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FUZZY LOGIC BASED AUTOMATIC VOLTAGE REGULATOR FOR DAMPING POWER OSCILLATIONS

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ABSTRACT
This paper proposes a novel fuzzy logic based automatic voltage regulator. The proposed controller has one control loop, i.e. the voltage control loop, which function as automatic voltage regulating unit of synchronous machine. The input signals for voltage control are error of terminal voltage and its derivative. Comparison studies have been performed to see the performance of the proposed controller with the conventional automatic voltage regulator and conventional automatic voltage regulator along with power system stabilizer.

KEY WORDS
AVR, excitation control, fuzzy logic controller, power system oscillation, and power system stabilizer

1. Introduction

Low frequency oscillations in power system, in the range of 0.2 to 2.5 Hz could lead to instability and widespread blackout. Oscillations occur when the rotors of machines, behave as rigid bodies, oscillate with respect to one another using the electrical transmission path between them to exchange energy. There are many different modes in which such oscillations may occur, often simultaneously [1]. These modes can be differentiated by looking at the frequency of oscillation and the participation of various machines in each mode.

The traditional solution to power system oscillation problems is to install Power System Stabilizer (PSS) at appropriate machine. The objective of PSS is to add damping to rotor oscillations, which is accomplished by modulating voltage regulator set point such that resulting torque changes are in phase with shaft speed [2].

Fuzzy set theory has been applied in many engineering disciplines including process control [3]. In the fuzzy control approach, the inputs are transformed into a set of fuzzy variables through a process known as fuzzification. Given the interesting features of fuzzy controls, they can be applied in power system as well for damping power system oscillation. Researchers in [4] have applied the fuzzy logic controller for an automatic voltage regulator (AVR). However, they had considered only the terminal voltage.

This paper presents a novel fuzzy logic based automatic voltage regulator for damping power system oscillations. The terminal voltage error and its derivative are considered as input signals. Comparison also made with conventional AVR and conventional AVR + PSS.

2. Power System Model

A single-machine infinite-bus system as shown in Fig. 1 was used as the design model [5],[6]. The machine model includes sub-transient effects and the field voltage actuator is a solid state rectifier. The machine delivers the electrical power P_e to the infinite bus. The voltage regulator controls the input u to a solid-state rectifier excitation, which provides the field voltage to maintain the generator terminal voltage V_{term} at a referenced value V_{ref}. The states for the machine are its rotor angle δ, its speed ω, its direct- and quadrature-axis fluxes ψ_d and ψ_q, and its direct- and quadrature-axis voltage behind transient reactance E'_d and E'_q. The exciter is modeled with the voltage state V_R. All of the variables are normalized on a per-unit (p.u.) basis, except for δ which is in radians.

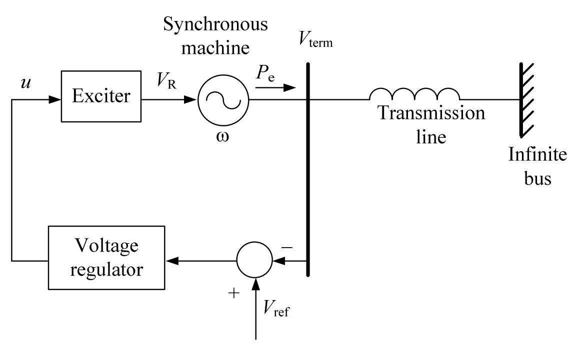

Figure 1 Single-machine infinite-bus system.

The power system model is linearized at a particular equilibrium point to obtain the linearized system model can be expressed in state-space form given by (1)

$$\Delta\dot{x} = A\Delta x + B\Delta u, \qquad \Delta y = C\Delta x \tag{1}$$

where Δ denotes the perturbation of the states, input, and outputs from their equilibrium values, with

$$x = \begin{bmatrix} \delta & \omega & E'_q & \psi_d & E'_d & \psi_q & V_R \end{bmatrix}^T \quad (2)$$

$$y = \begin{bmatrix} V_{term} & \omega & P_e \end{bmatrix}^T . \quad (3)$$

The matrices in (1) derived from typical machine parameters are given in Appendix A. The dominant poles of (1) are the real poles s = -0.105 associated with the field voltage response, and the electromechanical (swing) mode s = -0.479 $\pm j$9.33 with a small damping ratio ξ = 0.0513, representing the oscillation of machine against the infinite bus.

