Fuzzy Based SVC with coordinated POD for Damping of Oscillations of Power System

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Abstract

This paper is aim to present the SVC intelligent control strategy to achieve improvement in damping of oscillations of two machine system. The most of SVC controllers are proportional integral (PI) type, however its performance under varying system conditions is not satisfactory. This paper compared the performance of SVC with PI type and fuzzy based control schemes under various system conditions. The details of intelligent fuzzy control of SVC have been design to achieve smooth reactive power control. The input signal for fuzzy logic controller is deviation in measured voltage at SVC location. The minimum fuzzy rules are applied to achieve maximum performance of the controller. The additional power oscillation damping (POD) signal is applied with fuzzy controller to suppress the local mode as well as inter area mode of oscillations. The proposed fuzzy controller coordination with POD provides significant improvement in damping of the system. The effectiveness of the proposed control strategy is demonstrated in two machine systems. The results are validated in MATLAB.

Keywords: SVC, Fuzzy logic control, damping of oscillations, power system.

1 Introduction

Power system oscillation stability refers to the damping of electromechanical oscillations occurring in the power system with oscillation frequency in the range of 0.2 Hz to 2Hz. These low frequency oscillations are the consequences of the development of interconnection of large power systems. A low frequency oscillation in a power system constrains the capability of power transmission, threatens system security and damages the efficient operations of the power system. To ensure satisfactory operation of the increasingly large and more complex electric power systems, stability improvement and robustness of stabilizing controllers are of major concern[1-4].

The fast advancement in the filed of power electronics technologies applied to power industry by utilizing the Flexible AC Transmission systems (FACTS) devices like Static VAR Compensators (SVC). It is proven that a suitable supplementary control signal to the SVC voltage control loop through a controller can improve transient stability and support to damp power system oscillations. It can provide damping to the inter area and local mode oscillations of the generating units in a multi-machine power system[4-7].

PSS are widely used through the excitation system of generator to improve the stability of power system, which has been becoming more complicated in recent year[1]. SVC is placed in a power system for maintaining bus voltage at or near constant level however contribution to damping is very poor. A significant contribution to system damping can be achieved when an additional damping signal applied to SVC voltage control loop[2-7].

Most of the SVC controllers are based on PI controller. Although the PI controllers are simple and easy to design, their performance deteriorates when the system operating conditions vary widely and large disturbance occur. Various control techniques have been used to develop SVC controllers. Among these, fuzzy logic control schemes have received considerable attention as a novel computational system because of the variety of advantages it offers over the conventional computational systems [8-18]. Fuzzy logic controllers (FLC) are capable of tolerating uncertainty and imprecision to a greater extent. So, they produce good results under changing operating conditions and uncertainties in system parameters. Ref.[9] described the full scale fuzzy and PID combine together based SVC for stability analysis with large nos of rule base without considering the damping approach POD. Ref.[13]demonstrated the fuzzy PID based SVC with more nos of rule base. This paper presents the independent fuzzy logic control based SVC with additional damping signal POD. The minimum nos of rule base has been design to achieve maximum damping performance in a two machine power system. The effectiveness of fuzzy based SVC is compared with conventional PI based SVC on damping of local and inters area modes of oscillations in a test power system under abnormal system conditions. The simulations have been carried out in MATLAB environment.

2 System Model

In this study, a two machine power system shown in Fig.1 is considered for study. An SVC device is connected at the middle bus 3 of the transmission line. The detail system data is given in appendix I. The basic elements that form the excitation system block are the voltage regulator and the exciter. The typical TSC-TCR type SVC with firing control system is shown in Fig.1. The detail mathematical model of power system , exciter & PSS is given in appendix II.

3 Static Var Compensator

A Static Var Compensator consists of capacitors and reactors connected in shunt, which can be quickly controlled by thyristor switching. The suscepatnce is varied in response to system voltage conditions by a thyristor controlled reactor in parallel with switched capacitors. Direct and rapid bus voltage control forms the principal basis of SVC for transient stability enhancement. SVC increases power transfer during low voltage conditions while fault on the system by decreasing generator acceleration and vice versa . when the fault is cleared. If SVC is on the system, it reduces the adverse impact of the fault on the generator's ability to maintain synchronism[4-6].

