Conventional and Fuzzy Logic Controllers at Generator Location for Low Frequency Oscillation Damping

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Abstract—This paper investigates and compares performance of various conventional and fuzzy logic based controllers at generator locations for oscillation damping. Performance of combination of conventional and fuzzy logic based controllers also studied by comparing overshoot on the active power deviation response for a small disturbance and damping ratio of the critical mode. Fuzzy logic based controllers can not be modeled in the state space form to get the eigenvalues and corresponding damping ratios of various modes of generators and controllers. Hence, a new method based on tracing envelop of time domain waveform is also presented and used in the paper for comparing performance of controllers. The paper also shows that if the fuzzy based controllers designed separately combining them could not lead to a better performance.

I. INTRODUCTION

IN interconnected power systems, there are hundreds of generating units with varying size, complexity and mechanical speed integrated. These units are connected with load centers that are often far away by long transmission lines. One of the major challenges in operation and control of such complex large networks is maintaining of electrical speed or synchronism among those generating units. Whenever power systems are subjected to small and sudden disturbances one or more of the generating units tend to exhibit oscillatory behavior. If the oscillations are not controlled, they would grow in amplitude, limit power transfer capability of transmission lines, induce stress in the system and trigger protection devices to function. Hence, threatens system security and hamper the efficient operation of the entire system.

Low-frequency oscillations were first observed in the Northern American power systems in the early 1960s during a trial interconnection of the northwest power pool and the

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Southwest Power Pool. Later, low frequency oscillation reported in many countries. Among various oscillatory problems, a low frequency, typically in the range of 0.1-0.4 Hz is considered as severe. This oscillation problem often referred to as inter-area oscillation results from participation of several generating units from different areas.

There is a wide variety of controllers that can be installed both at generator locations [1]-[4] or elsewhere used to effectively damp out such oscillations. However, power systems are complex dynamic systems and their operations are stochastic in nature. The characteristics of generating units are nonlinear, the gain of them increases with generator loading and AC system strength. Thus controller parameters that are optimum for one set of operating conditions may not be optimum for another set of operating conditions. Hence, fuzzy logic based power system stabilizers [5]-[7] and automatic voltage regulators [8]-[11] have been developed.

In practice, utilities may use conventional controllers such as automatic voltage regulator (CAVR), Power System Stabilizers (CPSS) or fuzzy logic based controllers like automatic voltage regulator (FLAVR), conventional fuzzy logic based power system stabilizer (FLPSS). However, a combination of both may be suitable in some situation. Hence, this paper investigates and compares different controllers both individually and in combination. In addition, a new technique is proposed to find damping ratio of critical mode from time domain simulation results, to help compare the performance of the controllers, which normally require mathematical models to find eigenvalues and evaluate damping ratios. The proposed technique is useful for evaluating the damping performance of fuzzy logic controllers for which mathematical models are not feasible.

II. LOW FREQUENCY OSCILLATION DAMPING

Installation of supplementary excitation control, power system stabilizers are simple and economical methods for improving oscillatory stability. Most of modern power plants are installed with PSS and there are wide varieties PSS proposed in the literature and applied in practice. Given the configuration and complexity of the system these solutions might not always sufficient in some cases.

About three decades back after rapid advancement of power electronics a number of Flexible AC Transmission controllers

were also introduced power oscillation damping [12]. Both series and shunt FACT controllers have been used for this purpose. These controllers include TCSC and SVC, voltage source converter based FACTS controllers such as SSSC, STATCOM and UPFC and other FACTS controllers such as TCPAR and IPFC.

These controllers can be designed as either conventional controllers or fuzzy logic or neuro-fuzzy controllers. Apart from this, there are other ways of providing oscillation damping with the help of re-dispatching of generators, Super Conducting Magnetic Energy Storage (SMES), fly wheel or even load shedding.

In fuzzy logic controls (FLC) there are several attractive features such as its programming structure that allows the use of estimates, control programs can be constructed with as little as one-tenth the rules of conventional systems. This results in shorter program development time and much faster program execution. Also, instead of developing complex mathematical formula, the engineer converts personal knowledge and experience into words as the computer is programmed. The operational and control laws of the system are also expressed linguistically, which make it intuitively easier to understand and justify.

