This simplifies the equation to:

$$D\frac{d\Delta\delta}{dt} + K_d\Delta\delta = \Delta T_m$$

Taking the Laplace transform:

$$D(s\Delta\delta(s)) + K_d\Delta\delta(s) = \Delta T_m(s)$$

$$\Delta\delta(s)(Ds + K_d) = \Delta T_m(s)$$

$$\Delta\delta(s) = \frac{\Delta T_m(s)}{Ds+K_d}$$

To achieve the form , we set *D=1* and *Kd=1*:

$$\Delta\delta(s) = \frac{\Delta T_m(s)}{s+1}$$

Transfer Function

The transfer function of the synchronous generator in this first-order approximation is:

$$\frac{\Delta\delta(s)}{\Delta T_m(s)} = \frac{1}{s+1}$$

This transfer function indicates that the system's response to a step change in mechanical torque input (*ΔTm*) is a first-order system with a time constant of 1 second.

3.2 MODELLING OF AMPLIFIER

The first-order approximation of the amplifier block within an Automatic Voltage Regulator system is derived. This simplified model helps in understanding the behaviour of the amplifier, which is crucial for the stability and control of the AVR system.

An Automatic Voltage Regulator ensures the stability of a synchronous generator by maintaining the desired output voltage. The amplifier in the AVR system amplifies the error signal to drive the excitation system. A first-order approximation of the amplifier's dynamics simplifies the analysis and design of the control system. The dynamics of an amplifier can typically be modelled by a first-order differential equation. This equation relates the input signal (Vin) to the output signal (Vout) of the amplifier. The general form of this equation is:

$$\tau_a \frac{dV_{out}(t)}{dt} + V_{out}(t) = K_a V_{in}(t)$$

where:

- *Vin(t)* is the source signal to the amplifier,
- *Vout(t)* is the response signal of the amplifier,
- τa is the amplifier time constant,
- *Ka* is the amplifier gain.

First-Order Approximation

To derive the transfer function, the Laplace transform of the equation is taken considering zero initial values.

$$\tau_a s V_{out}(s) + V_{out}(s) = K_a V_{in}(s)$$

Factor out *Vout(s)*:

$$V_{out}(s)(\tau_a s + 1) = K_a V_{in}(s)$$

The transfer function *Ga(s)* of the amplifier is then obtained by:

$$G_a(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{K_a}{\tau_a s+1}$$

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Transfer Function

For a first-order amplifier approximation, the transfer function is:

$$G_a(s) = \frac{K_a}{\tau_a s+1}$$

This transfer function indicates that the amplifier's response to a change in input signal is a first-order system with a time constant τa and a gain *Ka*.

3.3 MODELLING OF EXCITER

The first-order approximation of the exciter block within an Automatic Voltage Regulator system is obtained. This simplified model aids in understanding the behaviour of the exciter, which is critical for the stability and control of the AVR system.

For simplicity, the dynamics of an exciter can typically be modelled by a first-order differential equation. This equation relates the input voltage *(Vin)* to the excitation voltage *(Vf)* produced by the exciter. The general form of this equation is:

$$\tau_e \frac{dV_f(t)}{dt} + V_f(t) = K_e V_{in}(t)$$

where:

- *Vin(t)* is the input signal to the exciter,
- *Vf(t)* is the excitation voltage of the exciter,
- τe is the exciter time constant,
- *Ke* is the exciter gain.

The Laplace transform is

$$\tau_e s V_f(s) + V_f(s) = K_e V_{in}(s)$$

Factor out *Vf(s):*

$$V_f(s)(\tau_e s + 1) = K_e V_{in}(s)$$

The transfer function *Ge(s)* of the exciter is then given by:

$$G_e(s) = \frac{K_e}{\tau_e s+1}$$

This transfer function indicates that the exciter's response to a change in input voltage is a first-order system with a time constant τe and a gain Ke

3.4 MODELLING OF SENSOR

The derivation of the first-order approximation of an Automatic Voltage Regulator sensor's dynamic model is obtained. This simplified model is essential for understanding and analysing the sensor's behaviour in the control loop of an AVR system.

