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Improve the performance of automatic voltage regulator for power system using self-tuning fuzzy-PID controller

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ABSTRACT

The optimal design of the automatic voltage regulators for a synchronous machine are positively reflected on the quality of voltage stability. This paper is concerned with the design of an AVR by adopting three control techniques. The first one was designed according to the traditional proportional integration-derived (PID) controller while the fuzzy logic was adopted in design the second powerful controller, finally the fuzzy PID controller for an automatic voltage regulator (AVR) based on fuzzy logic technology, self-tuning fuzzy proportional integration-derived (STFPID) have been designed to tuning the gains of the PID controller (KP, KI and KD). To confirm the efficiency of the proposed control systems, a simulation was carried out, and the results showed that the designed STFPID controller achieves the best performance of the AVR system, and gives the preferable tracking low rise time, lower overshoot, least stetting time, minimal steady state error, and gives the ideal response against PID and fuzzy logic technology.

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1. INTRODUCTION

In general, control techniques seek to gaudiness the system to achieve the desired dynamic response with the basic requirements of feedback system. Most power plant specialists seek to ensure that the synchronous generator's terminal voltages match the predetermined voltages. The synchronous generator voltage is maintained through the generator excitation control. Proportional integration-derived (PID) control systems are the most common for this field [1].

Due to the nonlinear properties and time-varying dynamics of the synchronous generator, conventional controllers cannot guarantee step response throughout the generation range, so conventional control techniques such as Ziegler Nichols PID (ZN-PID), phase margin gain PID (PMG-PID) and the Cohen coon PID (CC-PID) may fail in reaching to optimal parameters for PID controller [2], [3]. To avoid the drawbacks of tuning the parameters of the PID by traditional algorithms, there was a need to rely on metaheuristic tuning algorithms, such as genetic algorithm PID (GA-PID) [4], [5], particle-swarm optimization PID (PSO-PID) [6], ant colony optimization PID (ACO-PID) [4] PID Tuner [7], cuckoo search optimization PID (CSO-PID) algorithm [8], moth fame optimization (MFO) algorithm [9], water cycle optimization PID (WCO-PID) algorithm [10], teaching-learning-based optimization (TLBO-PID) [11], [12]. Hill climbing optimization PID (HCO-PID) algorithm [13] bacteria-foraging optimization PID (BFO-PID) [14].

In spite of metaheuristic tuning techniques have contributed to reducing systems overshoot and steady state error as well as delays in both rise and stabilization time. However, the need for further improvement to reach the optimal values embodied the motivation for this research. The remnant of this paper is organized as follows: Section 2 demonstrate the AVR system with enhanced by an explanatory diagram and the used values. Section 3 derivation of the mathematical model for AVR. Section four offers control methodology that adopted with implementation and simulation of self-tuning fuzzy proportional integration-derived (STFPID) controller. Finally results, discussion and conclusion are reviewed in sections five and six respectively.

2. AUTOMATIC VOLTAGE REGULATOR (PROBLEM FORMULATION)

In generating stations, the continuous change in the load demand is negatively reflected on the generating units. The imbalance between real power generated and required are effects on the frequency of the synchronous generator while the imbalance between reactive power generated and required are effect on the output voltage of the generator. Electromechanical deviations affect the dynamic stability of the power system. All synchronous generators are fitted with an AVR-supervised excitation unit and a stabilizer power system stabilizer (PSS) to enhance their dynamic stability [15]. Figure 1 shows the schematic diagram of the AVR system with linear argument units during closed loop operation. The AVR regulates the terminal voltage by setting the excitation generator produced in the exciter coil.

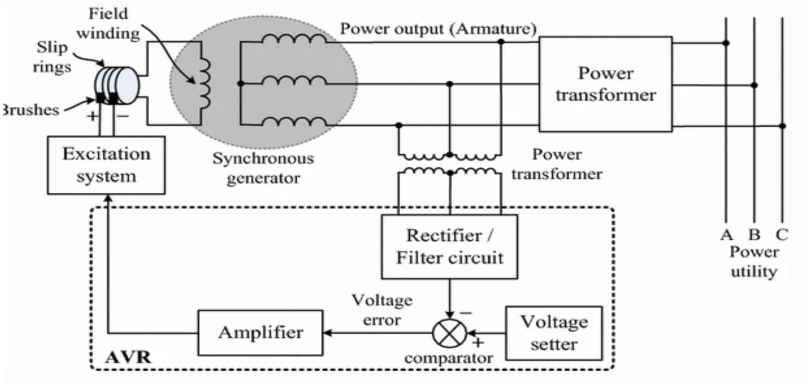


Figure 1. Schematic diagram of AVR system for synchronous generator [16]

AVR, is one of the effective control channels in power generation systems. It has ability to adjust the generated terminal voltage in transient cases by setting the exciter voltage of the synchronous generator [17]. The AVR system composed of several basic components such as an amplifier, an exciter, a generator, and a sensor. Figure 2 shows the over all block diagram for AVR system, the basic components of which are shown in Figure 2(a). Mathematically, transfer functions of each components as shown in Figure 2(b) may be represented as (1) [18], [19].

