

Performance Analysis of Conventional and Fuzzy Logic Controlled Automatic Voltage Regulator Systems in a Noisy Environment

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Abstract:

The increasing demand for electric power is leading to complex interconnected power systems. As a result, generation units are being operated under stressed conditions with smaller stability margins. The power supplied by the generator involves active and reactive components and good control of active and reactive power is essential in order to maintain a satisfactory steady state as these components can disturb the parameters of the power system. To regulate the reactive power and voltage magnitude of generation unit, AVR (Automatic Voltage Regulation) system is used in the forward path of the closed loop system of the generator. The addition of a conventional Proportional Integral and Derivative (PID) controller in the forward path of the AVR system can improve the dynamic response significantly but this may be at the cost of additional noise (introduced by the derivative component) which may reduce the overall effectiveness of the controller and this is a matter of concern in practice.

This paper primarily focuses on the issue of noise vulnerability of PID controlled AVR systems. An alternative and more effective fuzzy logic controlled approach is proposed to tackle these issues encountered with conventional controllers. The proposed solution uses a Fuzzy Inference System (FIS) to control the magnitude and rate of change of error, while the two nonlinear fuzzy membership functions are used to mitigate the noise effects. Simulations models of the PID controlled AVR system and proposed fuzzy logic controlled AVR systems are developed and results are compared to demonstrate the potential of the proposed design. Simulation results confirm the superiority of the proposed fuzzy logic controlled AVR system under noisy conditions.

Key Words: Automatic Voltage Regulation, Proportional Integral and Derivative Controller, Fuzzy Logic, Synchronous Generator

1. INTRODUCTION

The prime objective of power system control is to deliver and generate power to an interconnected system as cost-effectively and securely as possible while maintaining the supply voltage and frequency within specified limits [1]. The power supplied by the generator involves active and reactive components. Good control of active and reactive power is necessary to keep the system in a satisfactory steady-state condition as these components can disturb the power system parameters [2]. The frequency of the system is mainly affected by changes in the real power demand whereas increase in the reactive power demand has a significant effect on system voltage [3]. Real and reactive powers are therefore controlled independently through separate AVR and Load-Frequency Control (LFC) loops. Primary control equipment are installed for each generator

in a generation unit to provide the required stability and reliability in terms of the system frequency and voltage stabilization [4]. The real power and frequency are effectively controlled by LFC loop while the AVR system loop regulates the reactive power and voltage magnitude. When the generator is connected to the load, the real component of the power stresses the rotor in mechanical terms and opposes its rotation. This reduces the speed of the rotor and thus decreases the frequency of the generated voltage. Although reactive power lowers the frequency of the generated voltage this effect is small compared to the reduction of the e.m.f with increased reactive power. The active component is in the quadrature with the direction of the field but the reactive component directly opposes the excitation field. Thus, as the reactive power increases, the opposition to the excitation field increases which in turn reduces the generated e.m.f. This effect must be compensated so that the generator remains synchronized with the system.

In literature different approaches are used to achieve the regulation of reactive power and voltage magnitude of generation unit either using power system stabilizing (PSS) components [5], conventional PID controllers [6], fuzzy logic controllers [5] and hybrid controllers [10]. Techniques such as genetic algorithms [7] and other evolutionary algorithm [8] and particle swarm optimization methods [9] have also been considered for optimization and tuning of these controllers, but these control system design approaches usually consider only the ideal environmental conditions by neglecting the effect of noise which introduces high frequency disturbances, the effects of which are reflected in the overall system behavior.

This paper investigates the effect of PID controlled and fuzzy logic controlled AVR systems in terms of regulation of the reactive power and generated voltage while taking the noisy environment into account. Simulink models have been developed for both controllers and the performance characteristics are compared in terms of system output response and system response error.

The organization of the paper is as follows. In Section 2, the generator control loop configuration of the AVR is discussed. A state space representation and simulation model of AVR system using PID controller is detailed in Section 3. In Section 4, the fuzzy logic controlled AVR system is proposed. Conclusion and suggestions relating to future work are given in Section 5.

2. GENERATOR CONTROL LOOP BASED AVR SYSTEM

The reactive power demand and voltage magnitude of generation unit reduce the terminal voltage of the generator and control of this change in voltage is desired to ensure power system stability. This task is accomplished

by the generator excitation system using an AVR control loop through a closed loop system of the generator. The control loop of the generator continuously monitors the produced voltage level at the generator terminals and accordingly regulates the excitation level of the rotor using any appropriate type of controller (e.g. a microcontroller) system and firing circuit (based on thyristors, for example). The magnitude of the voltage is sensed and measured by a potential transformer which steps down the voltage and then measures its magnitude. This measured voltage is then rectified through a three-phase rectifier and then converted to the digital form to feed to the microcontroller where it is compared with the reference value set by the operator. The error signal, if exists, is then amplified to increase the excitation field which in turn increases the generated voltage until the error signal is reduced.

