Power System Damping Using Hierarchical Fuzzy Multi- Input Power System Stabilizer and Static VAR Compensator

Mohammad Hasan Raouf, Ebrahim Rasooli Anarmarzi, Hamid Lesani, and Javad Olamaei

Abstract**—**This paper proposes the application of a hierarchical fuzzy system (HFS) based on multi-input power system stabilizer (MPSS) and also Static Var Compensator (SVC) in multi-machine environment.The number of rules grows exponentially with the number of variables in a conventional fuzzy logic system. The proposed HFS method is developed to solve this problem. To reduce the number of rules the HFS consists of a number of low-dimensional fuzzy systems in a hierarchical structure. In fact, by using HFS the total number of involved rules increases only linearly with the number of input variables. In the MPSS, to have better efficiency an auxiliary signal of reactive power deviation (ΔQ) is added with $\Delta P+\Delta\omega$ input type Power system stabilizer (PSS). Phasor model of SVC is described and used in this paper. The performances of MPSS, Conventional power system stabilizer (CPSS), hierarchical Fuzzy Multi-input Power System Stabilizer (HFMPSS) and the proposed method in damping inter-area mode of oscillation are examined in response to disturbances. By using digital simulations the comparative study is illustrated. It can be seen that the proposed PSS is performing satisfactorily within the whole range of disturbances.

Keywords**—**Power system stabilizer (PSS), hierarchical fuzzy system (HFS), Static VAR compensator (SVC)

I. INTRODUCTION

ONE of the problems that electrical engineers are always facing with them is low frequency oscillations in power systems. Power system stabilizer is one of the auxiliary controllers that damp these oscillations by installing on the excitation system of power plants [1].

In the last two decades, several types of PSS are designed and investigated. Classic PSS is one of the earliest types that is contained of several lead-lag compensators and is used frequently in power systems. PSS is used based on different control methods in power systems, such as neural networks [2], fuzzy control [3], and genetic algorithm [4]. Also, FACTS devices are used for damping the low frequency oscillations [5]. Using the MPSS can damp low frequency oscillation by adding reactive power signal to classic stabilizer input. This method is introduced by Kitauchi [6] and modified by Ozaki [7].

In fact, one of the most important problems in a conventional fuzzy system is dimensions of the system variables. The number of rules grows exponentially with the number of variables in a standard fuzzy system.

If there are n input variables and m membership functions are defined for each of these, then the number of rules in the fuzzy system is m^n. In fact, the complexity of problem increases exponentially with the number of variables involved. To avoid the problem, the hierarchical fuzzy system (HFS) structure was reported [8-11].

Static Var Compensator (SVC) is one of the most common Flexible AC Transmission Systems (FACTS) devices that behave like a variable shunt susceptance. This device consists of several power electronic equipments such as thyristor switch capacitor (TSC) and thyristor controlled reactor (TCR) along with some harmonic filters and controllers. The simplest form of a SVC could be consisting of a TCR that is parallel with a fixed capacitor bank. SVC can be used as a reactive power supply. It can consume the spare inductive reactive power from the grid or supply capacitive reactive power to the grid. One of the SVC main advantages is to compensate the reactive power [12]. In previous work by the authors the performances of hierarchical Fuzzy Multi-input Power System Stabilizer (HFMPSS), MPSS and CPSS under similar transient conditions were studied [13].

In this paper, the effect of hierarchical fuzzy Multi-Input PSS and SVC (HFMPSS & SVC) on the increase of low frequency oscillation damping of the system and also the increase of capability of the system by variation in its working situation is studied. The effectiveness of the proposed method is then demonstrated through digital computer simulation. Also, its performance is compared with a MPSS and CPSS. It is shown that, by application of proposed method, good dynamic performance can be obtained.