III. FUZZY LOGIC CONTROL

Fuzzy logic is a system of logic developed for representing conditions that cannot be easily described by the binary terms "true" and "false". The concept was first introduced by Lotfi Zadeh in 1965 [13]. Unlike Boolean logic, fuzzy logic is multi-valued and handles the concept of partial truth as well.

In control engineering PID control is the most common type of control technique presently used in automated systems. It utilizes mathematical equations or Boolean expressions to perform the process. Some types of applications that use mathematical models are often difficult, or impossible, to calculate because of the complexity involved. The math function required is often too difficult to write, or takes too long time to solve because it requires massive computations. An example is a system where one or more controlled variables change completely or irregularly. These situations typically require human intervention to make the necessary adjustments to correct the operation.

A revolutionary control technique called fuzzy logic is capable of performing some of the operations that are too complex for PID systems. Fuzzy logic is a form of artificial intelligence that enables a computer to simulate human reasoning. When people make decisions, the present conditions are observed by our biological sensory inputs. The human response is based on rules that have been formulated through personal knowledge and experience. However, instead of using hard and fast rules, each rule is weighed based on its importance. The human thinking process differentiates significant conditions from insignificant conditions to decide on the appropriate action to take. The operation of fuzzy logic is designed to make decisions in a similar manner.

FLC are rule-based controllers. The structure of the FLC resembles that of a knowledge-based controller except that it utilizes the principles of fuzzy set theory in its data representation and its logic. The basic configuration of the FLC can be simply represented in four parts, as shown in Fig. 1.
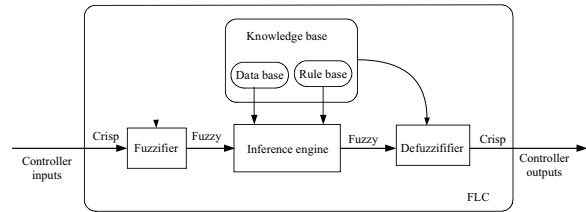

Fig. 1 Schematic diagram of the FLC building blocks

• *Fuzzification module*: the function of this module are first to read, measure, and scale the control variable (e.g. speed, acceleration) and, second, to transform the measured numerical values to the corresponding linguistic (fuzzy) variables with appropriate membership values.

• *Knowledge base module*: it includes the definitions of the fuzzy membership functions defined for each control variables and the necessary rules that specify the control goals using linguistic variables.

• *Inference mechanism*: is the kernel of the FLC. It should be capable of simulating human decision making and influencing the control actions based on fuzzy logic.

• *Defuzzification module*: it converts the inferred decision from the linguistic variables back to numerical values.

IV. SYSTEM DESIGN

A single-machine infinite-bus system as shown in Fig. 2 was used as the design model [3]. 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.

The power system model is represented by differential and algebraic equations (1) to draw the system in state-space model as shown in Fig. 2.
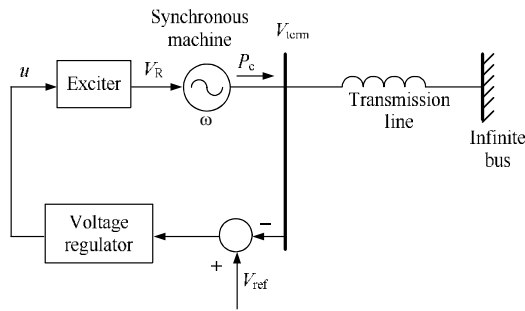
$$\Delta\dot{x} = A\Delta x + B\Delta u, \quad \Delta y = C\Delta x \tag{1}$$

where Δ denotes the perturbation of the states, input, and outputs from their equilibrium values, with
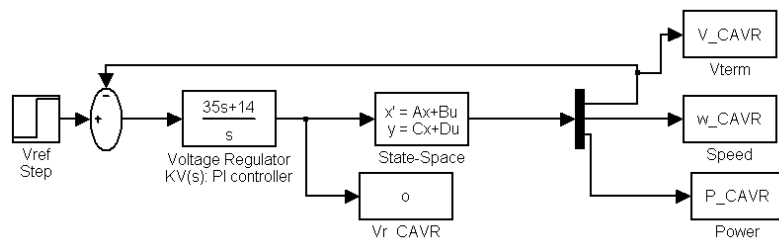
$$x = \begin{bmatrix} \delta & \omega & E'_q & \psi_d & E'_d & \psi_q & V_R \end{bmatrix}^T \tag{2}$$