The terminal voltage is constantly sensed by a voltage level sensor, which is then rectified and regulated before comparing with DC reference signal in the comparator. Subsequently, if the comparison results in an error voltage signal, this will then be amplified and forwarded to the controller. In order to regulate the field windings of the generator, the exciter system can be used along with the output of the controller. For proper generator excitation, the AVR loop is configured to achieve the required reliability and the steadiness of the generator terminal voltage [11]. The AVR control loop configuration and sequence of events are illustrated in Fig.1.

The load voltage is first stepped down to a voltage suitable for measurement and then measured through a measuring device like voltmeter. The measured voltage is initially processed through an analog to digital converter (ADC) before being fed to the microcontroller for comparison. After conversion, the controller compares the ADC values with the terminal voltage set by operator. In case of any difference in the measured and the reference quantity, an error signal is generated from the controller's output. The error signal generated is in digital form and needs to be converted in its analog equivalent before feeding to the amplifier.

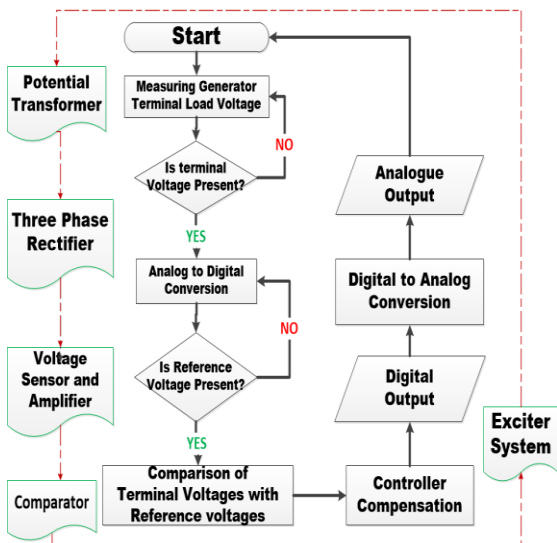


Figure1: AVR System Generator Control Loop Configuration and Event Flow Chart

Based on the generator control loop configuration of Figure 1, the AVR system can be designed to regulate and control the reactive power and voltage magnitude. The generalized AVR system is comprised of four basic units; i.e. Amplifier, Exciter, Generator and Sensor as shown in Figure 2. The system operating conditions and targeted set points are defined and are continuously monitored. Any abnormality in the system resulting in an error is amplified and forwarded to the controller. The controller can be of a conventional type like PID or an intelligent controller such as a fuzzy logic controller. The amplifier unit is responsible to strengthen the signal level without compromising on the shape of the signal [12]. The excitation can be achieved through solid state rectifiers (e.g. SCR or Thyristors). The rectifier's output is a nonlinear function of the field voltage due to magnetization created by overloaded saturation effects.

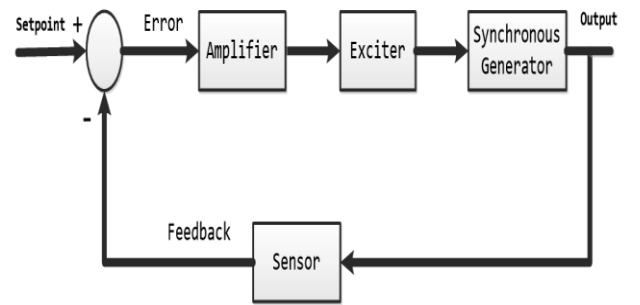


Figure 2: Generalized AVR System Model

For control system design, the saturation and nonlinearity effects of the system are usually ignored in the initial stages of the process and a linearized model is used. The e.m.f produced by the synchronous generator is closely related to the machine magnetization curve [13]. The terminal voltage of generator depends on the generator load. The voltage signal sensed by potential transformer is finally rectified into DC form.