The AVR sensor typically consists of components such as transformers, filters, and signal conditioners, which together introduce a certain response time. The sensor's dynamic behaviour can be approximated by a first-order differential equation, which describes the relationship between the input voltage *(Vin)* and the measured output voltage *(Vout).*

The first-order differential equation for the sensor can be written as:

$$\tau_s \frac{dV_{out}(t)}{dt} + V_{out}(t) = V_{in}(t)$$

where:

- *Vin(t)* is the input voltage to the sensor,
- *Vout(t)* is the output voltage of the sensor
- τs is the sensor time constant.

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The Laplace transform is

$$\tau_s s V_{out}(s) + V_{out}(s) = V_{in}(s)$$

Factor out *Vout(s)*:

$$V_{out}(s)(\tau_s s + 1) = V_{in}(s)$$

The transfer function *Gs(s)* of the sensor is then given by:

$$G_s(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{1}{\tau_s s+1}$$

This transfer function indicates that the sensor's response to a change in input voltage is a first-order system with a time constant τs.

4. FUZZY LOGIC CONTROLLER

A Fuzzy Logic Controller (FLC) is an intelligent control system that uses fuzzy logic principles to make decisions and control processes. Unlike conventional control systems that require precise mathematical models and crisp values, fuzzy logic controllers can handle imprecise, ambiguous, or vague information, making them particularly useful in complex, nonlinear systems where precise mathematical modelling is difficult or impractical.

4.1 COMPONENTS OF A FUZZY LOGIC CONTROLLER

A typical fuzzy logic controller consists of four main components: Fuzzification, knowledge base, Inference engine, Defuzzification [4], [5]

Fuzzy logic operates by converting precise input values into fuzzy linguistic variables using membership functions, a process called fuzzification. These fuzzy inputs are then processed through a set of IF-THEN rules, which are evaluated using fuzzy operators to determine the activation level of each rule. The outputs of all activated rules are combined in the fuzzy inference process, resulting in a fuzzy output set. This fuzzy output is then converted back into a precise value through defuzzification, typically using methods like centroid calculation. The resulting crisp output is used to control the system or make a decision, and this process iterates continuously in control applications.

4.2 INFERENCE METHODS

The schematic of fuzzy inference system is shown in figure 4.1. Fuzzy inference methods in fuzzy logic control determine how the fuzzy rules are combined to produce a fuzzy output. The two main types are Mamdani and Sugeno methods, with Mamdani using fuzzy sets for both antecedents and consequents, while Sugeno uses crisp functions for consequents. In both methods, the antecedents of rules are evaluated using fuzzy operators (like AND, OR), and the resulting activation levels determine how strongly each rule's consequent contributes to the output.

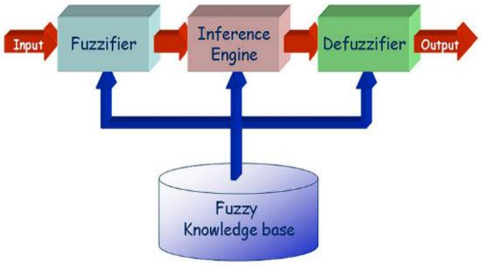

Fig.4.1 Block diagram of Fuzzy Inference System

5. IMPLEMENTATION OF FUZZY LOGIC CONTROLLER IN AUTOMATIC VOLTAGE REGULATOR

The implementation of an FLC in an AVR involves the following steps:

- **System Modeling**: Develop a model of the power system and the AVR. This model is used to simulate the behaviorction of the system and to design the FLC.
- **Input and Output Selection**: Identify the input and output variables for the FLC. For an AVR, common input variables include the voltage error (difference between the desired and actual voltage) and the rate of change of voltage error. The output variable is typically the control signal for the exciter.
- **Fuzzification**: Define the membership functions for the input and output variables. These functions map the crisp values into fuzzy sets. For example, the voltage error can be described using fuzzy sets such as "Low," "Medium," and "High."
- **Rule Base Design**: Develop a set of fuzzy rules that describe the control strategy. These rules are based on expert knowledge and define the correlation between the input fuzzy sets and the output fuzzy sets.
- **Inference Engine**: Implement the inference mechanism that applies the fuzzy rules to the fuzzified inputs to generate fuzzy outputs. This typically involves the use of logical operations such as AND, OR, and NOT.
- **Defuzzification**: Convert the fuzzy output values back into crisp values to produce the final control signal. Common defuzzification methods include the centroid and the maximum membership method [7], [8]

5.1 Fuzzy Rules Table

Table 4.1 Fuzzy rules

Change in Voltage	Excitation
EL	VL
VL	VL
L	EL
N	VL
H	VL
VH	L
EH	H
EH	VH
EH	EH

The table 4.1 shows the rules applied for the fuzzy controller. Nine IF-THEN rules framed for If the change in voltage is extremely low, then the excitation should be very low

5.2 Simulation and Results

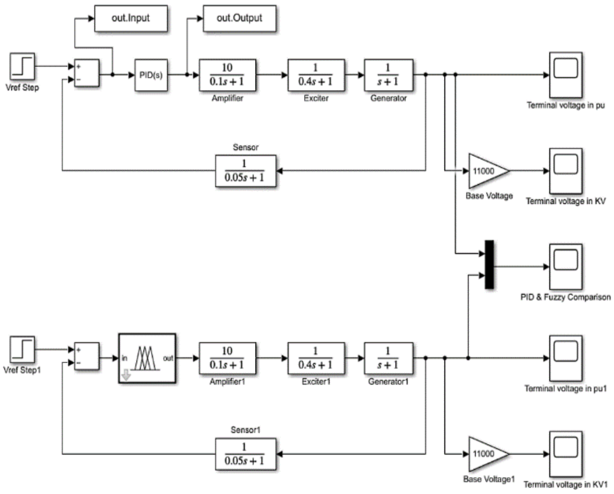

Fig.5.1 Simulink model of Synchronous machine with AVR using Fuzzy Logic Controller

Figure 5.1 shows the Simulink model of the AVR using the PID and Fuzzy Logic Controller. The upper part of the portion shows the AVR using PID controller and the lower part shows the AVR using Fuzzy Logic Controller. It consists of amplifier block, exciter block, generator block and sensor block. The gain is 10 for amplifier, 1 for exciter, generator and sensor. The time constant is 0.1 for amplifier, 0.4 for exciter, 1 for generator and 0.05 for sensor.

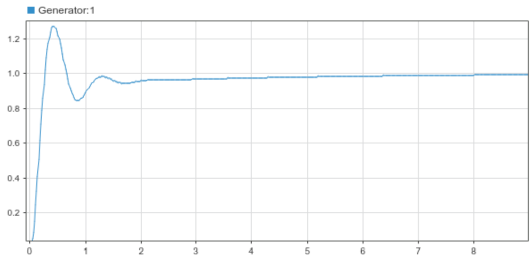

Fig.5.2. Generator response with PID controller

The figure 5.2 shows the response of the generator with AVR. It shows the peak overshoot value of 1.25 p.u. and has the settling time of 5 seconds.

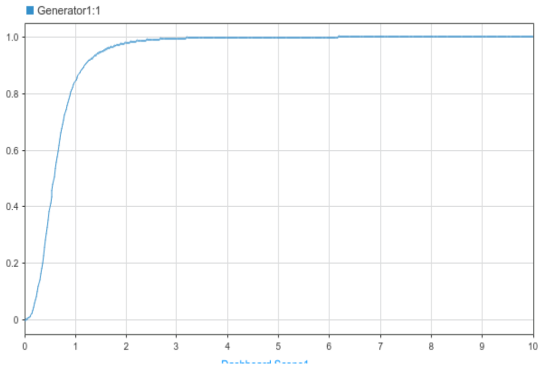

Fig.5.3 Generator response with fuzzy controller

The figure 5.3 shows the response of the generator with fuzzy controller. It has no peak overshoot and has settling time of 3 seconds.