$$Transfer\ Function\ for\ amplifier = \frac{V_{ref(s)}}{V_{e(s)}} = \frac{K_A}{1+\tau_{A(S)}} \quad (1)$$

Where (K_A,V_{ref}(s),V_e and τ_A) represented the amplifier gain, reference voltage, error voltage and time constant in (s) domain respectively. The standard magnitude of K_A is (10-400) and for τ_A (0.02-0.1) second for an exciter, the transfer function could be represented as:

$$\frac{V_{f(s)}}{V_{ref(s)}} = \frac{K_E}{1+\tau_{E(S)}} \quad (2)$$

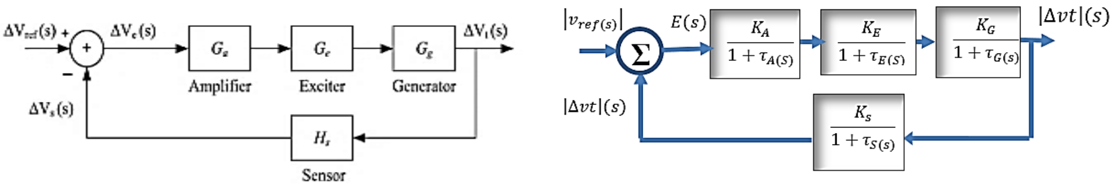
where K_E & $\tau_{E\ (s)}$ represent both the exciter gain and the time constant in the S-field. Standard values for K_E are (10-400) and the time constant is about (0.5-1) second. And the same in the case with the transfer function of the generator, which shows the effect of the field voltage on the output voltage of the generator, according to the (3).

$$\frac{V_{T(s)}}{V_{ref(s)}} = \frac{K_G}{1+\tau_{G(s)}} \quad (3)$$

The rang of (K_G , $\tau_{G(S)}$) from full load to no load could approximate (0.7 to 1.0) & (1.0 to 2.0) second at last, first-order transfer function may be adopted in modelling the sensor.

$$\frac{V_{s(s)}}{V_{t(s)}} = \frac{K_S}{1+\tau_{S(s)}} \tag{4}$$

where $\tau_{S(s)}$ between 0.001 and 0.06 s.



(a) (b)

Figure 2. Block-diagram of AVR (a) basic components and (b) transfer function for each component

3. CONTROL METHOD ADOPTED FOR AVR

For the optimal design of automatic voltage regulators for synchronous machines, the mathematical model represents the initial requirement. Three control techniques were used in the current paper. The first is according to the traditional PID controller while fuzzy logic is adopted in the design of the second powerful controller, and finally the AVR's PID fuzzy controller based on fuzzy logic technology, (STFPID) is designed to adjust the gain of the PID controller (KP, KI and KD). With the help of MATLAB, the mechanisms for design and simulation are clarified for each one in the time domain.

3.1. Traditional PID controller

The PID controller comprise three terms control as shown in Figure 3, proportional, integral and derivative terms, with standard coding (P, I, D). (P), depends on error at the current time, while (I): depends on the accumulative error of preceding time, finally (D): is predication of further errors according to the rate change of error. The weighted sum of these control terms has been used to adjust the process variable. By tuning the three constants (K_P, K_I, K_D), PID controller can insurance control action desired for particular process requirement. Control signal of traditional PID, u(t) is represented by the (5) [20].

$$u(t) = K_p e(t) + K_I \int_0^t e(t)d(t) + K_D \frac{de(t)}{d(t)} \tag{5}$$

Where, *u(t)* is controller output, *e(t)* is error i.e., the difference of the actual terminal voltages from the reference value while (K_P), (K_I) and (K_D) are the gain for proportional, integral and differential term control. Laplace transform of (5) identifies transfer function of a PID controller.

$$\frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} + K_D s = \frac{K_D s^2 + K_P s + K_I}{s} \tag{6}$$

According to Simulink/MATLAB environment, the parameters of AVR is shown Table 1.

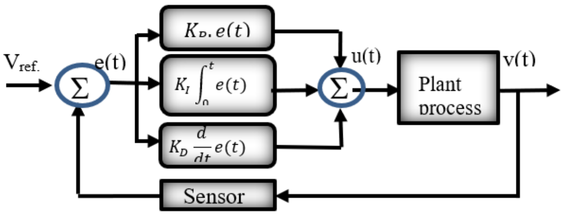


Figure 3. Block diagram of PID controller

Table 1. Parameters of AVR

Basic components	Gain	Time constant
Amplifier	K_A= 10	T_A=0.1
Exciter	K_E = 1	T_E = 0,4
Synchronous generator	K_G= 0.8	T_G = 1.4
Sensor	K_S = 1	T_S=0.05

Some MATLAB's tools such as design configuration and automated PID turning have been adopted to tune parameters of PID for AVR. The PID controller has been automatically adjusting the gain constants (K_I, K_P and K_D) to minimize the error. the desired goal was reached by applying the MATLAB "pidtune" function (PID turning algorithm) of the linear model and launched PID tuner. When the PID tuner is turned on, the gain constants that achieved the system's closed loop step response are (K_I=0.748, K_P=0.2983 and K_D=0.1524). Modelling for an AVR included PID controller based on Simulink/MATLAB environment are shown in Figure 4.