3. SYSTEM MODELING

3.1 The state space representation model

The relationship between state variables of the system is typically non-linear; but for computational convenience a linearized state space model is used in the initial stages of design. The linearized mathematical model of system is given in equation (1). The detailed derivations of the model and system equations are given in [14, 15].

$$\begin{bmatrix} \Delta \dot{\omega}_r \\ \Delta \dot{\psi}_{fd} \\ \Delta \dot{v} \end{bmatrix} = \begin{bmatrix} -\frac{R_a}{L_a} & \frac{1}{L_a} & 0 \\ \frac{1}{L_{fd}} & -\frac{R_{fd}}{L_{fd}} & 0 \\ 0 & 0 & -\frac{1}{T_D} \end{bmatrix} \begin{bmatrix} \Delta \omega_r \\ \Delta \psi_{fd} \\ \Delta v \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} & 0 & 0 \\ 0 & \frac{1}{L_{fd}} & 0 \\ 0 & 0 & \frac{1}{T_D} \end{bmatrix} \begin{bmatrix} \Delta E_{fd} \\ \Delta E_{fd} \\ \Delta E_{fd} \end{bmatrix} \quad (1)$$

Where Δ is the change from nominal values, ω_r is the angular velocity of the rotor, ψ_{fd} is the magnetic field constant, K_D is the damping coefficient, v is the generator excitation voltage, L_{fd} is the field inductance, R_{fd} is the

field resistance, ω_0 is the initial rotor speed and T_m is the mechanical torque.

3.2 PID CONTROLLED AVR SYSTEM MODEL

A controller is the most important part of any system model, as it not only maintains the operating characteristics of the system but also effectively regulates, modifies and influences the process by remedying the abnormalities within defined limits. The simplest and most widely used conventional controller is the PID controller. The generalized transfer function of a PID controller [16] is given by

$$G_c(s) = K_p + \frac{K_I}{s} + K_D s \quad (2)$$

Where K_p is the proportional gain factor, K_I is the integral gain factor, K_D is the derivative gain factor, and s is the Laplace operator. The values of K_p , K_I and K_D can be tuned through system optimization.

3.2.1 PID Simulation Model

As discussed earlier, an AVR system is used to regulate the reactive power and voltage magnitude which results in system stability in form of response errors. To eliminate the response error, the PID controller is added in the forward path of the AVR system to improve the dynamic response and minimize the error. A Simulink model from equation (1) is developed to demonstrate the potential of the idea. Figure 3 shows the designed Simulink model of PID controller to demonstrate the system response and error of the AVR. The basic units of AVR system i.e. amplifier, exciter and generator units are integrated in the Synchronous Generator Model. A Hall Effect sensor is used to measure the voltage and provides a feedback path back to the controller. It offers the exceptional linearity and accuracy, improved thermal drift and high tolerance to the external interference [17]. Using the characteristics of the synchronous generator, a set point is defined and the PID controlled system output response and system error are investigated by considering two scenarios. Initially it is assumed that the effect of noise is negligible, while in the second scenario, noise has been added.

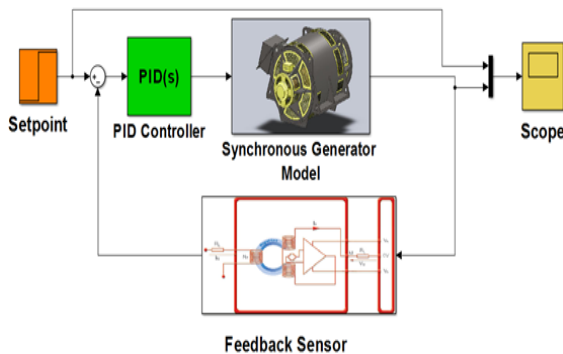


Figure 3: Synchronous Generator Model with PID Compensation

Figure 4 shows the output response of the PID controlled AVR system when noise effect is not considered. Although the overshoots produced by the PID controller during transients are very high but the response of the system after the transients is acceptable.

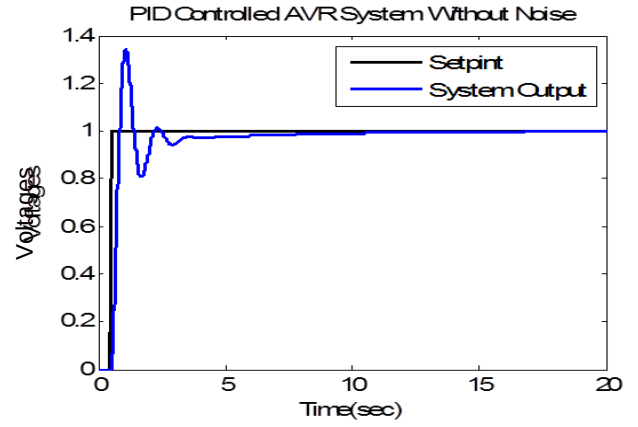


Figure 4: Response of PID Controlled System without Noise

Figure 5 shows the error of the system without noise. It is evident from the figure that once the transients are over; the error converges to zero within acceptable time limits. However, in these simulation results (Figure 4 and Figure 5), the noise added by the feedback sensor is not considered. It is a well-known fact that the derivative component of the PID controller is vulnerable to noise. Therefore from practical aspects, the sensor noise is added in simulation model and simulation results are shown in Figure 6 and Figure 7 respectively.