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

Fig. 2 Single-machine infinite-bus system

The matrices in (1) derived from typical machine parameters are given in Appendix. The critical mode of the above system are the purely real one, -0.105 associated with the field voltage response, and the electromechanical (swing) modes, $-0.479 \pm j9.33$, with a damping ratio of $\xi = 0.0513$, representing the oscillatory behavior of machine against the infinite bus with 1.5 Hz initial frequency of oscillation.

A. CAVR

Figure 3 shows SIMULINK diagram of CAVR along with the test system. In this configuration, the system consists of PI-voltage regulator, State-space model given in (1). Detail of design CAVR can obtained from [3]. Output blocks include V_CAVR (the terminal bus voltage of system), w_CAVR (the rotor speed deviation of machine), P_CAVR (the active power deviation), Vr_CAVR (the excitation voltage of machine).


Fig. 3 SIMULINK diagram the system with CAVR

B. FLAVR

In this structure, fuzzy logic controller is used instead of conventional PI-controller for automatic voltage regulator. A 49-rules fuzzy logic control is used with two input signals, namely, the terminal voltage error (e) and its derivative $(\dot{e})$.

Figure 4 shows the structure of fuzzy logic based AVR. 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.

Fig. 4 Structure of the fuzzy logic based AVR

Figure 5 shows SIMULINK diagram of system with FLAVR. Unit delay block gives the previous values of excitation signal, U-old. FLC block gives the changing values of excitation signal, ΔU, and the summation of these signals provide the new values of excitation voltage, U-new.

Fig. 5 SIMULINK diagram of the system with FLAVR
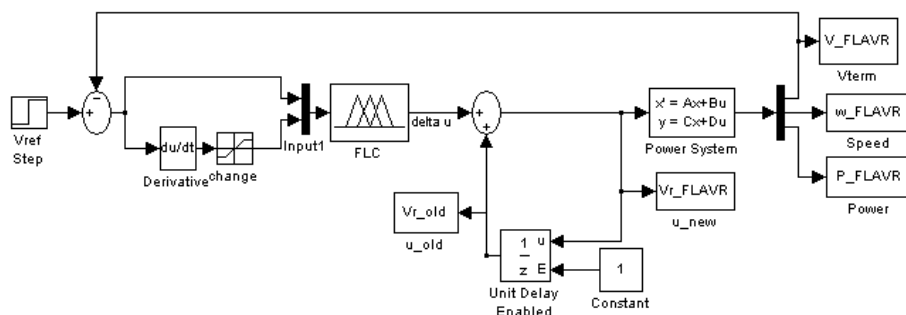
Figure 6 illustrates seven membership functions of the terminal voltage error. Membership functions for the terminal voltage derivation and excitation signals are shown in Figs. 7 and 8, respectively.
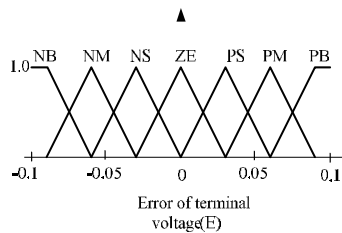
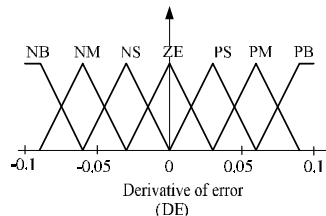Fig. 6 Membership functions of terminal voltage error

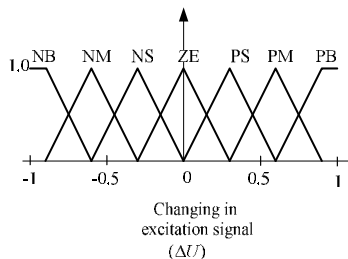Fig. 7 Membership functions of terminal voltage error derivative

Fig. 8 Membership functions of excitation signal

Table 1 shows forty nine rules for generating excitation signals.