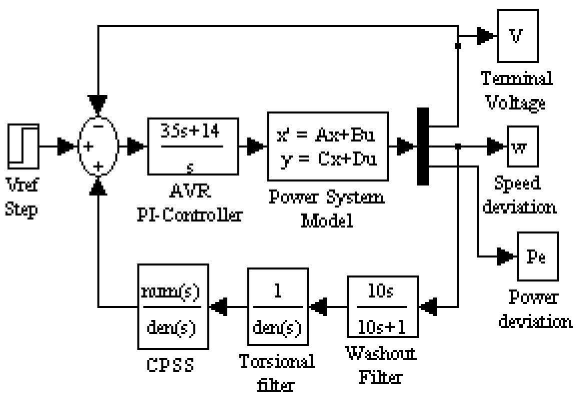

Figure 2 Simulink diagram of the conventional automatic voltage regulator with power system stabilizer

Figure 2 illustrates the Simulink block diagram of conventional automatic voltage regulator, which uses a PI-controller. The diagram included the conventional power system stabilizer (CPSS) for damping power oscillations. The parameters of the system were obtained from the reference [6]. Transfer functions of the CPSS and torsional filter are as following:

$$\mathrm{CPSS} = 1.13\left[\frac{14(\mathrm{s}+2.94)}{\mathrm{s}+34.9}\right]^2$$

$$\text{torsional filter} = \frac{1}{1+0.061\mathrm{s}+0.0017\mathrm{s}^2} .$$

3. Fuzzy Logic Controller

Fuzzy logic is a system of logic developed for representing conditions that cannot be easily described by the binary terms “true” and “false” [8]. The concept was introduced by Lotfi Zadeh in 1965. Unlike Boolean logic, fuzzy logic is multi-valued and handles the concept of partial truth. *Fuzzy set* is a set with fuzzy boundaries, such as “short”, “average”, or “tall” for men’s height. To represent a fuzzy set in a computer, we express it as a function and then map the elements of the set to their degree of membership. *Degree of membership* is a numerical value between 0 and 1 that represents the degree to which an element belongs to a particular set. Also referred to as membership value. *Linguistic variable* is a variable that can have values that are language elements such as words and phrases. In fuzzy logic, terms linguistic variables and fuzzy variable are synonyms. *Fuzzy variable* is a quantity that can take on linguistic values. For example, the fuzzy variable “temperature” might have values such as “hot”, “medium” and “cold”. *Linguistic value* is a language element that can be assumed by a fuzzy variable. For example, the fuzzy variable “income” might assume such linguistic values as “very low”, “low”, “medium”, “high” and “very high”. Linguistic values are defined by membership functions. *Fuzzy rule* is a conditional statement in the form: IF x is A THEN y is B, x and y are linguistic variables, and A and B are linguistic values determined by fuzzy sets. *Fuzzy inference* is the process of reasoning based on fuzzy logic.

Fuzzy inference includes four steps: fuzzification of the input variables, rule evaluation, aggregation of the rule outputs and defuzzification.

Fuzzification is the first step in fuzzy inference; the process of mapping crisp (numerical) inputs into degrees to which these inputs belong to the respective fuzzy sets. *Rule evaluation* is the second step in fuzzy inference; the process of applying the fuzzy inputs to the antecedents of fuzzy rules, and determining the truth values for the antecedent of each rule. If a given rule has multiple antecedents, the fuzzy operation of intersection or union is carried out to obtain a single number that represents the result of evaluating the antecedent. *Aggregation* is the third step in fuzzy inference; the process of combining clipped or scaled consequent membership functions of all fuzzy rules into a single fuzzy set for each output variable. *Aggregate set* is a fuzzy set obtained through aggregation. *Defuzzification* is the last step in fuzzy inference; the process of converting a combined output of fuzzy rules into a crisp (numerical) value.