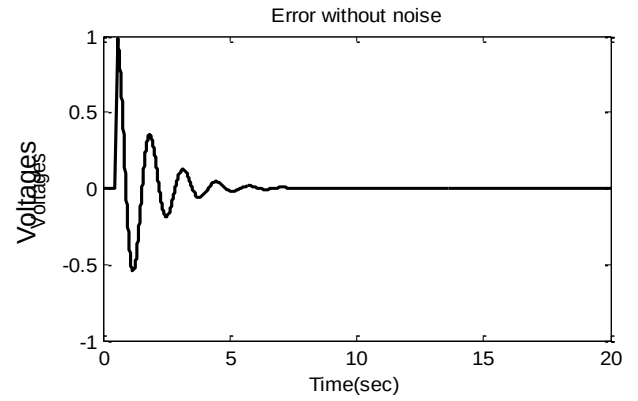


Figure 5: System Error without Sensor Noise

In Figure 6, the output of the PID controlled AVR system does not settle due to the presence of noise. The high frequency voltages fluctuations are induced in the output of the synchronous generator which cannot be removed completely using PID controller alone. Figure 7 shows the overall behaviour of the system error.

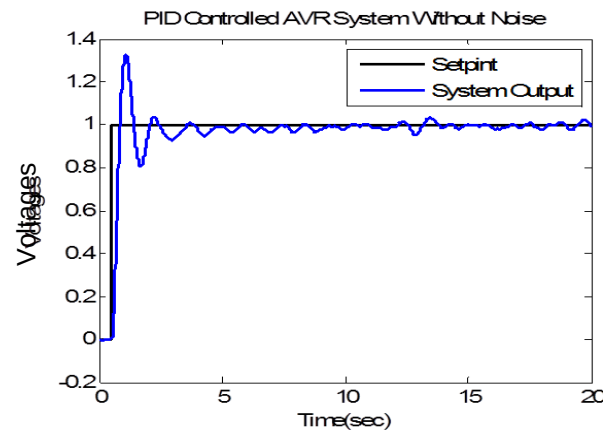


Figure 6: Output of PID Controlled AVR System with Sensor Noise

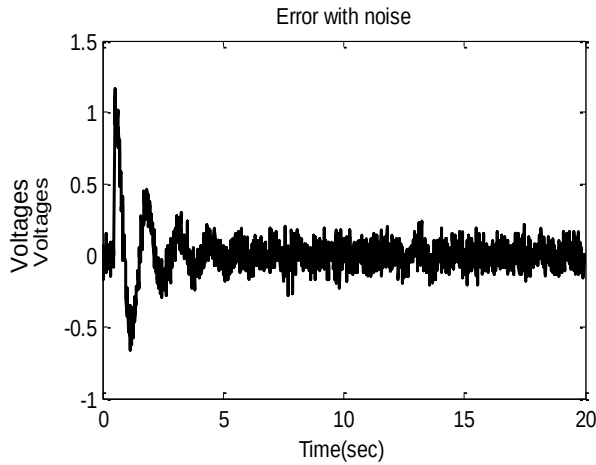


Figure 7: PID Controlled AVR System Error with Sensor Noise

During the steady state, the error is not able to converge to zero but it is continuously swinging around zero. These high frequency voltage fluctuations due to non-zero error state are harmful for electronic devices and may reduce the reliability of the system. It is therefore obligatory to have a regulated system output under varying load conditions. The limitations of PID controller are well proved in the above simulation results, so the need of an alternative and effective approach is evident.

4. FUZZY LOGIC CONTROLLED AVR SYSTEM

In this work, a fuzzy logic controller is designed to compensate for the limitations of the PID controller when it is operated in a noisy environment. The fuzzy logic controller is well known for its simplicity and effectiveness and this is why more research is being carried out specifically in industry aspects of fuzzy logic control [18, 19]. The designed Simulink model of fuzzy logic controlled AVR system is shown in Figure 8. In this work, for design of Fuzzy Inference System, we have used Memdani model [20] which is more suitable for non-linear application. The membership functions of Inputs and Output are shown in figure 9, 10 and 11 respectively. The inputs of the designed fuzzy controller are error and error rate, and the output of the controller is calculated using the centre of gravity method. This method is the most widely used defuzzification method [21].