The relation between the compensator inductive susceptance B_L and the conduction angle α for fundamental frequency in nonlinear which is given as follows :

$$B_L(\alpha) = \frac{\alpha - \sin\alpha}{\pi X_L} \quad (1)$$

The total susceptance of SVC has the magnitude

$$B = B_L - B_C \quad (2)$$

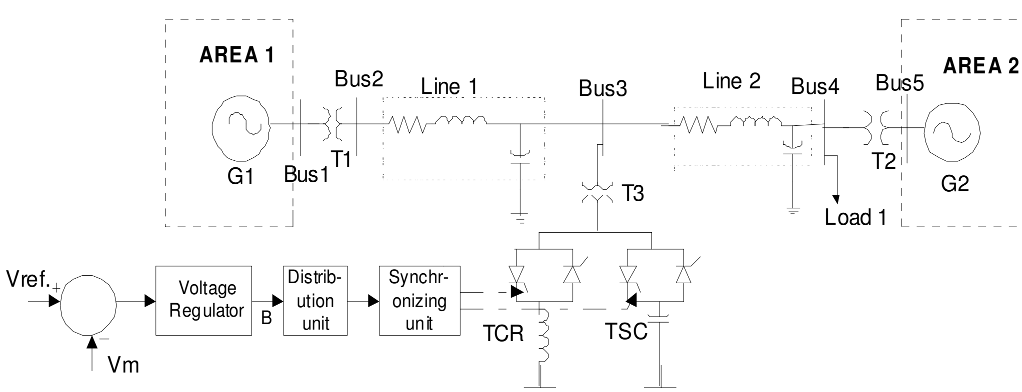

Fig.1: Two machine system with SVC

Where B_C is a biasing capacitor that allows the range of the compensator to enter both the capacitive and inductive regions. The SVC voltage regulator control block diagram is shown in Fig. 2. An additional damping signal is applied through power oscillation damping (POD) which is described in section 4.

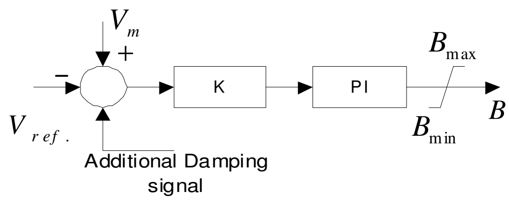

Fig. 2. Voltage regulator block diagram

4 Power System Oscillations Damping Controller (POD)

A damping controller is provided to improve the damping of power system oscillations. The damping controller is considered as comprising two cascade connected blocks. The input signal is speed deviation signal which is the difference of area 1 and area 2 speeds. The gain K_{pod} is chosen by trial and error method and wash out time constant T_w is chosen in between 0 to 20. The second block comprises a lead lag compensator. The Fig.3 shows the block diagram of power oscillation damping (POD) controller. The parameters of POD controller is tuned by using trail and error method, so as to achieve the desired damping ratio of the electromechanical mode and compensate for the phase shift between the control signal and the resulting electrical power deviation. The output of the damping controller modulates the reference setting of voltage of bus 2. In Fig. 3, the ΔV deviation signal is replaced by ΔV +U in order to include the POD for improvement of dynamic performance.

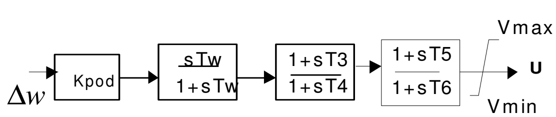

Fig. 3. POD Block diagram

5 Fuzzy Logic Controller

Fuzzy logic controller is one of the most practically successful approaches for utilizing the qualitative knowledge of a system to design a controller. Fuzzy logic has successfully been applied for feedback signal based coordination. The fuzzy coordination controller involves following three stages:

(1) Fuzzification (2) Rule-Base
(3) Defuzzification

5.1 Fuzzification

It is a process whereby the input variables are mapped onto fuzzy linguistic variables. Each fuzzified variable has a certain membership function. The input signal deviation in voltage (dV) is fuzzified using three fuzzy sets: HI (high), OK (okay) and LO (low) as shown in Fig 4, the second input is integral of dV is fuzzified using three fuzzy sets: NE (negative), NO (none) and PO (positive) as shown in Fig 5. The output signal with five fuzzy sets: CF (close fast), CL (close slowly), NC (no change), OL (open slow) and OF (open fast) as shown in Fig.6.