The input for the defuzzification process is the aggregate set and the output is a single number. *Union*: In classical set theory, the union of two sets consists of every element that falls into either set. For example, the union of tall men and fat men contains all men who are either tall or fat. In fuzzy set theory, the union is the reverse of the intersection, that is, the union is the largest membership value of the element in either set. *Intersection*: In classical set theory, an intersection between two sets contains elements shared by these sets. For example, the intersection of tall men and fat men contains all men who are tall and fat. In fuzzy set theory, an element may partly belong to both sets, and the intersection is the lowest membership value of the element in both sets. *Centroid technique* is a defuzzification method that finds the point, called the *centroid* or *centre of gravity*, where a vertical line would slice the aggregate set into two equal masses.

3.1 Justification of Fuzzy Control Rules

There are two principal approaches to the derivation of fuzzy control rules [9]. The first is a heuristic method in which a collection of fuzzy control rules is formed by analyzing the behavior of a controlled process. The control rules are derived in such a way that the deviation from a desired state can be corrected and the control objective can be achieved. The derivation is purely heuristic in nature and relies on the qualitative knowledge of process behavior. The second approach is basically a deterministic method which can systematically determine the linguistic structure and/or parameters of the fuzzy control rules that satisfy the control objectives and constraints.

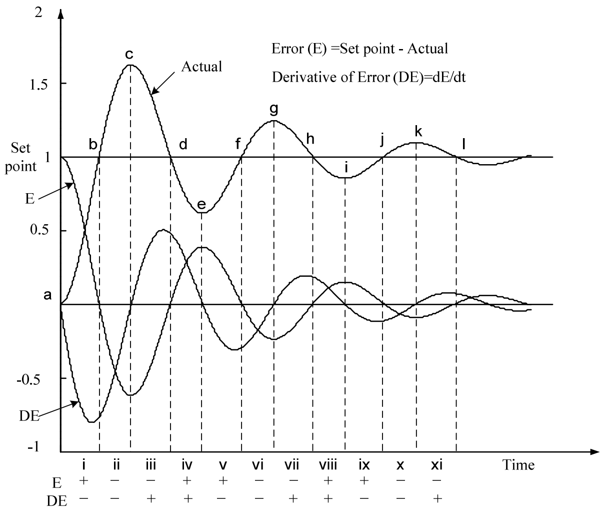

Figure 3 Rule justification by step response.

Figure 3 shows the system response of a process to be controlled, where the input variables of the FLC are the error (*E*) and derivative of the error (*DE*). The output is change of the process input (*CI*). We assume that the term sets of input/output variables have the same cardinality, 3, with a common term {negative, zero, positive}. The prototype of fuzzy control rules is tabulated in Table 1 and a justification of fuzzy control rules is added in Table 2. The corresponding rule of region *i* can be formulated as rule R_i and has the effect of shortening the rise time. Rule R_{ii} for region *ii* decreases the overshoot of the system's response. More specifically,

R_i: If (*E* is positive and *DE* is negative)
Then *CI* is positive,
R_{ii}: If (*E* is negative and *DE* is negative)
Then *CI* is negative.

Better control performance can be obtained by using finer fuzzy partitioned subspaces, for example, with the term set {NB: negative big, NM: negative medium, NS: negative small, ZE: zero, PS:positive small, PM: positive medium, PB: positive big}. The prototype and the justification of fuzzy control rules are also given in Table 3 and Table 4.

Table 1
Prototype of Fuzzy Control Rules with Term Sets {Negative, Zero, Positive}

Rule No.	*E*	*DE*	*CI*	Reference Point
1	*P*	*Z*	*P*	a, e, i
2	*Z*	*N*	*N*	b, f, j
3	*N*	*Z*	*N*	c, g, k
4	*Z*	*P*	*P*	d, h, l
5	*Z*	*Z*	*Z*	set point

Table 2
Rule Justification with Term Sets {Negative, Zero, Positive}

Rule No.	*E*	*DE*	*CI*	Reference Point
6	*P*	*N*	*P*	i (rise time), v
7	*N*	*N*	*N*	ii (overshoot), vi
8	*N*	*P*	*N*	iii, vii
9	*P*	*P*	*P*	iv, viii
10	*P*	*N*	*Z*	ix
11	*N*	*P*	*Z*	xi