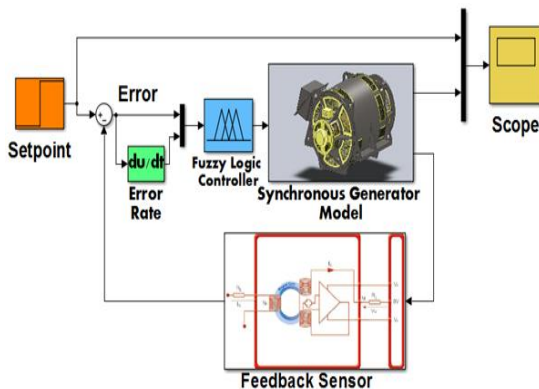


Figure 8: Simulation Model of Fuzzy Logic Controlled AVR System

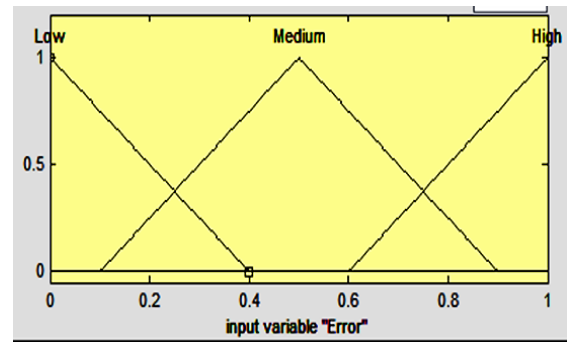


Figure 9: Membership Function of Error Input

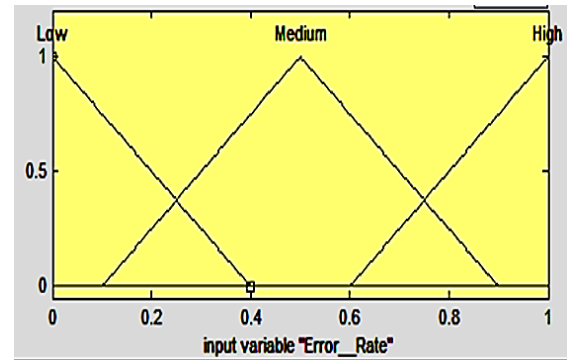


Figure 10: Input Membership Function of Error Rate

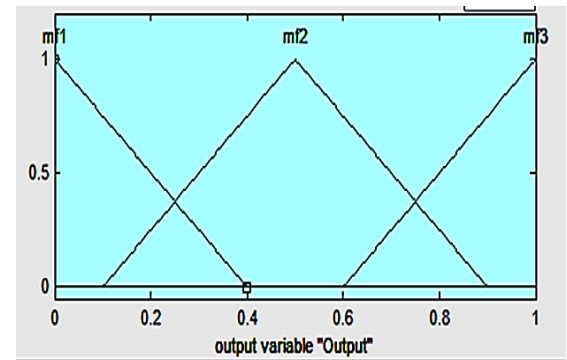


Figure 11: Output Membership Function

Figure 12 shows the surface plot of fuzzy logic rules with respect to error and error rate. When error and error rate are low, the output of the fuzzy logic controller is also low. When either of inputs is high, the fuzzy logic controller reacts accordingly to prevent the system error to exceed the bounded limits.

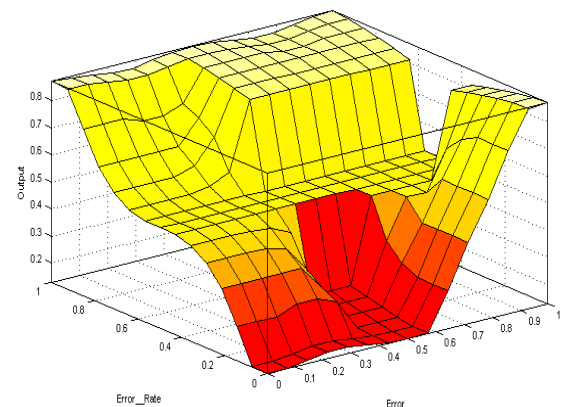


Figure 12: Surface Plot of Fuzzy Logic Rules

Figure 13 and Figure 14 show the system response of the fuzzy controlled AVR system and error without noise. The only difference between the fuzzy logic controlled AVR system and the PID controlled AVR system without noise is transient behavior. The response of fuzzy logic controlled AVR system varies smoothly until the steady state is achieved. On the contrary, the transient behavior of PID controlled AVR was observed as damped oscillations until the steady state is accomplished. The smooth variation in the output of the fuzzy logic controlled AVR system produces a smooth decay of error, as shown in Figure 14.