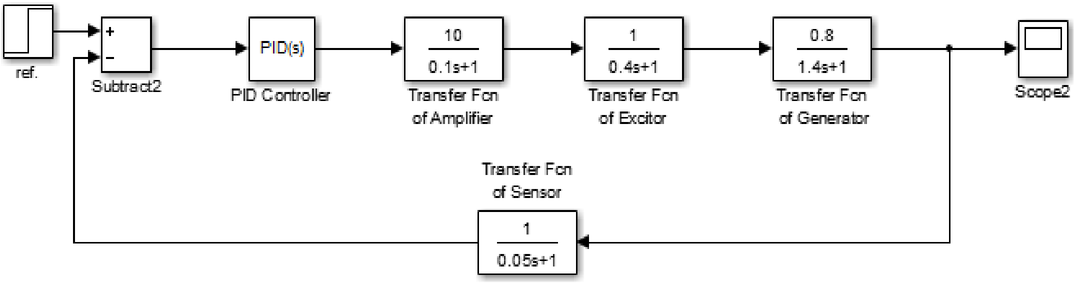


Figure 4. Modelling of AVR with PID controller using Simulink/MATLAB environment

3.2. Fuzzy logic controller

Fuzzy logic controller (FLC) is a technique that has ability to simulate human experience through some fuzzy rule-based system by varying linguistic control into automatic control algorithm. Since syn. generators are represented by a nonlinear mathematical model, FLC is very suitable because of its high ability to control systems without the need for a mathematical model for it [21]. The architecture of the FLC is illustrated in Figure 5.

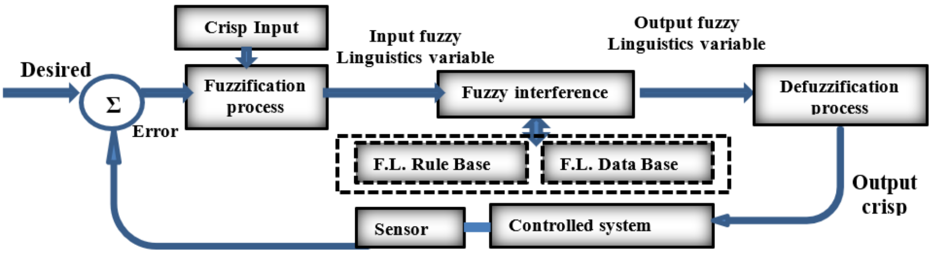


Figure 5. Architecture of the FLC

Figure 6 show the design FLC for AVR and simulation in MATLAB, the following steps are adopted [22]: i) Two fuzzy logic control inputs with seven membership function for each input (E and CE) and outputs are defined; ii) A rules have been created in the FIS Editor; iii) Gain values are adjusted for\inputs (G(E), G(CE)) and output, G(U), and iv) The amount of overlap between membership functions are adjusted.

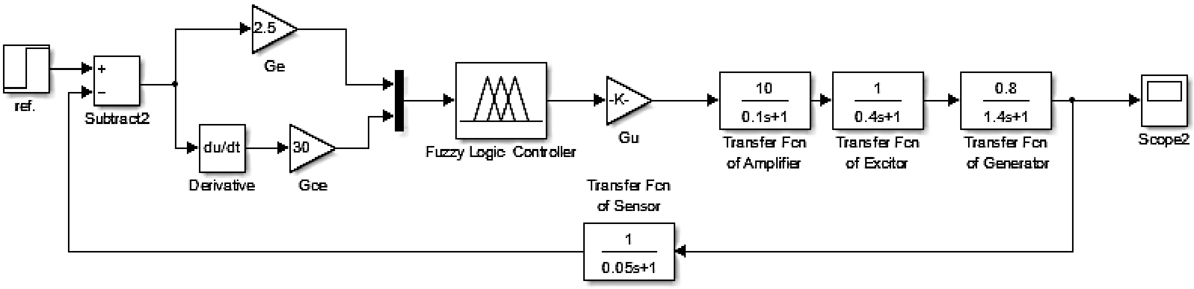
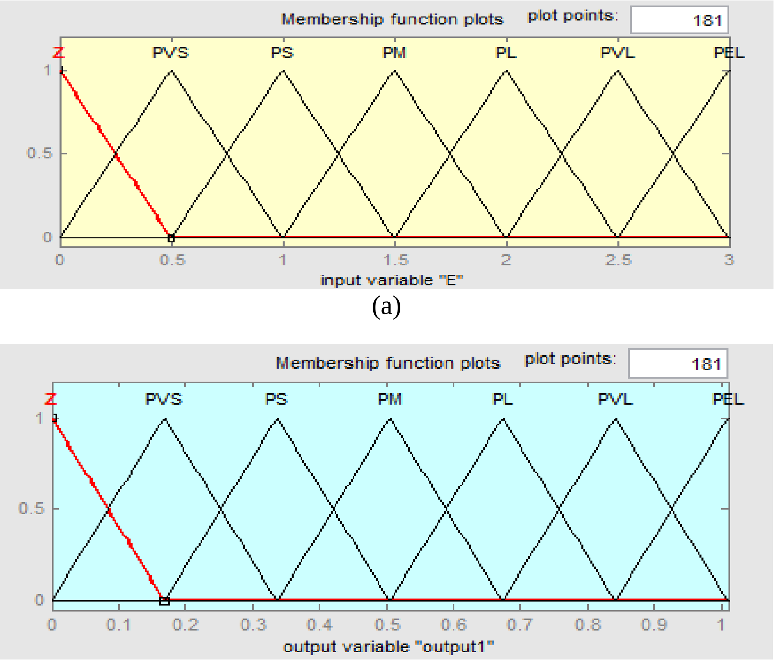