Table 3
Prototype of Fuzzy Control Rules with Term Sets {*NB*, *NM*, *NS*, *ZE*, *PS*, *PM*, *PB*}

Rule No.	*E*	*DE*	*CI*	Reference Point
1	*PB*	*ZE*	*PB*	a
2	*PM*	*ZE*	*PM*	e
3	*PS*	*ZE*	*PS*	i
4	*ZE*	*NB*	*NB*	b
5	*ZE*	*NM*	*NM*	f
6	*ZE*	*NS*	*NS*	j
7	*NB*	*ZE*	*NB*	c
8	*NM*	*ZE*	*NM*	g
9	*NS*	*ZE*	*NS*	k
10	*ZE*	*PB*	*PB*	d
11	*ZE*	*PM*	*PM*	h
12	*ZE*	*PS*	*PS*	l
13	*ZE*	*ZE*	*ZE*	set point

Table 4
Rule Justification with Term Sets {*NB*, *NM*, *NS*, *ZE*, *PS*, *PM*, *PB*}

Rule No.	*E*	*DE*	*CI*	Reference Point
14	*PB*	*NS*	*PM*	i (rise time)
15	*PS*	*NB*	*NM*	i (overshoot)
16	*NB*	*PS*	*NM*	iii
17	*NS*	*PB*	*PM*	iii
18	*PS*	*NS*	*ZE*	ix
19	*NS*	*PS*	*ZE*	xi

Figure 4 gives the block diagram of the fuzzy logic based automatic voltage regulator, which has two input signals i.e. the terminal voltage error (e) and its derivative ($\dot{e}$). When the system is in steady state, the signal ΔU unchanged. Then signal U(old) (the previous values of excitation signal) and U(new) (the new values of excitation signal) are the same values.

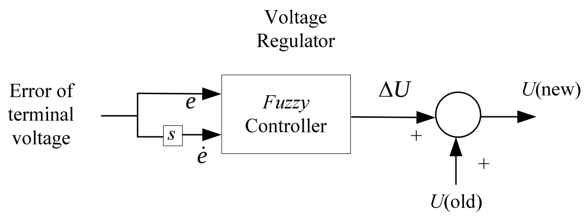

Figure 4 Structure of the fuzzy logic based automatic voltage regulator

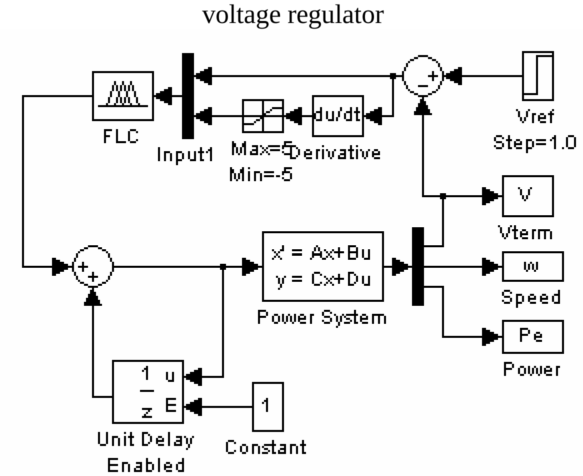

Figure 5 Simulink diagram of the fuzzy logic based automatic voltage regulator without stabilizer

Figure 5 shows the Simulink diagram of the fuzzy logic based automatic voltage regulator, Unit Delay block gives the previous values of excitation signal, U(old), FLC block gives the changing values of excitation signal, ΔU, the summation of these signals provide the new values of excitation signal, U(new).