TABLE I
FORTY NINE RULES FOR GENERATE EXCITATION SIGNAL

		Derivative of error (DE)						
		NB	NM	NS	Z	PS	PM	PB
Error (e)	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

From Table 1, it can be described that rule 1 (upper left corner), if the terminal voltage error (e) is NB (negative big) and its derivative (DE) is NB, then the changing in excitation voltage is NB, means a big decrease in excitation voltage from the previous value. Similarly, if the terminal error (e) is PS (positive small) and its derivative is NB (negative big), then the changing in excitation voltage is NS (negative small), means a little decrease in excitation voltage from the past value.

C. CAVR and CPSS

In this structure, as show in Fig. 9, a combined controller of CAVR with CPSS is used. The optimum parameters of this structure are obtained from [3]. Input of the power system stabilizer using the rotor speed deviation. More details of this combination of controller configuration can be found in [14].
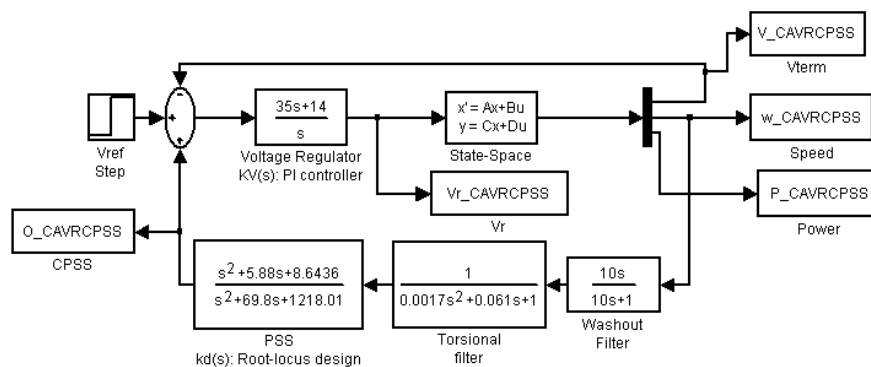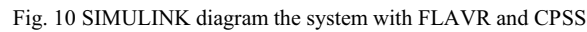

Fig. 9 SIMULINK diagram the system with CAVR and CPSS

D. FLAVR and CPSS

Figure 10 shows SIMULINK diagram of the system with FLAVR and CPSS. Design of FLAVR is same as the one in Section B and CPSS design is same as the one in Section C.

Fig. 10 SIMULINK diagram the system with FLAVR and CPSS

E. CAVR and FLPSS

In this configuration, CAVR and FLPSS are used as shown in Fig. 11. Two input signals, i.e. active power deviation and its derivative are used as control input signals for FLPSS. More detail of the structure of FLPSS can be found in [15].
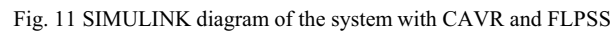
Fig. 11 SIMULINK diagram of the system with CAVR and FLPSS

Figures 12 to 14 show three membership functions of the active power deviation, derivation of power deviation and stabilizing signals, respectively.

Fig. 12 Membership functions of power deviation (E)

Fig. 13 Membership functions of derivative of power deviation (DE).
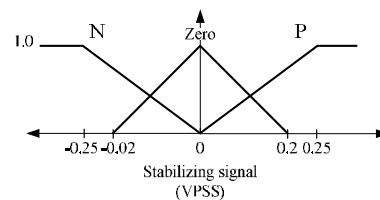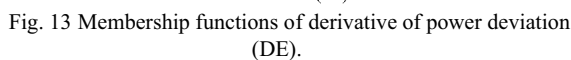
Fig. 14 Membership functions of stabilizing signal (VPSS)