Figure 6. Simulation model of AVR together with FLC for generating unit

Fuzzification interface used for altering crisp input signals to suitable linguistic variables and assorting it into membership functions. In this paper the fuzzy input and output were represented by a trigonometric membership functions, Figure 7 show that membership function for [E, CE] as shown in Figure 7(a) and Figure 7(b) show membership function for [U], have been encoded by a linguistic variable such as zero (Z), positive very small (PVS), positive small (PS), positive medium (PM), positive large (PL), positive very large (PVL), positive extremely large (PEL) respectively [23].



(a)

(b)

Figure 7. Membership function (a) degree of the inputs (E, CE) and (b) degree of the output (U)

The decision-making logic is carried out by knowledge base that comprise of a data base and a rule base, the data base gives information for the suitable operation of FLC such as (I/P & O/P) MFs. the rule base is aggregate of linguistic phrases connecting the input signals to desired outputs, and then the rule base deduces the fuzzy output, the requisite function of the inference process is to define the magnitude of the controller output based on the sharing of each rule in the rule base. The parameters are handled by an inference engine that executes 49 rules (7×7) which applied for all parameters as shown in Table 2. Based on the inputs and outputs (E, CE, U) and a predefined set fuzzy logic rule, Figure 8 shows the 3D behavior of the fuzzy controller.

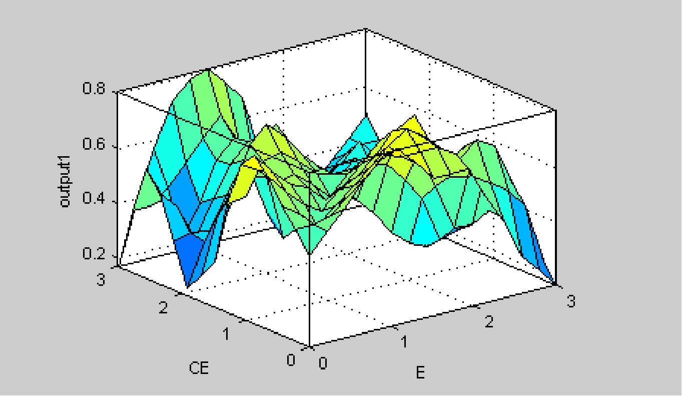


Figure 8. Dimensional behavior of FLC

Table 2. Fuzzy logic rules

		Change in error						
	U	Z	PVS	PS	PM	PL	PVL	PEL
Error	Z	PM	PL	PVL	PS	PVS	PL	PVS
	PVS	PL	PM	PL	PVL	PS	PVS	PL
	PS	PVL	PL	PM	PL	PVL	PL	PVL
	PM	PL	PVL	PL	PM	PS	PVS	PL
	PL	PL	PL	PVL	PS	PM	PS	PVS
	PVL	PS	PVL	PS	PVS	PS	PM	PS
	PEL	PVS	PS	PS	PS	PVS	PS	PM

3.3. Self tuning PID controller

Due to its straightforward with strong response, fuzzy PID controller is excessively applied in control of practical system, especially in the nonlinear system. The incorporation of PID control strategies and fuzzy logic concepts has been applied in many areas such as the control of induction motors [24]. STFPID controller has proven its effectiveness in dealing with nonlinear systems with improved dynamic performance. Itis utilized to achieve the optimal logical link between the parameters of the PID controller ($K_P K_I K_D$) based on speed and error.

Mainly, the construction of STFPID Controller includes of two divisions, the adaptable parameter PID and fuzzy logic control , as shown in Figure 9 [25]. The working principal of self-tuning fuzzy logic controller (STFLC) is summed up by reaching a logical fuzzy link between the parameters of the controller and two inputs (E and CE). Determining the error and the change of error during the operating cycle of the controller directly contributes to adjusting on line the controller’s gain.