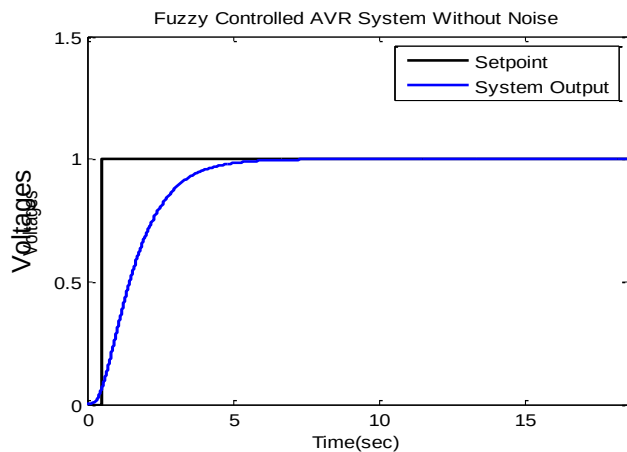


Figure 13: Response of Fuzzy Logic Controlled AVR System without Noise

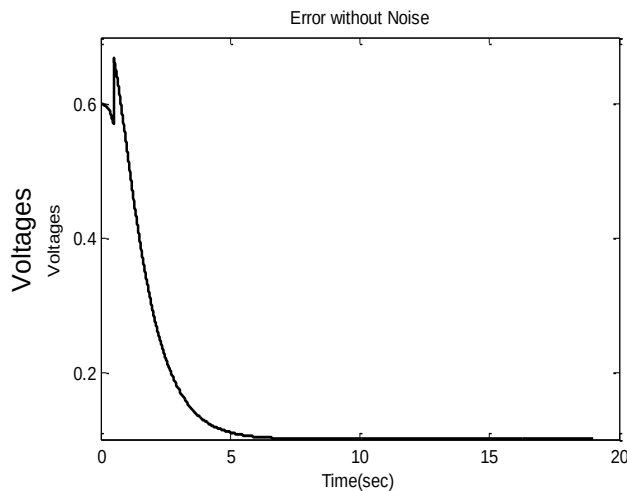


Figure 14: Error Response of Fuzzy Logic Controlled AVR System without Noise

When noise is added to fuzzy logic controller, the system response with noise and the corresponding system error are shown in Figure 15 and Figure 16 respectively. It is evident from both figures that the system response and error of the fuzzy controlled AVR system stabilizes much earlier compared to PID controlled AVR system, even in the presence of noise.

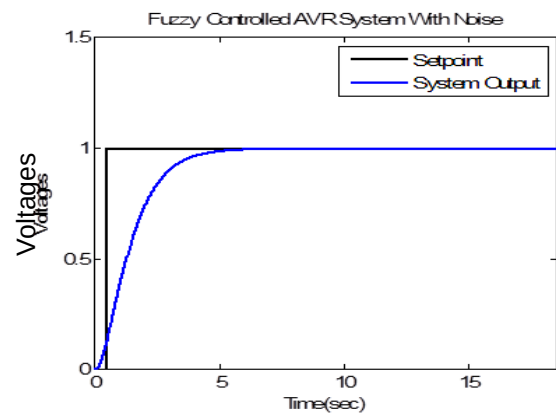


Figure 15: Response of Fuzzy Logic Controlled AVR System with Noise

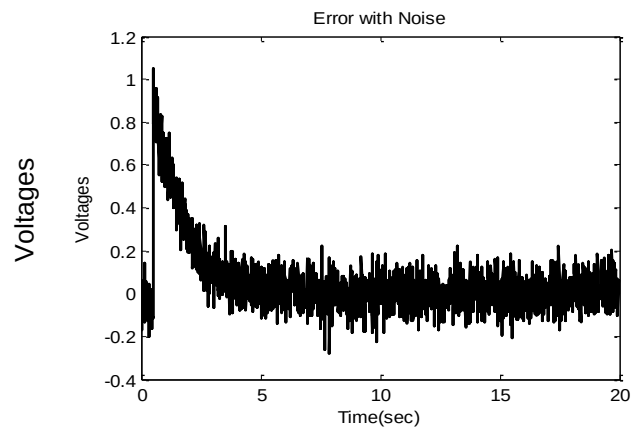


Figure 16: Error Response of Fuzzy Logic Controlled AVR System with Noise

The overall system response and error of the fuzzy controlled and PID controlled AVR systems are summarized in Figure 17 and Figure 18.