5.2 Rule-Base

The general form of the rules is IF premise THEN consequent. The design of these rules depends on the operator's knowledge and experience. With two inputs voltage deviation (ΔV) and integral of voltage deviation $\left(\int \Delta V\right)$ and three linguistic terms for each of these. The out put is firing signal to SVC has five linguistic terms. The rules are formed with less numbers so that feasibility for practical implementation will be easy , without losing the maximum performance

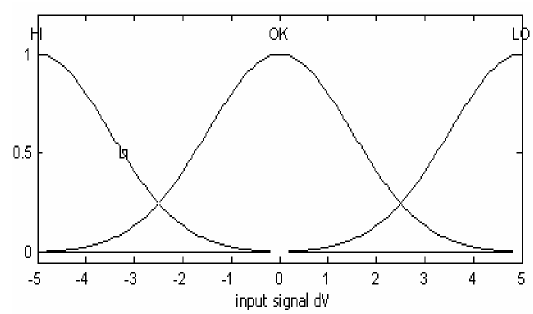

Fig. 4. Input signal deviation in voltage (dV)

of the controller. The rules are listed as under:

1. If (ΔV is OK) then (Firing signal is NC)
2. If (ΔV is LO) then (Firing signal is OF)
3. If (ΔV is HI) then (Firing signal is CF)
4. If (ΔV is OK) and ($\int \Delta V$ is PO) then (Firing signal is CL)
5. If(ΔV is OK) and ($\int \Delta V$ is NE) then (Firing signal is OL)

The inference is design to achieve improved damping performance of the system. It is easy to adjustable with additional damping signal. The proposed minimum rule base is capable to improve damping performance of the system.

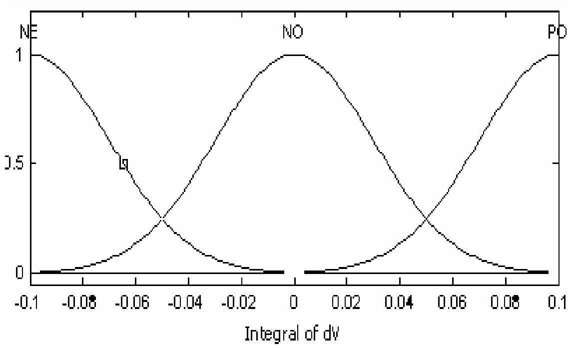

Fig. 5. Second input signal integral of deviation in voltage (dV)

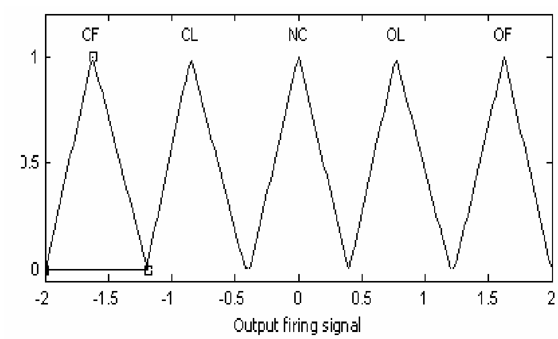

Fig. 6. Output of fuzzy controller

Defuzzification

This stage produces the final crisp output of FLC on the base of fuzzy inputs. The center of gravity (COG) law is employed here. The out put expression is as follow

$$O / P = \frac{\sum_{i=1}^{5} b_i \int \mu_{(i)}}{\sum_{i=1}^{5} \int \mu_{(i)}} \qquad (3)$$

Where b_i denotes the center of the membership function and $\mu_{(i)}$ is the membership of member i of output fuzzy set.

6 Simulation Results

Simulation of two machine test system has been carried out in MATLAB environment. The proposed fuzzy based SVC is compared with conventional PI based SVC on performance of the primary function as well as secondary function of SVC.The controllers are tested under normal and abnormal system conditions.

6.1 Response of the system without SVC

The three phase short circuits at bus 2 for the duration of 0.05 second has been applied. The system simulation response under no fault condition is shown in result. Fig.7 indicate that the generator 1 terminal voltage is steady during no fault condition. Fig. 8 & Fig. 9 indicates that the local mode and inter area mode of oscillations are stable without fault. The response of the three phase fault indicates that the system experienced the oscillations and it takes more than 5sec. for settling.