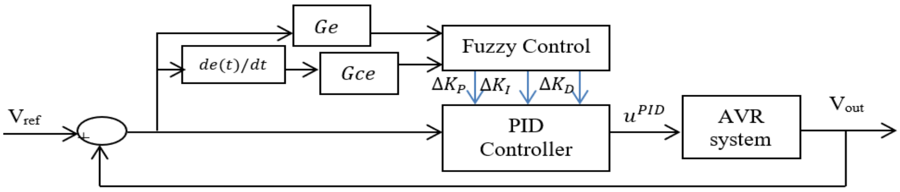


Figure 9. Architecture of STFLC

The STFPID transfer function that used in this work is:

$$u^{PID} = (K_P + \Delta K_P)e(t) + (K_I + \Delta K_I)\int_0^t e(t)dt + (K_D + \Delta K_D)\frac{de(t)}{d(t)} \quad (7)$$

structure of fuzzy PID controller with (E, CE) as inputs and ($K_P K_I K_D$) as outputs was implemented which achieved using Simulink/MATLAB as shown in Figure 10 [26]. From fuzzy logic toolbox of the membership function, editor trimf are chosen by a trigonometric membership function for two inputs (E, EC) as referred in Figure 7 and picked for outputs as Figure 11 shown.

Fuzzy rules are the gist of a fuzzy controller, its used to tune PID parameters in real time. The parameters are handled by an inference engine that executes 49 rules (7×7) which applied for each parameter as shown in Table 3. these rules are setup based on the knowledge of the generation unit behavior and the experience of control engineers. The proficiency in drafting of fuzzy rules are directly and effectively influence on the whole control system [27].

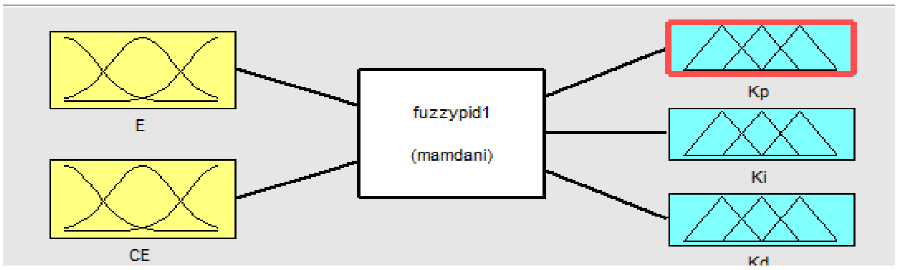


Figure 10. Fuzzy inference block

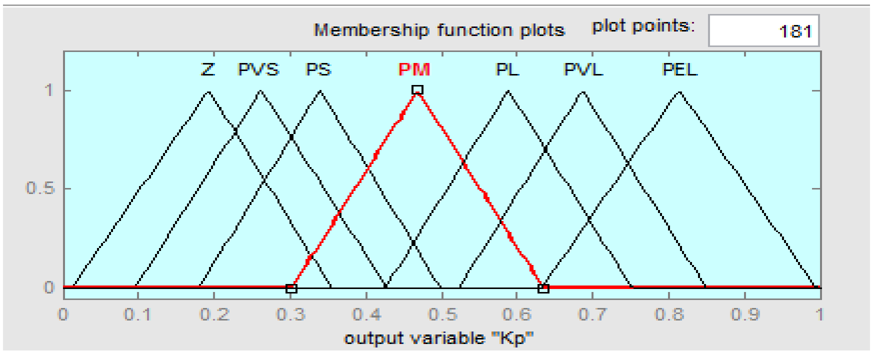
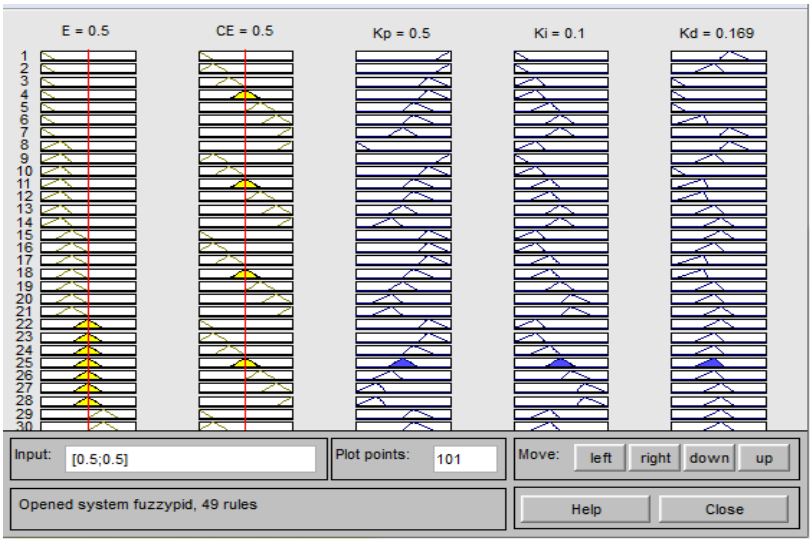