II. EFFECT OF REACTIVE POWER DEVIATIONS AUXILLARY SIGNAL ON THE POWER SYSTEM STABILIZER

Stabilizers based on Δw signal are used widely in different types of power plants, especially water units, since middle of 1960s. This kind of stabilizer damps rotor oscillations, but it may cause unstability in torsional modes. Therefore, the main drawback of this stabilizer is using the torsional filter. Also in order to weakening the torsional components of the stabilizer signal, the filter causes some phase lag in low frequencies.

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The occurred phase lag has a destroying effect on the stability of exciting mode and limits the total efficiency of stabilizer on the damping of system oscillation. ΔP+ΔW stabilizer is used to solve the above problem. Torsional components in the integral of signal ΔP are weakened and therefore, there is no need to torsional filter [9]. But by increasing δ, sensitivity of ΔP to oscillation is reduced. Thus, the efficiency of ΔP+ΔW stabilizer is decreased. A system contain of a synchrone generator connected to an infinite bus by X_e impedance is shown in Fig 1.

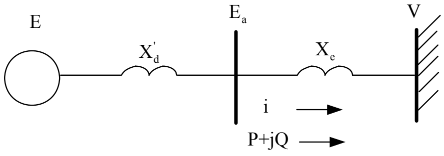

Fig. 1 Model of machine connection to the infinite bus system

Where X′d transient reactance of machine, V system voltage, E generator voltage and Ea generator bus voltage

$$P = \frac{EV \sin\delta}{X'_d + X_e} \tag{1}$$

$$Q = \frac{E\left(E - V \cos\delta\right)}{\left(X'_d + X_e\right)} \tag{2}$$

By linearizing the above equations around working point δ = δ0, one has:

$$\Delta P = \frac{\partial P}{\partial \delta}.\Delta\delta = \frac{EV}{X'_d + X_e}\cos\delta_0\left(\Delta\delta\right) \tag{3}$$

$$\Delta Q = \frac{\partial Q}{\partial \delta}.\Delta\delta = \frac{EV}{X'_d + Xe}\sin\delta_0\left(\Delta\delta\right) \tag{4}$$

Equations 3 and 4 are plotted in figure 2.

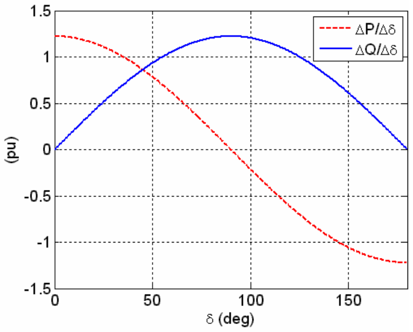

Fig. 2 Variations of $\frac{\Delta P}{\Delta\delta}$ and $\frac{\Delta Q}{\Delta\delta}$ vs. δ

As it can be seen in figure 2 by increasing δ, ΔP and ΔQ decreases and increases respectively in the range of 0-90 degrees.Therefore, sensitivity of ΔP to rotor angle variation decreases and sensitivity of reactive power to rotor angle variation increases. Since ΔP is the signal input of stabilizer type ΔP+ΔW, its sensitivity decrease reduces stabilizer efficiency. To compensate this defect and increase the stabilizer efficiency, an auxiliary signal of reactive power deviation (ΔQ) is used. Thus, in angles 45°≤δ, increase of reactive power sensitivity to δ variation can be used to increase the efficiency of PSS.

III. Multi-Input Stabilizer Structure

MPSS is introduced to increase damping of power low frequency oscillations in large power system and to improve the control of power system by changing the structure and operation conditions. In classic PSS, active power deviation and or angular velocity are used as input. In MPSS, reactive power deviation (ΔQ) is added to PSS input too. MPSS structure is shown in figure 3. 2 lead-lag compensators are used for every input signal [14]. But determining the compensator parameter is difficult.