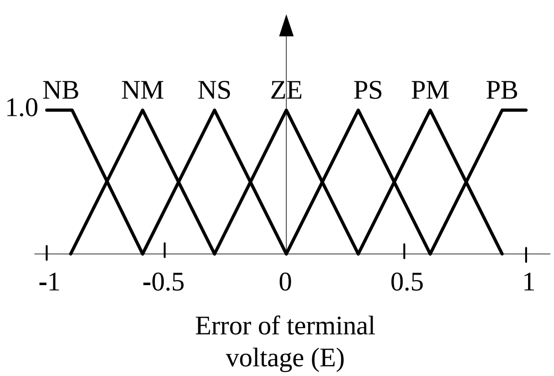

Figure 6 Seven membership functions of terminal voltage error

Figure 6 illustrates membership functions of terminal voltage error.

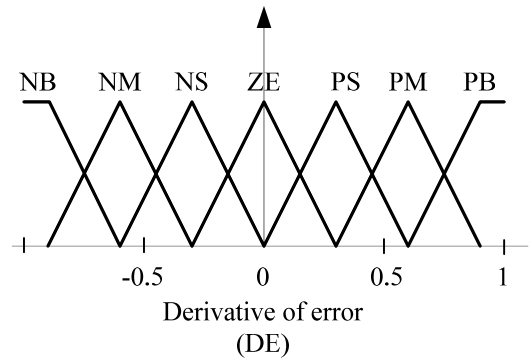

Figure 7 Seven membership functions of error derivative

Figure 7 shows membership functions of terminal voltage error derivative.

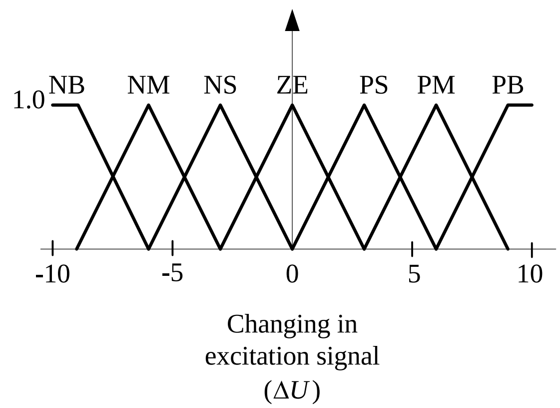

Figure 8 Seven membership functions of control excitation voltage

Figure 8 illustrates membership functions of changing in excitation signal.

Table 5
Forty nine rules for generate excitation signal

Derivative of error (DE)

Error (e)	NB	NM	NS	Z	PS	PM	PB
NB	NB	NM	NM	NS	ZE	ZE	ZE
NM	NB	NM	NM	NS	ZE	ZE	ZE
NS	NB	NS	NS	ZE	ZE	ZE	PS
Z	NM	NS	NS	ZE	PS	PS	PM
PS	NS	ZE	ZE	ZE	PS	PS	PB
PM	ZE	ZE	ZE	PS	PM	PM	PB
PB	ZE	ZE	ZE	PS	PM	PM	PB

The entries of matrix in Table 5 refer to the changing in excitation signal as conditions of terminal voltage error and its derivative. Using Fuzzy Logic Toolbox [7] and Simulink drawing diagram show in Fig. 4. The parameter of FLPSS structure has chosen fuzzy *mamdani* type. Mamdani's fuzzy inference method is the most commonly seen fuzzy methodology. In this work, the AND fuzzy operator used minimum type, the implication method used minimum type which truncates the output fuzzy set, the aggregation method used maximum type, and the defuzzification method used the centroid calculation.

4. Simulation Results

Simulink model of systems and controllers in Figures 2 and 5 were used to show the performance of the proposed control and compare the results with other conventional controllers. Here a step size of T = 0.001 sec is used through out the simulation.

Figure 9 shows the terminal voltage with conventional automatic voltage regulator (CAVR) and Fuzzy Logic based automatic voltage regulator (FLAVR) for a 1.0 p.u. step change in the reference voltage. As can be seen from the results the FLAVR gives a better performance compared to CAVR. When FLAVR is used in the synchronous machine the terminal voltage stabilizes very quickly. In the case of CAVR, the terminal voltage shoots up to a higher value over the nominal value and stabilizes around it. Notice also an oscillation in the terminal voltage with small amplitude in the case of CAVR.