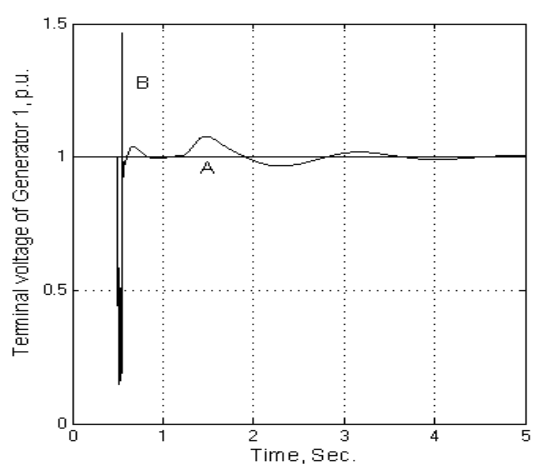

Fig. 7: System response without SVC
A: Generator 1 terminal voltage with no fault
B: Generator 1 terminal voltage with fault

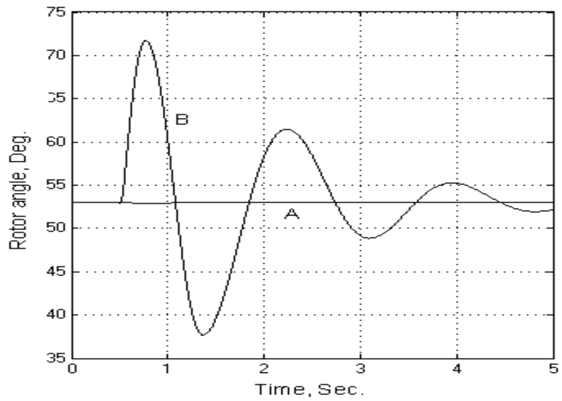

Fig. 8 : System response without SVC
A: Rotor angle with no fault
B: Rotor angle with fault

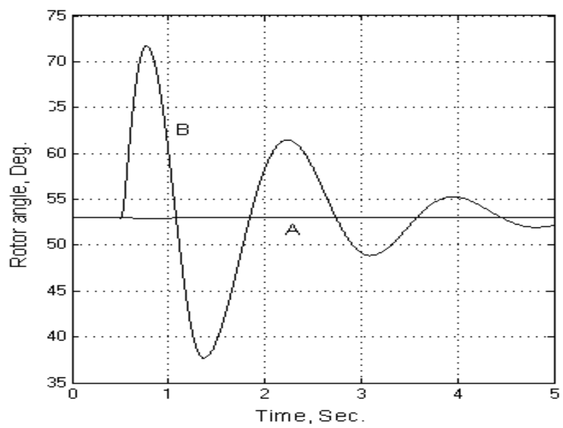

Fig. 9: System response without SVC
A: Difference of speed with no fault
B: Difference of speed with fault

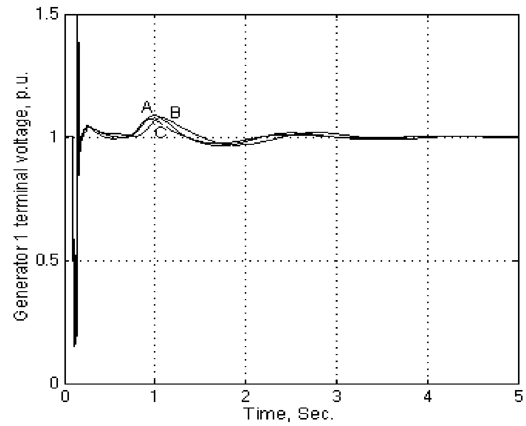

Fig. 10 : Response of the Two machine system
A: With out SVC B: PI based SVC without POD C: PI based SVC with POD

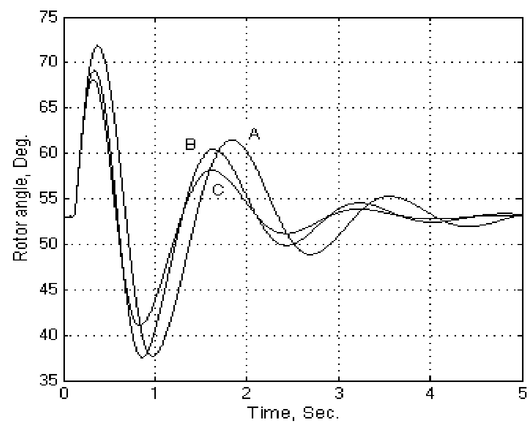

Fig. 11 : Response of the Two machine system
A: With out SVC B: PI based SVC without POD
C: PI based SVC with POD