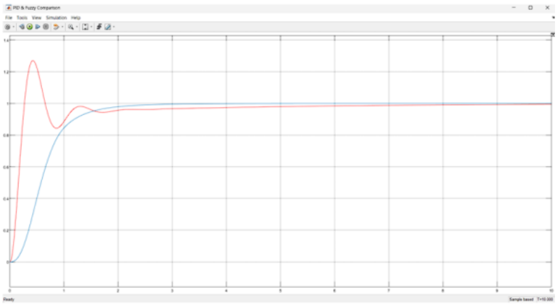

Fig.5.4 Comparison of generator output response with PID and Fuzzy controllers

The figure 5.4 shows the comparison of output voltage of synchronous generator with PID and Fuzzy controllers. It is inferred that the fuzzy based response has no peak overshoot and shorter settling time. Table 5.1 shows the comparison of output response with PID and fuzzy controllers.

Table 5.1 Performance comparison

Type of controller	**Peak overshoot (p.u.)**	**Settling time (S)**
PID controller	1.25	5
Fuzzy Logic Controller	0	3

6 CONCLUSION AND FUTURE SCOPE

6.1 CONCLUSION

The mathematical modelling of synchronous generator with AVR is obtained and simulated in MATLAB/Simulink. The output response is obtained with PID and fuzzy controllers. The Automatic Voltage Regulator using Fuzzy Logic Controller has performed well than the traditional PID controller by having no peak overshoot and shorter settling time. By fine tuning of the Fuzzy systems, the better results can be achieved.

AVRs could be part of larger systems that manage voltage across extensive geographical areas. As electric vehicle adoption grows, AVRs will help manage the associated voltage fluctuations. AVRs will work alongside battery storage to smooth out voltage variations. Future AVRs will need robust security features to protect against potential cyber threats. Digital AVRs offer improved monitoring, control, and integration capabilities. Advanced AVRs can address issues like harmonics and flicker, enhancing overall power quality.

REFERENCES

[1] T. Gupta and D. K. Sambariya, "Optimal design of fuzzy logic controller for automatic voltage regulator," 2017 International Conference on Information, Communication, Instrumentation and Control (ICICIC), Indore, India, 2017.

[2] MD Shadan Salik and Shaurya Priyal, 2020. “Fuzzy Logic based Automatic Generation Control”, Proceedings of the Fifth International Conference on Communication and Electronics Systems (ICCES 2020).

[3] Niketa N and Shantharama Rai.C, 2013. “Design and Modeling of Fuzzy Logic Based Voltage Controller for an Alternator”, International Journal of Recent Technology and Engineering (IJRTE) ISSN: 2277-3878 (Online), Volume-2 Issue-2, May 2013.

[4] Aye Aye Mon, 2009. “Fuzzy Logic PID Control of Automatic Voltage Regulator System”, World Academy of Science, Engineering and Technology, International Journal of Electrical and Computer Engineering Vol:3, No:2, 2009.

[5] N. Mazibukol and K. T. Akindejil, 2022. “Implementation of a FUZZY logic controller (FLC) for improvement of an Automated Voltage Regulators (AVR) dynamic performance”, 2022 IEEE PES/IAS Power Africa.

[6] Ahmed M. H. AL-Yousif, 2019. “Automatic Voltage Regulator based Fuzzy Logic”, International Journal of Computer Applications. 181, 36 (Jan 2019), 29-32.

[7] Maman Jimoh Lawal and Suleiman Usman Hussein, 2023. “Intelligent fuzzy-based automatic voltage regulator with hybrid optimization learning method”, Scientific African, Volume 19, 2023, e01573, ISSN 2468-2276.

[8] Farouk, Naeim & Sheng, Liu. (2012). “Design and Implementation of a Fuzzy Logic Controller for Synchronous Generator.”, Research Journal of Applied Sciences, Engineering and Technology.