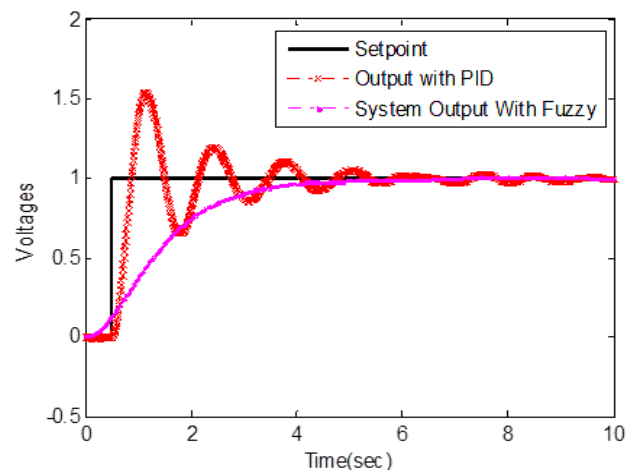


Figure 17: System Response Comparison of Fuzzy Logic and PID Controlled AVR System

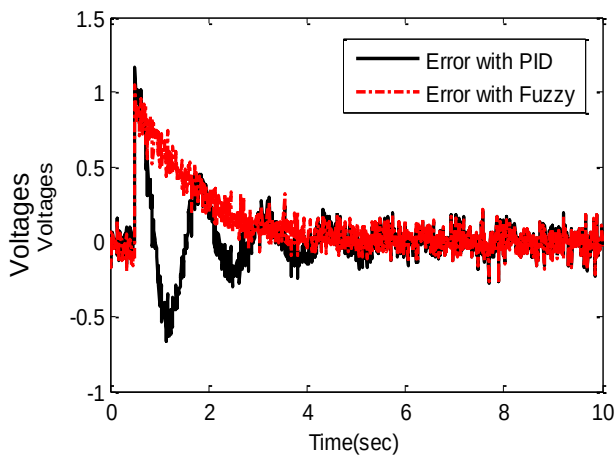


Figure 18: Error Response Comparison of Fuzzy Logic and PID Controlled AVR System

The simulation results confirm the suitability of the fuzzy logic approach to be used in a noisy environment. Even with the added noise, the response of fuzzy controlled AVR system is robust and quickly adjusts the system response. Hence, the system error converges to zero within acceptable time span. Thus, it is evident from the simulation results that the fuzzy logic controlled AVR system outperforms the PID controlled AVR system for these simulated test conditions.

5. CONCLUSION

Automatic voltage regulators with PID controllers do not perform well under varying load conditions. The noise added by system components further degrades the performance of PID controlled AVR systems. In order to solve this problem low pass filters can be used to filter the noise but that will require extra circuitry in the system which in turn will increase the cost and complexity of the system. Even after adding the extra circuits, the performance of the system is not guaranteed. Therefore, in this paper an alternative approach is proposed to solve this issue without adding extra signal conditioning components. The efficacy of the proposed solution is evident from the simulation results presented in this paper. Further work is planned to simulate the behaviour of fuzzy logic controllers under varying load conditions.