Figure 11. The membership degree function of $\triangle K_P$, $\triangle K_I$ and $\triangle K_D$

Table 3. STFPID controller rules

		Change in error						
	$\triangle K_P/\triangle K_I/\triangle K_D$	Z	PVS	PS	PM	PL	PVL	PEL
Error	Z	PEL/Z/PL	PEL/Z/PS	P PVL/ PVS/Z	P PVL/ PVS/Z	PL/PS/Z	PL/PM/PVS	PM/PM/PL
	PVS	Z/PVS/PL	PEL/Z/PS	PVL/PVS/Z	PL/PS/PVS	PL/PS/PVS	PM/PM/PS	PS/PM/PM
	PS	PVL/PVS/ PM	PVL/PVS/ PS	PVL/PS/ PVS	PL/PS/PVS	PM/PM/PS	PS/PL/PS	PS/PL/PM
	PM	PVL/PVS/ PM	PVL/PVS/ PS	PL/PS/PS	PM/PM/PS	PS/PL/PS	PVS/PVL/PM	PVS/PVL/PM
	PL	PL/PS/PM	PL/PS/PM	PM/PM/PM	PS/PL/PM	PS/PL/PM	PVS/PVL/PM	PVS/PEL/PM
	PVL	PL/PM/PEL	PM/PM/PL	PS/PL/PL	PVS/PL/PL	PVS/PVL/PL	PVS/PVL/PL	Z/PEL/PEL
	PEL	PM/PM/ PEL	PM/PM/ PVL	PVS/PL/ PVL	PVS/PVL/ PVL	PVS/PVL/PL	Z/PEL/PL	Z/PEL/PEL

Since error and changing rate of error were occur during different fuzzy intervals, then the controller variables $\triangle K_P$ $\triangle K_I$ and $\triangle K_D$ take different fuzzy intervals also. The rule viewer lists the parameters of fuzzy PID controller in Figure 12, Including 49 rules are defined. Based on the grade of membership, fuzzy sets, rule sets and all controls parameters have been calculated, Mamdani-type inference system STFPID is developed sophisticated with the "fuzzy" simulation toolbox of MATLAB. Implementation and Simulation of STFPID Controller for an AVR, An STFPID Controller was implemented to test their ability to tune an AVR. Referring to Figure 10 and according to Simulink/MATLAB environment, Figure 13 illustrate block diagram of an AVR with STPID controller. Figures 14-15 show precise details about the special package of fuzzy PID control and fuzzy controller modules.



Input: [0.5;0.5]