TABLE II
NINE-RULES OF FLPSS

| | | Derivative of power derivative (DE) | |
	N	Z	P
Power deviation (E) — N	N	N	N
Power deviation (E) — Z	N	Z	P
Power deviation (E) — P	P	P	P

F. FLAVR and FLPSS

The configuration shows in Fig. 15, includes FLAVR and FLPSS. The structure of FLAVR is the same as in Section B

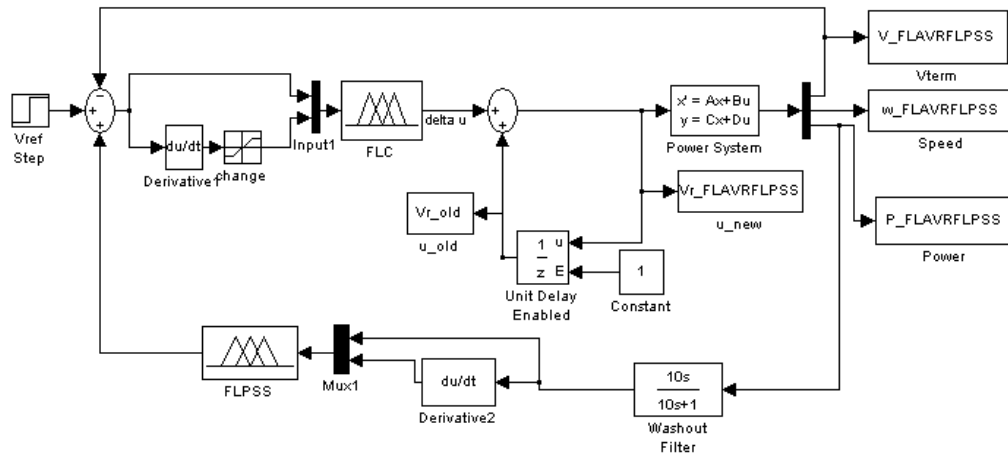and the structure of FLPSS is the same as Section E.

Fig. 15 SIMULINK diagram of the system with FLAVR and FLPSS

V. DAMPING RATIO FROM TIME DOMAIN SIMULATION

One drawback of fuzzy based controllers design is that non availability of mathematical functions. Hence, getting a state space model, apply small signal analysis and getting eigenvalues and damping ratio for performance comparison is not feasible. The time domain simulation method can be used here to analyze the performance of the controller. This type of comparison may result in error as only eye judgment is used to see which controller is providing a damped wave form. One way of overcoming this problem is to find weak modes and damping ratio from time domain data obtained from numerical integration of differential equations and this can be done using Prony analysis. However, in this work a new method is introduced to find eigenvalues and damping ratio by tracking the envelope of time domain simulation.

Methodology to find damping ratio from time domain have procedure the following steps.

Step 1 Pre-processing: The steady state value of the state variable is forced to zero as this is needed for the method. Time domain data, which may be obtained from recorded data in control center or simulated data, are added or subtracted with a dc component equal to the steady state value.

Step 2 Calculation of frequency (f_d): The frequency of oscillation is calculated using (4), where times are corresponding to the maximum and minimum points in the typical plot shown in Fig. 16.

$$f_d = \frac{1}{T_d} = \frac{1}{|T_{max} - T_{min}| * 2} \tag{4}$$

where f_d is the frequency of oscillation in Hz and T_d is the time period in second.
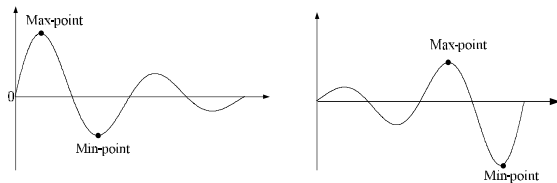

Fig. 16 A typical plot of state variables in low frequency oscillation studies

Step 3 Prediction of damping ratio: We predict the damping ratio by observing the amplitude of the graph, if it the response is gradually decreasing, it means a small positive damping ratio approach to zero. If it is rapidly decreasing, it indicates a large positive damping ratio closer to 1. The predicted damping ratio will be used in Steps 4 and 5.