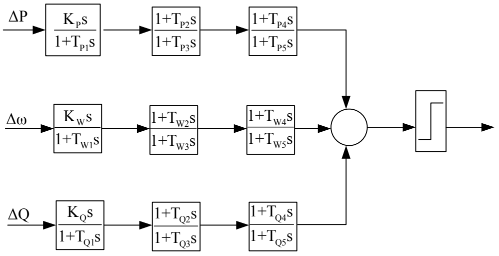

Fig. 3 Configuration of the MPSS

In this paper, HFMPSS & SVC is used. In this type of stabilizer, hierarchical fuzzy controller is used instead of lead-lag compensators and static VAR compensator that have better efficiency than conventional power system stabilizer (CPSS).

IV. Hierarchical Fuzzy Controller

Fuzzy system is attractive for nonlinear systems applications because it does not require mathematical model, and it can cover a wide range of operating conditions [15].

The aim of fuzzy control systems is to make use of fuzzy logic to reduce the number of iterations and decrease computation time, has been developed and tested successfully [16]. The idea of a Hierarchical FLCs (HFLCs) is to reduce the number of rules to a linear function of system variables [17].

In a hierarchical form the total number of involved rules increases only linearly whereas it is exponential in a conventional fuzzy logic system. In hierarchical fuzzy systems the number of rules is altered by decomposing the fuzzy system to a set of simpler fuzzy subsystem connected in a hierarchical manner [18] as shown in Fig 4.

In a hierarchical fuzzy logic controller (HFLC) structure the most influential system variables are chosen in the first level, the next most important variables are chosen in the second level, and so on [19].

In this hierarchy, the first level gives an approximate output which is then modified by the second level rule set. This procedure can be repeated in succeeding levels of hierarchy. The number of rules in a complete rule set is reduced towards a linear function of the number of variables by the hierarchy [20]. However, in the hierarchical structure, each input variable is used in a two-input FLC and the knowledge can be easily redesigned when adding or removing an input variable.

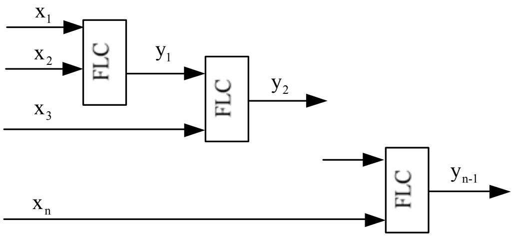

Fig. 4 Hierarchical FLC structural representation

V. HIERARCHICAL FUZZY MULTI-INPUT POWER SYSTEM STABILIZER

State variables that are controller inputs are equal to ΔQ, ΔW and ΔP signals. Fuzzy rules with seven elements are defined as table 1. They are PB (Positive Big), PM (Positive Medium), PS (Positive Small), ZE (Zero), NS (Negative Small), NM (Negative Medium) and NB (Negative Big).

In this paper, Hierarchical control structure is constructed by two fuzzy subsystems where each subsystem has only two inputs. The ΔQ and Δω are the input variables of the first subsystem. The output of the first subsystem and the variable ΔP are the input variables of second subsystem as shown in Fig 5.

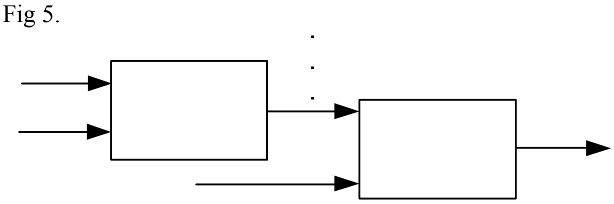

Fig. 5 Detailed HFC structure

The triangular membership functions are used to define the degree of membership as shown in Fig 6. Mamdani-minimum inference system and centroid defuzzification are used in this paper to design the fuzzy system. The adopted fuzzy rules are reported in Tables 1 and 2.

The triangular membership functions are normalized using the following factors:

$K_W = 33.33$, is the Speed change input coefficient;

$K_Q = 0.058$, is the Reactive power change input coefficient;

$K_P = 0.5$, is the Active power change input coefficient;

$K_{U1} = 1$, is the Output coefficient (in subsystem 1); and

$K_{UPSS} = 1$, is the Output coefficient (in subsystem 2).