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REFERENCES

- [1] Halepoto, I.A., Uqaili, M.A., and Chowdhry, B.S., "Least Square Regression Based Integrated Multi-Parametric Demand Modeling for Short Term Load Forecasting", *Mehran University Research Journal of Engineering & Technology*, Jamshoro, Pakistan, Volume. 33, No. 2, pp. 215-226, 2014.
- [2] Soares, F., Almeida, P.R., and Lopes, J.A.P., "Advanced Models and Simulation Tools to Address Electric Vehicle Power System Integration (Steady-State and Dynamic Behavior)", Springer book chapter in *Electric Vehicle Integration into Modern Power Networks*, pp. 155-202, 2013.
- [3] Hashmani, A.A., Uqaili, M.A. and Memon, R.A., "Delayed-Input Wide Area Power System Stabilizer for Mode Selective Damping of Electromechanical Oscillations", *Mehran University Research Journal of Engineering & Technology*, Jamshoro, Pakistan, Volume. 30, No. 2, pp. 289-296, 2011.
- [4] Soundarrajan, A., Sumathi, S., and Sivamurugan, G., "Voltage and frequency control in power generating system using hybrid evolutionary algorithms", *Journal of Vibration and Control*, Volume 18, No. 2, pp. 214-227, 2012.
- [5] Soundarrajan, A. and Sumathi, S., "Fuzzy-based intelligent controller for power generating systems. *Journal of Vibration and Control*, Volume. 17, No. 8, pp. 1265-1278, 2011.
- [6] Wong, C.C., Li, S.A., and Wang, H.Y., "Optimal PID controller design for AVR system", *Tamkang Journal of Science and Engineering*, Volume. 12, No. 3, pp. 259-270, 2009.
- [7] Kahouli, A., Guesmi, T., Hadj Abdallah, H., Ouali, A., "A genetic algorithm PSS and AVR controller for electrical power system stability, 6th IEEE International Multi-Conference on Systems, Signals and Devices (SSD'09), pp. 1-6, 2009.
- [8] Iruthayarajan, M.W. and Baskar, S., "Evolutionary algorithms based design of multivariable PID controller, *Expert systems with Applications*, Volume. 36, No. 5, pp. 9159-9167, 2009.
- [9] Gaing, Z.L., "A particle swarm optimization approach for optimum design of PID controller in AVR system", *IEEE Transactions on Energy Conversion*, Volume. 19, No. 2, pp. 384-391, 2004.
- [10] Kim, D.H., "Hybrid GA-BF based intelligent PID controller tuning for AVR system", *Applied soft computing*, Volume. 11, No. 1, pp. 11-22, 2011.
- [11] Galaz, M., Ortega, R., Bazanella, A.S., Stankovic, A.M., "An energy-shaping approach to the design of excitation control of synchronous generators. *Automatica*, Volume. 39, No. 1, pp. 111-119, 2003.
- [12] Halepoto, I.A., Kumar, W., Memon, T.D., Ismaili, I.A., "Quantifying the effect of Look up Table Size and Coefficients Complexity for Non-Linearity Compensation in Power Amplifiers", *Sindh University Research Journal (Science Series)* Volume. 45, No. 2 pp. 447-452, 2013.
- [13] Hallenius, K.E., Vas, P., and Brown, J., "The analysis of a saturated self-excited asynchronous

generator", IEEE Transactions on Energy Conversion, Volume 6, No. 2, pp. 336-345, 1991.

- [14] Ramya, R. and Selvi, K., " Simulation of Synchronous Generator with Fuzzy based Automatic Voltage Regulator", International Journal of Electrical & Computer Engineering, Volume.2, No. 6, pp. 2088-8708, 2012.
- [15] Demiroren, A. and Zeynelgil,H., " Modelling and simulation of synchronous machine transient analysis using SIMULINK", International Journal of Electrical Engineering Education, Volume 39, No. 4, pp. 337-346, 2002.
- [16] Schei, T.S., "Automatic tuning of PID controllers based on transfer function estimation", Automatica, Volume. 30, No. 12, pp. 1983-1989, 1994.
- [17] Ramsden, E., " Hall-effect sensors: theory and application", Newnes Publishers, latest edition, ISBN: 13-978- 7506-7934-3, 2011.
- [18] Hussain I, Patoli, A.A., Kazi, K., "Fuzzy Logic Based Effective Anti-Lock Braking System Adaptive to Road Conditions", 1st international conference on modern communication and Computing Technologies (MCCT'14), 2014.
- [19] Hashmi, K., Graham, I., Mills, B., "Fuzzy logic based data selection for the drilling process", Journal of Materials Processing Technology, Volume. 108, No. 1, pp. 55-61, 2000.
- [20] Mamdani, E.H., "Application of fuzzy logic to approximate reasoning using linguistic synthesis", IEEE Transactions on Computers, Volume. 100, No. 12, pp. 1182-1191, 1977.
- [21] Hussain, I., Mei, T., Ritchings, R., " Estimation of wheel–rail contact conditions and adhesion using the multiple model approach", Vehicle System Dynamics, Volume. 51, No.1, pp. 32-53, 2013.

Quotations

- God gave burdens, also shoulders.
Yiddish Proverb
- Going slowly does not stop one from arriving.
West African saying
- A man's deeds are his life.
West African saying
- Your food is close to your stomach, but you must put it in your mouth first..
West African saying
- Don't call a man honest just because he never had the chance to steal.
Yiddish saying
- A journey of thousand miles begins with a single step.
Chinese Proverb
- The thoughtless strong man is the chief among lazy men.
West African Saying
- If it isn't perfect, make it better.
Japanese manufacturing slogan
- Modern is a tree with roots of contentment, and fruits of tranquility and peace.
North African saying
- Nothing is achieved in a dream.
West African saying
- You cannot prevent the birds of sorrow from flying over your head, but you can prevent them from building nests in your hair.
Persian Proverb
- He who hates, hates himself.
South African saying
- The man who is not jealous in love does not love.
North African saying
- The opinion of the intelligent is better than the certainty of the ignorant.
North African saying
- Not to know is bad; not to wish to know is worse.
West African saying
- It's nice to be important, but it's more important to be nice.
West African saying