Step 4 Calculation of undamped natural frequency (ω_n): By using this equation,

$$\omega_n = \frac{\omega_d}{\sqrt{1 - \zeta^2}} = \frac{2\pi f_d}{\sqrt{1 - \zeta^2}} \tag{5}$$

Where ω_n is the undamped natural frequency in rad/s; ω_d is the damped natural frequency in rad/s; f_d is the frequency of oscillation, which obtained in Step 2; ζ is the predicted damping ratio, which acquired in Step 3

Step 5 Fitting the envelope: The envelop equation was fitted with the help of parameters calculated in the previous steps.

$$Y_e = \pm C e^{-\zeta \omega_n t} \qquad (6)$$

where Y_e is the envelope equations both upper and lower lines. C is the constant value, normally value selected almost same as the maximum and minimum values.

Step 6 Plot the envelope equations with the graph: If the curve of the envelope line does not fit with the graph properly, i.e. envelop passing through the maximum and minimum points of each cycle, the predicted damping ratio, ζ or the constant value, C are adjusted until the envelop properly fit.

VI. SIMULATION RESULTS

The system presented in Section IV has been used for simulation. Figs. 17 to 20 show comparison of active power deviation for different cases for a small step change in reference voltage.
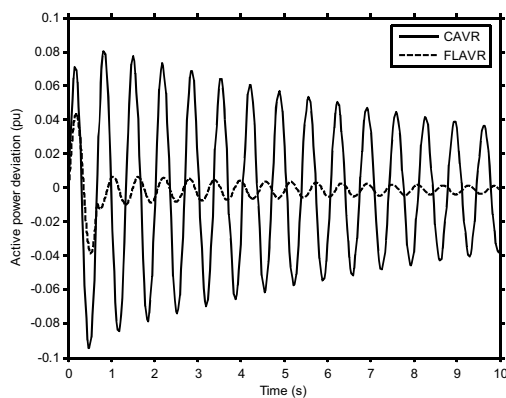

Fig. 17 Comparison of active power deviation for cases with CAVR and FLAVR

Figure 17 shows the comparison of active power deviation for the cases with CAVR and FLAVR. Based on the time domain results, it is obvious that FLAVR is a better option as it damp out oscillation faster than CAVR. However, the damping performance may not be clear like this in some cases as presented later.

Figure 18 shows the comparison of active power deviation for cases CAVR+CPSS and FLAVR+CPSS. In this case, it is clear that introduction of fuzzy logic controller in AVR does not produce a good performance compared to all conventional controllers. However, performances of FLAVR and CAVR+CPSS look similar.
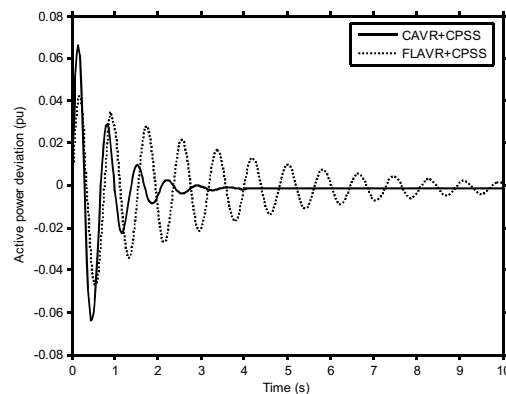

Fig. 18 Comparison of active power deviation for cases with CAVR+CPSS and FLAVR+CPSS