The oscillation is clearly shown in excitation voltage, power deviation and rotor speed deviation plots for those two cases as shown in Figures 10 to 12. In the case of CAVR, the power deviates little over 0.8 p.u. in both positive and negative half cycles while that with FLAVR is just under 0.1 p.u. It should be noted that the CAVR uses a simple PI controller with best controller parameter setting done through root locus technique [6].

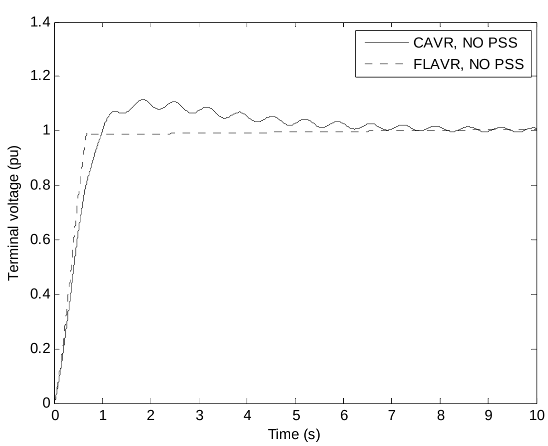

Figure 9 shows responses of terminal voltage after 1.0 p.u. step increase in reference voltage

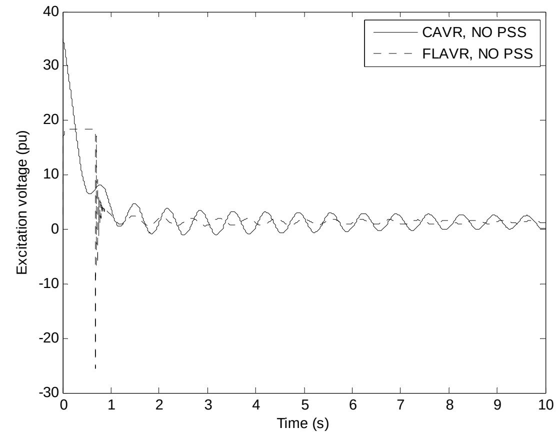

Figure 10 shows responses of excitation voltage after 1.0 p.u. step increase in reference voltage

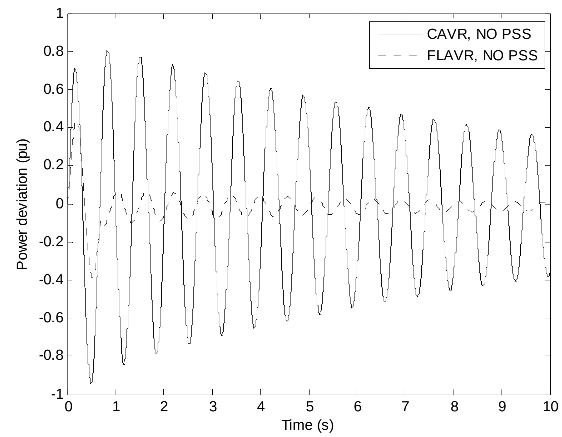

Figure 11 shows responses of active power deviation after 1.0 p.u. step increase in reference voltage

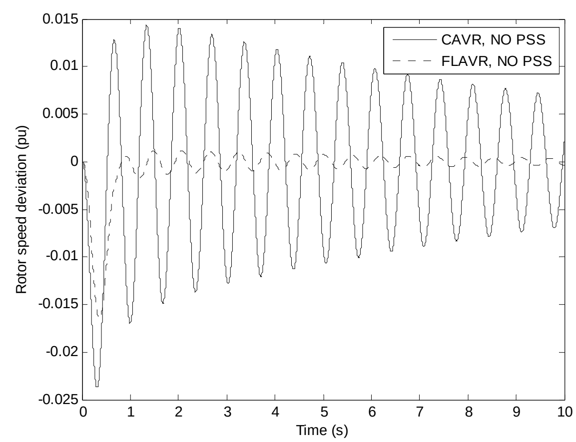

Figure 12 shows responses of rotor speed deviation after 1.0 p.u. step increase in reference voltage

Figures 13 and 14 compare the responses of the CAVR with a conventional power system stabilizer (CPSS) and a FLAVR. As clear shown in Figure 13, terminal voltage plot, the proposed FLAVR controls the terminal voltage much more effective than its conventional control along with a CPSS.