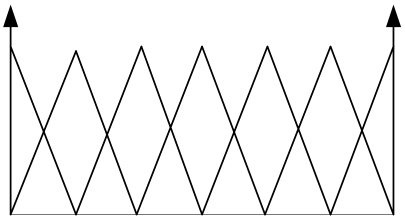

Fig. 6 Membership Function Scaled from –1 to 1

TABLE I
RULES TABLE

ΔQ / Δω	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	PS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

TABLE II
RULES TABLE

Δu₁ / ΔP	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NM	NS	ZE
NM	NB	NM	NM	NM	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NM	NM	NS	ZE	PS	PM	PM
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PM	PM	PM	PB
PB	ZE	PS	PM	PB	PB	PB	PB

VI. STATIC VAR COMPENSATOR (SVC)

SVC can be used to control and regulate voltage at the point of joint according as load changes. To study the transient stability in this paper, a fuzzy model of SVC is used to control and regulate the bus voltage. Since the power system damping must be existed under all sequences, the auxiliary control signal can be used in fuzzy model of SVC to prevent the power system oscillation [21]. The proposed fuzzy model for SVC devices is shown in the figure (7).

The ratio of change in voltage magnitude to current magnitude change over the linear control range of the compensator is called the slope or droop of the V-I characteristic [21]. Therefore, the slop Xs1 can be calculated as:

$$X_{sl} = \frac{\Delta V}{\Delta I} \tag{5}$$

The common value of slop is 3-5% [21]. Since, most of the voltage regulators are integrally controlled; therefore B_{ref} has a zero-error signal in steady state. To measure the SVC current, current transformers (CT) can be used. The SVC current can also be obtained by multiplying B_{ref} and V_{meas}. The proposed fuzzy model does not consist of any thyristor, synchronizing system or Gate Pulse Generator (GPG). The below transfer function can be used for this model [20]:

$$G_Y(s) = \frac{e^{-sT_d}}{1+sT_b} \tag{6}$$

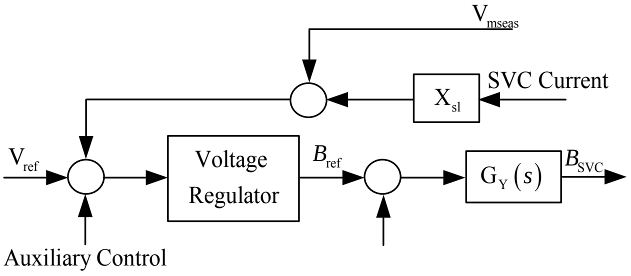

Fig. 6 SVC Controller

where T_d is the thyristor dead time, that is equal to one-twelfth cycle time, and T_b is the thyristor firing-delay time caused by sequential switching of thyristors, that is approximately equal to one-quarter cycle time.

VII. SYSTEM MODEL

A. Power System Model

To simulating by the proposed method, an 11-bus power system having 4 power plants is used [14]. In order to maintain system stability after faults, the transmission line is shunt compensated at its center by a 1Mvar SVC. This system is shown in figure 8.

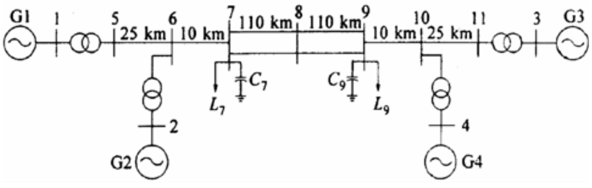

Fig. 7 Kundur's Two-area Test System

B. AVR and PSS

The excitation system is a dc exciter similar to described in [22] without the saturation function. The basic elements that form the excitation system block are the voltage regulator and the exciter.The conventional power system stabilizer (CPSS) is modeled by the nonlinear system as shown in Fig. 9. The optimization procedure of this CPSS is same as that of [14]. The values of Δω are given in Table 5.