Figure 19 shows the comparison of active power deviation for cases CAVR+FLPSS and FLAVR+FLPSS. Though the initial repose of FLAVR+FLPSS looks stable in the first few cycles, the system is unstable. It should be noted that these two controllers were designed separately and combined together in this case. Here, clearly CAVR+FLPSS combination gives a better performance, but it looks similar to the performances of FLAVR and CAVR+FLPSS. It should be noted that as per the time domain simulation the performances of FLAVR+CPSS and FLAVR+FLPSS look the same.
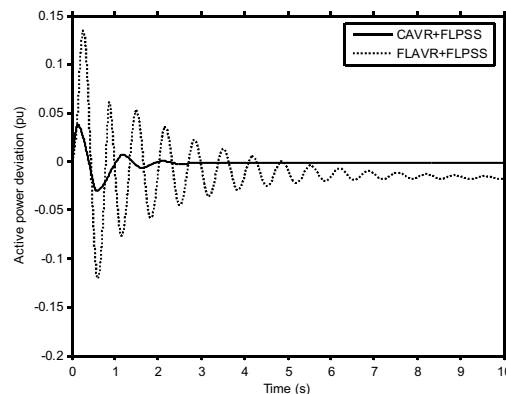

Fig. 19 Comparison of active power deviation for cases with CAVR+FLPSS and FLAVR+FLPSS

Figure 20 shows the comparison of active power deviation for all six cases. As can be seen from Fig. 20 some responses are very difficult to judge with their performance. Hence, the proposed method is used to clearly quantify the performances by calculating the damping ratio on the critical mode.
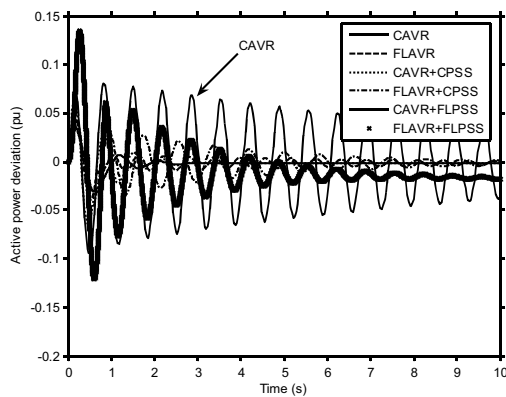
Fig. 20 Comparison of active power deviation for all the six cases

Figures 21 to 25 show the active power deviation response and its envelope for various cases. Here the enveloped is traced for the purpose of finding damping ratio on critical mode using the method and procedure described in Section V.
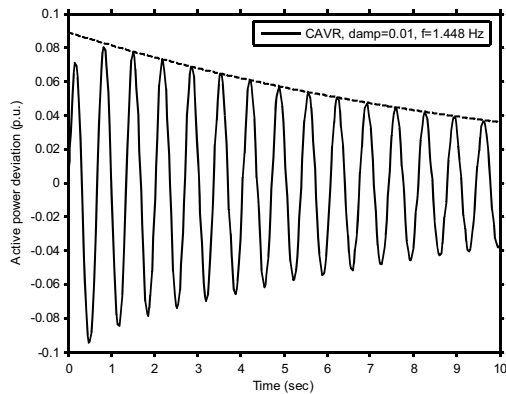

Fig. 21 Envelope fitting for active power deviation for the case with CAVR
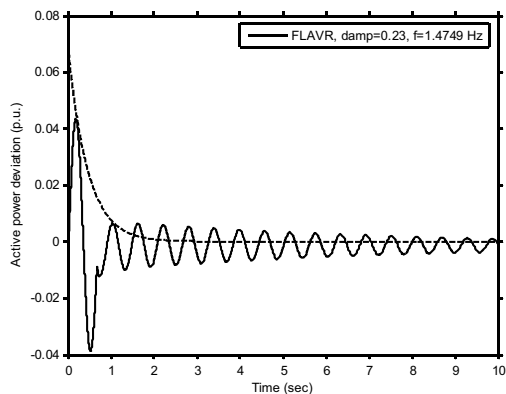

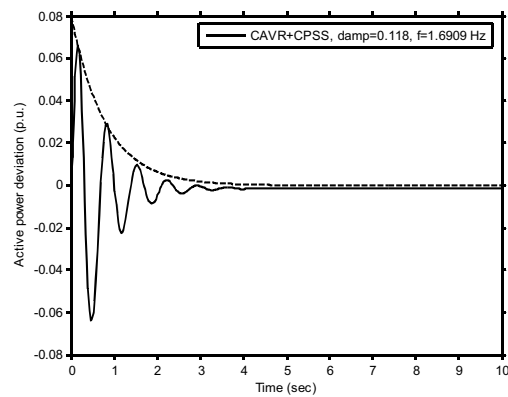Fig. 22 Envelope fitting for active power deviation for the case with FLAVR