Figure 14 shows the power deviation for these two cases. It looks the case of CAVR + CPSS give a slightly better result in terms of oscillation damping. However, the initial amplitude of oscillation of this case is too high, almost twice as high as the case for FLAVR.

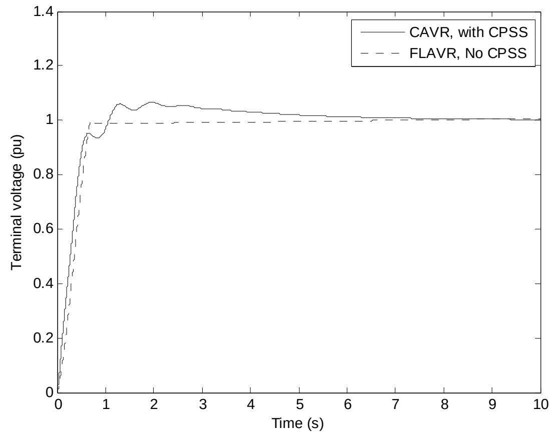

Figure 13 shows responses of terminal voltage after 1.0 p.u. step increase in reference voltage

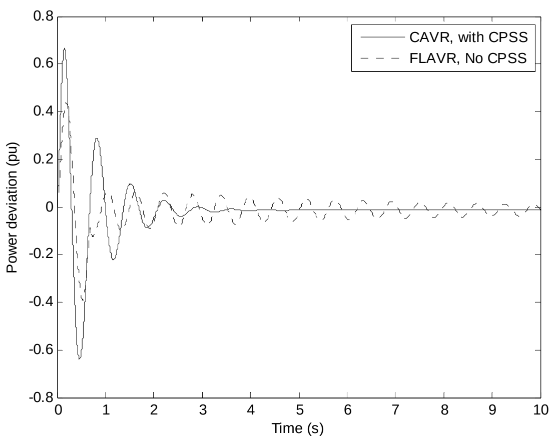

Figure 14 shows responses of active power deviation after 1.0 p.u. step increase in reference voltage

5. Conclusion

The paper presents fuzzy logic-based automatic voltage regulator design for damping power oscillation. It systematically explains the steps involved in fuzzy logic control design for oscillation damping in power system.

Comparison between the FLAVR and the CAVR shows that the FLAVR provides better performance than CAVR or CAVR with CPSS. The results show that the proposed FLAVR provides good damping and improves the dynamics. Though fuzzy based controllers have a number of advantages, different operating points need to be considered to see the robustness of the fuzzy based controllers.

Fuzzy logic controller can be controlled without the knowledge of its underlying dynamics. The control strategy learned through experience can be expressed by set of rules that describe the behaviour of the controller using linguistic terms. Proper control action can be inferred from this rules base that emulates the role of the human operator or a benchmark control action. Thus, fuzzy logic controllers are suitable for nonlinear, dynamic processes for which an exact mathematical model may not be available.

Fuzzy technology can be applied through computer or industrial programmable controller software, dedicated controllers, or through fuzzy microprocessors.

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Appendix

State-Space Model

Parameters of matrix A, B, C and D are used in the test system as following.

```
A=[   0      377.0      0        0        0         0        0;
     -0.246  -0.156  -0.137  -0.123  -0.0124  -0.0546    0 ;
      0.109   0.262  -2.17    2.30    -0.0171  -0.0753  1.27;
     -4.58    0       30.0    -34.3      0         0        0;
     -0.161   0        0        0      -8.44     6.33      0;
     -1.70    0        0        0       15.2    -21.5      0;
     -33.9   -23.1     6.86    -59.5    1.50     6.63     -114]
  B=[0;  0;  0;  0;  0;  0;  16.4]
  C=[-0.123  1.05     0.230  0.207  -0.105   -0.460    0;
          0      1        0        0        0        0       0;
       1.42    0.900  0.787  0.708  0.0713  0.314    0]
  D = [ 0; 0; 0]
```