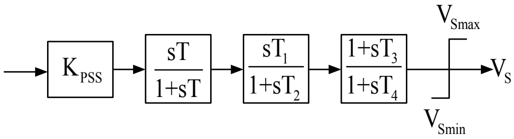

Fig. 8 Block diagram of the PSS

VIII. RESULTS

To evaluating the performance of the proposed method, two kinds of disturbances, small and large signal, are examined. The results are described as follows:

A. Small Disturbance

To study the efficiency of the proposed method in the case of small signal disturbance, 5% disturbance is applied to the reference voltage of machine 1 with both parallel transmission lines connected. The simulation results for rotor angle, terminal voltage and transmitted active power from area 1 to area 2 are shown in Fig. 10 to Fig. 12. Additional simulation results are presented in Fig. 13 to Fig. 15.

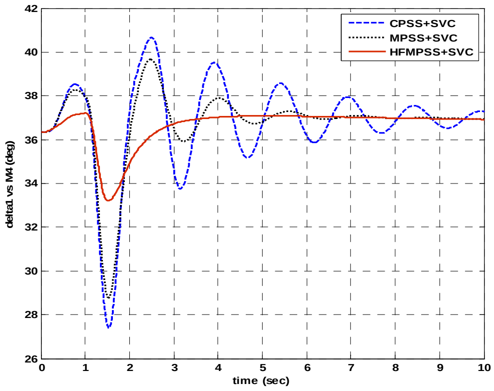

Fig. 9 Rotor angle deviation of machine 1 w.r.t. machine 4

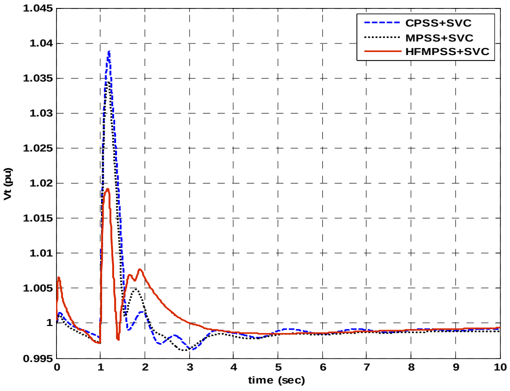

Fig. 10 Terminal voltage of machine 1

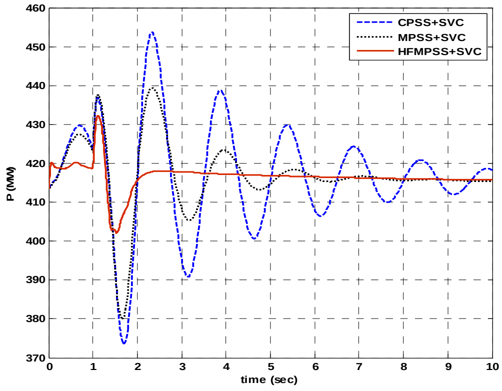

Fig. 11 Active power from area 1 to area 2

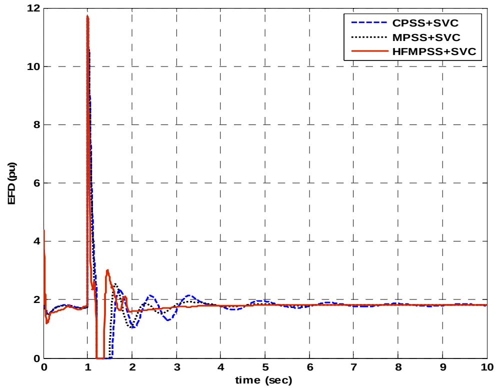

Fig. 12 Excitation voltage of machine 1

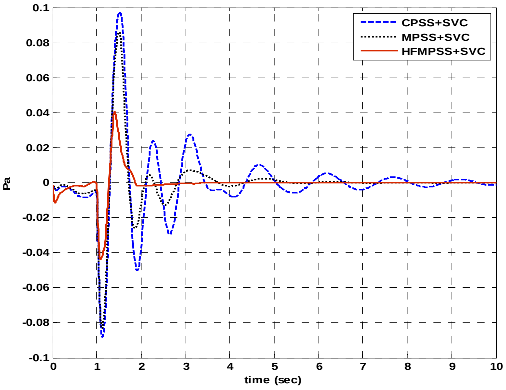

Fig. 13 Power deviation of machine 1

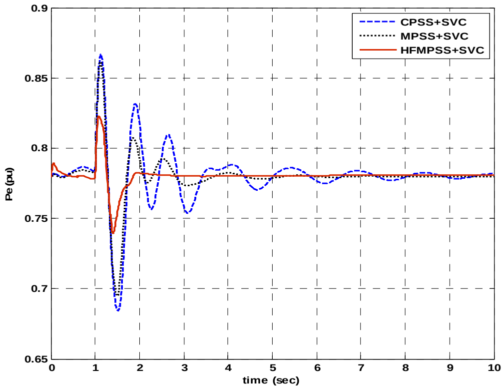

Fig. 14 Output power of machine 1

These simulations results show the superiority of HFMPSS&SVC compared to CPSS and MPSS. It can be seen from Figures 10-15 that HFMPSS&SVC may rapidly damp out oscillation. Comparison of Figures 10-12 with [13] show that the proposed method in [13] and HFMPSS&SVC have almost the same overshoot and settling time.

B. Large Disturbance