Plot points: 101

Opened system fuzzypid, 49 rules

Figure 12. The rule viewer for STFPID controller

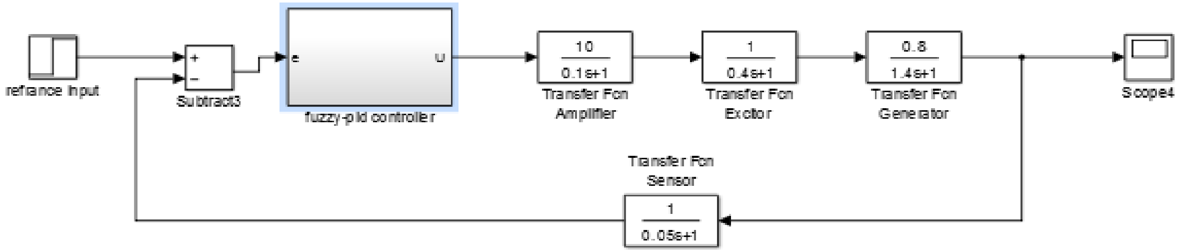


Figure 13. Complete Simulink/MATLAB block for STFPID controller for AVR

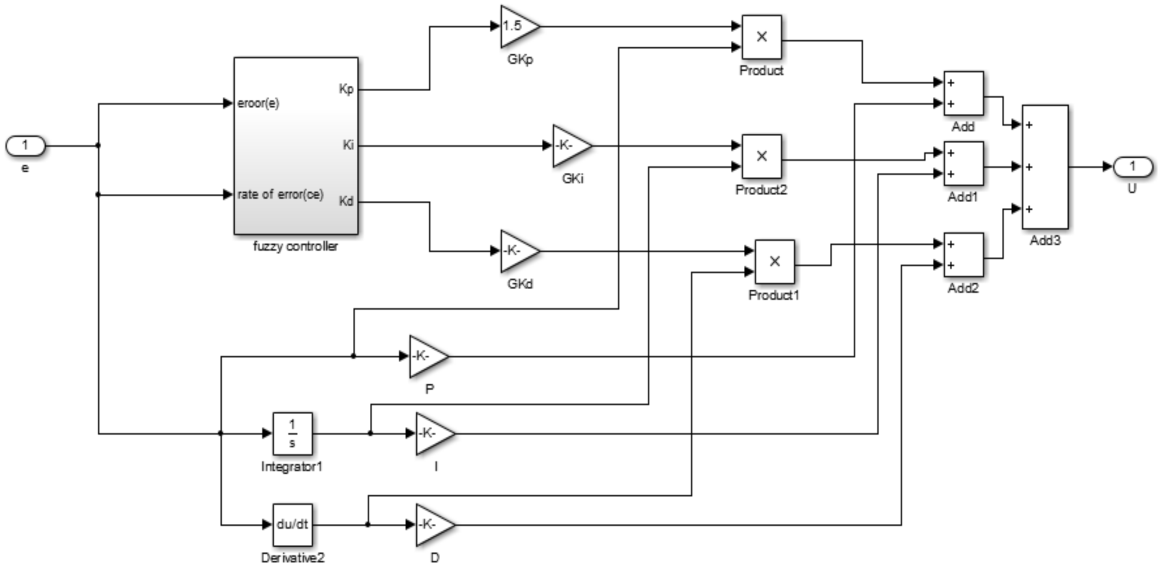


Figure 14. Fuzzy PID control module

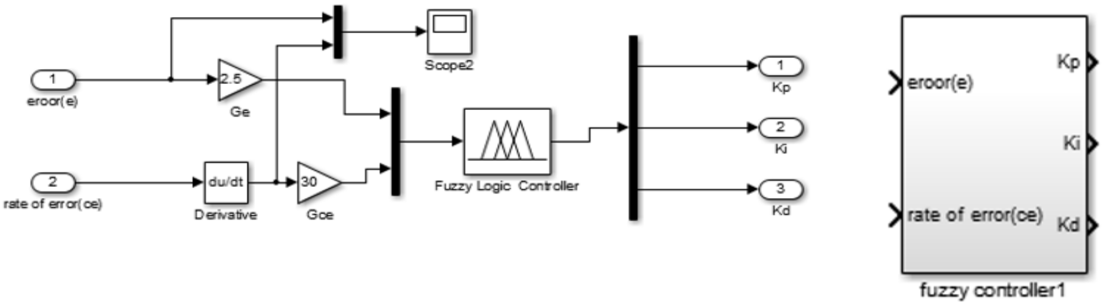


Figure15. Fuzzy controller and its package

4. RESULTS AND DISCUSSION

The simulation results of the voltage step response and error in closed loop of an AVR are shown in Figures 16-19. Figure 18 display the transient response comparison of the closed loop with all controllers for the AVR system represented by different colors. It shows that fuzzy logic PID controller produce good settling time with small overshoot and small steady state error. Table 4 illustrated grade of time response for an AVR without and with three type controllers. From the comparison Table 4, we conclude that STPID controller is the most effective in ensuring that the system returns to steady state in a shorter time. From the comparison table, we conclude that STPID controller is the most effective in ensuring that the system returns to steady state in a shorter time. Also, the MATLAB environment provides flexibility in simulating the system and smoothness in dealing with control rules.

Table 4. Comparison of dynamic responses of PID, FLC and STPID controllers

An AVR System	Max. overshoot	Rise time 0%-100%	Settling time 5%	Steady state (error estimation)	System response
Without controller	0.407	0.8 sec.	Not arrive	0.21	Unstable
With fuzzy controller	0.01	5.1 sec.	4.7 sec.	0.01	Stable
With PID controller	0.19	1.23 sec.	3.2 sec.	0.0002	stable
With fuzzy PID controller	0.125	0.7 sec.	2.4 sec	0.00018	stable