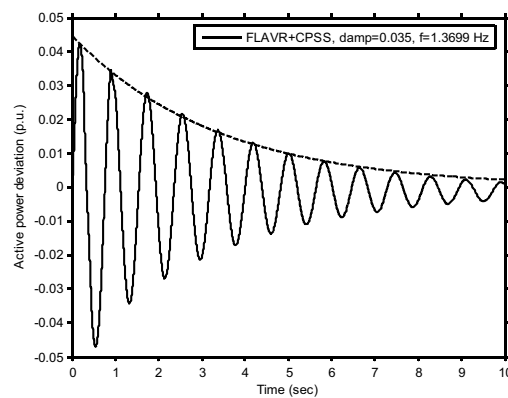Fig. 23 Envelope fitting for active power deviation for the case with CAVR+CPSS

Fig. 24 Envelope fitting for active power deviation for the case with FLAVR+CPSS
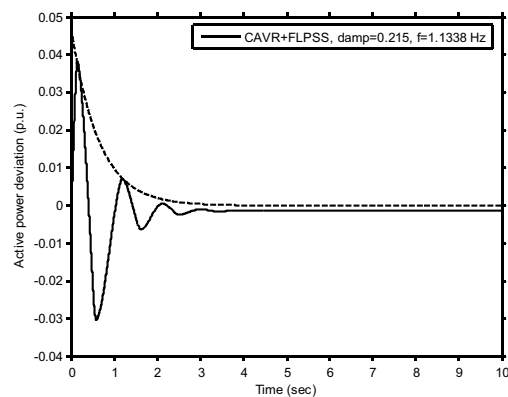
Fig. 25 Envelope fitting for active power deviation for the case with CAVR+FLPSS

Table 3 shows comparison of performance of controllers, AVR and PSS, conventional, fuzzy based and combination of both. Among various cases, CAVR shows the weakest performance in terms of maximum or minimum overshoot and damping ratio. Notice that the system power deviation overshoot for this case is 0.08 and 0.094 p.u. in positive and negative half cycles, respectively. The damping ratio on the

weakest mode (electromechanical) is 0.01. When CPSS is added to the FLAVR, the combined controller performance deteriorates and yield lower damping ratio than that obtained for FLAVR case. However, combination of conventional AVR and PSS gives a better performance than FLAVR+CPSS case. FLAVR and CAVR+FLPSS give almost similar damping ratio and overshoot values. Among all the options, in this case FLAVR gives the best performance.

TABLE III
FINDING FREQUENCY OF GRAPH USING TIME INTERVAL BETWEEN 0 TO 1 SECOND (I.E. FIST SWING OF GRAPH)

Cases	Overshoot		f_d (Hz)	ζ
	Max	Min		
CAVR	0.080	-0.094	1.44	0.01
FLAVR	0.043	-0.038	1.47	0.23
CAVR+CPSS	0.066	-0.063	1.69	0.118
FLAVR+CPSS	0.042	-0.046	1.36	0.035
CAVR+FLPSS	0.038	-0.030	1.13	0.215
FLAVR+FLPSS	unstable response			

VII. CONCLUSION

This paper investigates the performance of conventional and fuzzy based controllers at generator locations. CAVR, FLAVR, CAVR+CPSS, FLAVR+CPSS, CAVR+ FLPSS and FLAVR+FLPSS are considered in this comparison study. Damping ratios and overshoot from power deviation plot for a small step increase in voltage have been compared. The results show that all fuzzy, i.e. FLAVR+FLPSS not necessarily yield the best performance among all the cases. It should be noted that in this cases these two controllers were designed separately. However, in this case FLAVR and CAVR+FLPSS, i.e. introduce fuzzy logic controller for the last control block give the best results.

The paper also proposed a new method to calculate damping ratio from time domain simulation by fitting the envelope.

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]
```

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