In this section to study the efficiency of the proposed method, first three-phase to earth error is created at the middle of one of the Tie-Lines. The performances of CPSS and MPSS and HFMPSS&SVC under these transient conditions are shown in Figures. 16-21. As seen, the HFMPSS&SVC has better damping effectiveness and control performance in comparison with CPSS and MPSS in terms of settling times and damping effects.

At the same time, while the performance of the proposed method in [13] suffers from a larger overshoot of over 12.5% , the proposed HFMPSS&SVC shows a 8% of overshoot.

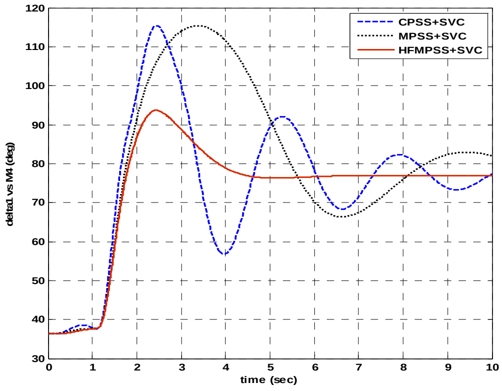

Fig. 15 Rotor angle deviation of machine 1 w.r.t. machine 4

IX. CONCLUSION

In this paper, a hierarchical fuzzy system based on Multi-input power system (MPSS) and Static Var Compensator (SVC) (HFMPSS&SVC) design is studied for test system is given in [14]. MPSS is obtained by adding ΔQ to classic stabilizer with ΔP+ΔW inputs for a long distance power system where δ is large. In the hierarchical method, the total number of rules increases only linearly with the number of input variables whereas it is exponential in conventional counterpart. SVC is one of the most effective devices for reactive power compensation and consequently voltage control in a power system. Simulation results show that the HFMPSS&SVC has good performance to damp low frequency power oscillations with respect to the CPSS and MPSS and the proposed method in [13], which proves the effectiveness of the proposed strategy in multi-input power system stability. According to the simulation results the HFMPSS&SVC has good robustness without changing any parameters.