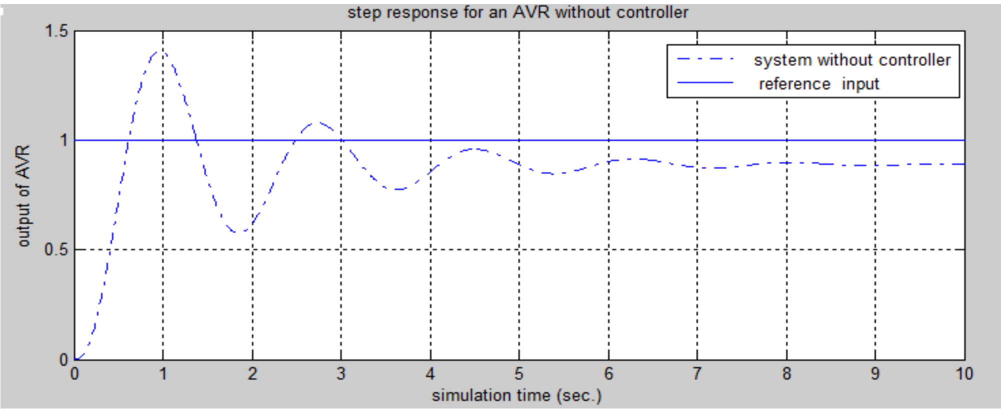


Figure 16. Voltage step response for an AVR without controller

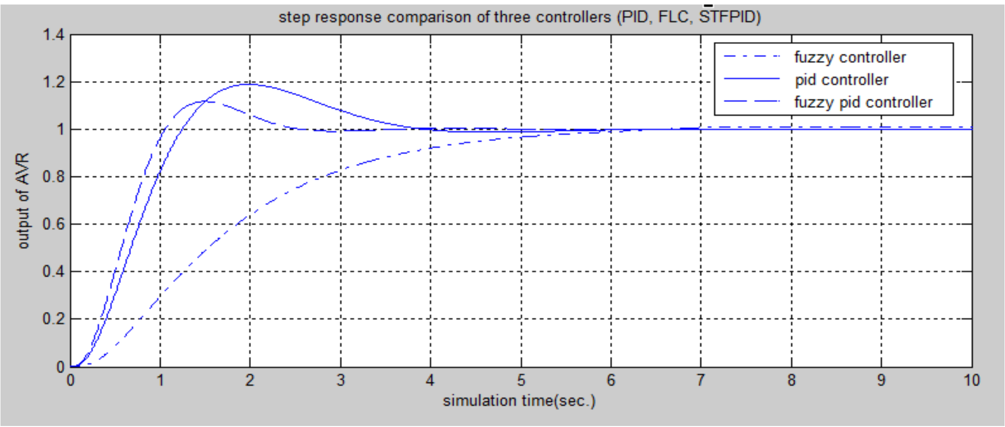


Figure 17. Shows the transient response comparison of three controllers (PID, FLC, STFPID)

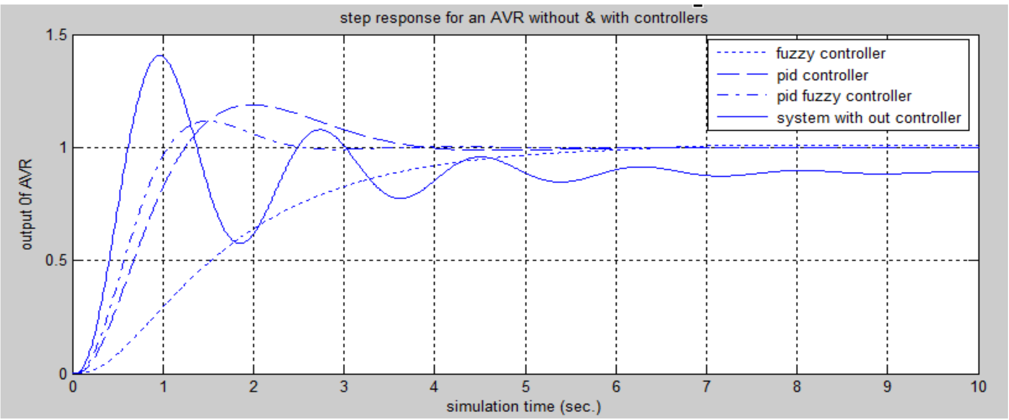


Figure 18. Voltage step response for an AVR without & with controllers

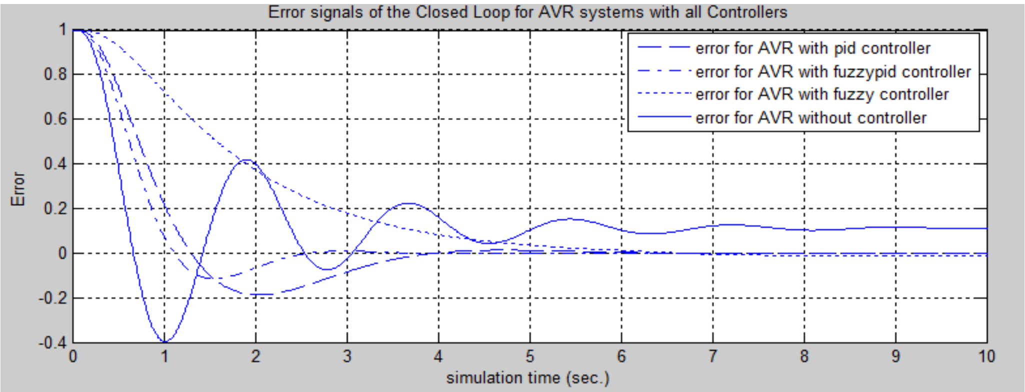


Figure 19. Error signals of the closed loop for AVR systems with all controllers

5. CONCLUSION

The present paper proposed to design an AVR through adopted three control techniques, (PID-fuzzy logic-self tuning of PID) controller. The analysis of simulation results showed that STFPID controller achieves best performance in both transient and steady state response of an AVR. The self-tuning fuzzy PID has superior dynamic response curve, depressed in response time, overshoot, peak amplitude, settling time and steady state error (SSE). Also, better steady precision compared to the conventional PID controller and fuzzy controller.

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