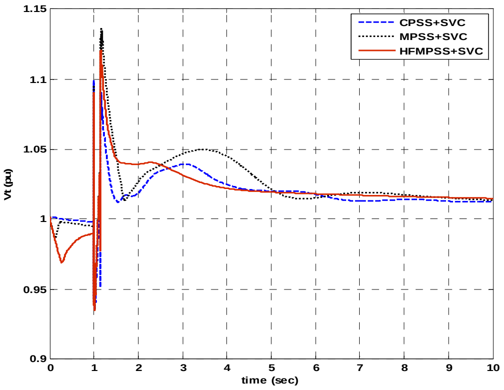

Fig. 17 Terminal voltage of machine 1

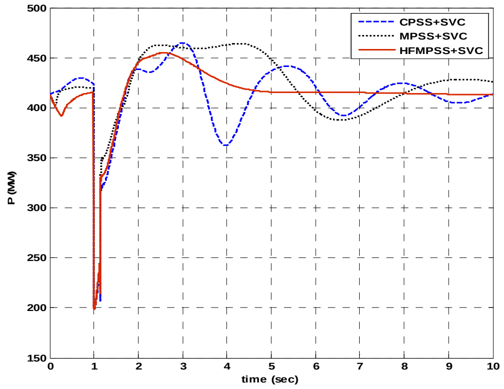

Fig. 18 Active power from area 1 to area 2

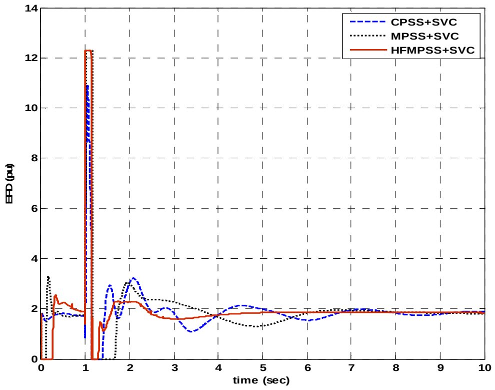

Fig. 19 Excitation voltage of machine 1

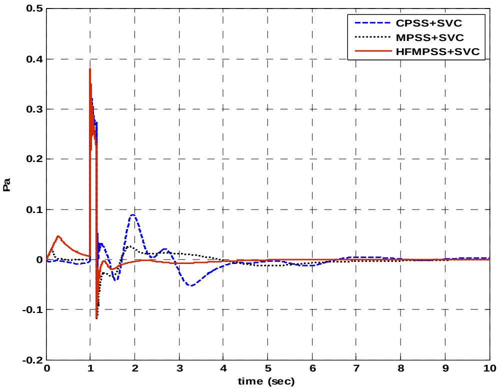

Fig. 20 Power deviation of machine 1

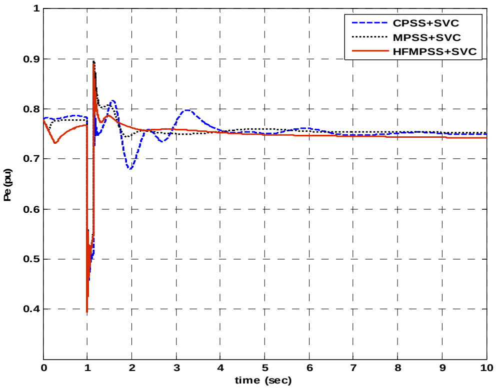

Fig. 21 Output power of machine 1

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APPENDIX

GENERATOR DATA

No. of Gen **Param.**	**G1,G2**	**G3,G4**
Type	**Steam**	**Steam**
Capacity (MVA)	900	900
Voltage (kV)	20	20
Xd (pu)	1.8	1.8
X'd (pu)	0.3	0.3
X"d (pu)	0.25	0.25
Xq (pu)	1.7	1.7
X'q (pu)	0.55	0.55
X"q (pu)	0.25	0.25
H (sec)	6.5	6.175
T'd0 (sec)	8	8
T"d0 (sec)	0.03	0.03
T'q0 (sec)	0.4	0.4
T"q0 (sec)	0.05	0.05

LOAD DATA

Param. **No. of Bus**	**P_l(MW)**	**Q_l(Mvar)**	**Qc(Mvar)**
7	967	100	387
9	1767	100	537

FUZZY CONTROLLER DATA

Input **Parameter**	**Δω**	**ΔP**	**ΔQ**
K_{PSS}	20	0.5	0.01
T (sec)	10	1	1
T_1 (sec)	3	0.06	0.06
T_2 (sec)	5.4	1	1
T_3 (sec)	3	0	0
T_4 (sec)	5.4	0	0