Table 1: Response of PI SVC for local mode

	First Peak	Settling time (s)	No. of Oscillations
Without SVC	72°	<5	<4
PI SVC	69°	<5	3
PI SVC and POD	67°	4.5	2

Table 2: Response of PI SVC for inter area

	First Peak(Rad/ses)	Settling time (s)	No. of Oscillations
Without SVC	0.006	<5	<3
PI SVC	0.006	4	2
PI SVC and POD	0.006	3.5	1.5

6.2 Response of the system with PI based SVC and POD

The system response during the three phase fault at Bus 2 of during 0.05 sec. The PI based SVC performance in terms of voltage regulation is shown in Fig.10. The additional damping signal POD applied to explore the improved damping performance of the SVC. The local mode of oscillations is demonstrated in Fig. 11 and inters area oscillations have been presented in Fig. 12. The Fig.11 & Fig. 12, indicated that the damping of the system improved by applying POD. The results analysis is presented in Table 1 and 2.

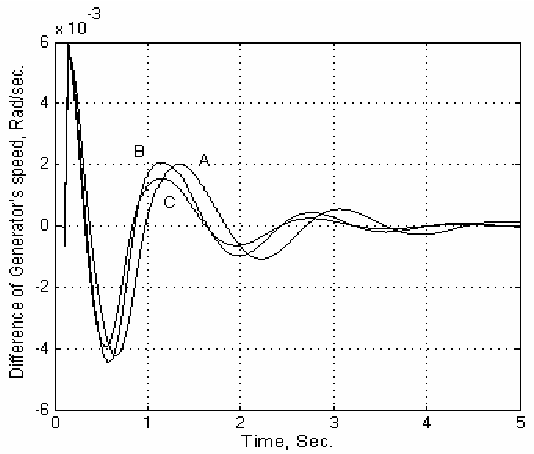

Fig. 12 : Response of the Two machine system
A: With out SVC B: PI based SVC without POD
C: PI based SVC with POD

6.3 Response of the system with Fuzzy based SVC and POD

The simulation response of the two machine test system with Fuzzy based SVC is demonstrated in this section. The voltage regulation function of SVC is improved under abnormal condition as shown in Fig.13. The damping performance is further improved by POD additional signal to Fuzzy based SVC controller. Fig. 14 shows the improved damping of local mode oscillations of the system and Fig.15 shows the improved damping of inter area oscillations of the system. The designed fuzzy inference fulfilled the basic objective of the fuzzy control strategy. The minimum rules are utilized to achieve proposed objective of the fuzzy logic controller.

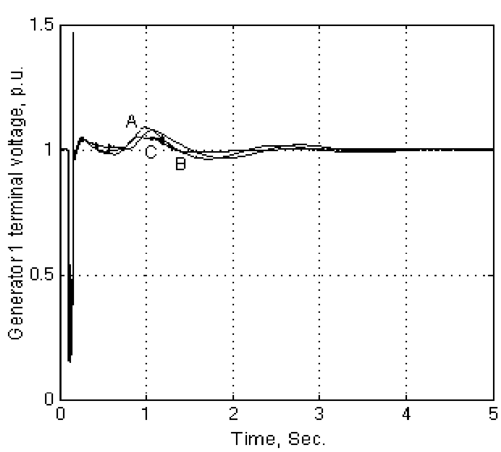

Fig.13: Response of the Two machine system
A: With out SVC, B: Fuzzy based SVC without POD, C: Fuzzy based SVC with POD

The minimum fuzzy rules are applied so that the feasibility of proposed controller for practical implementation has to be increase with out loosing performance .

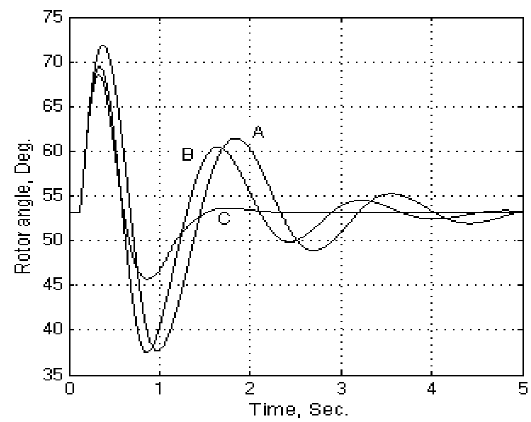

Fig.14 : Response of the Two machine system
A: With out SVC B: Fuzzy based SVC without POD C: Fuzzy based SVC with POD

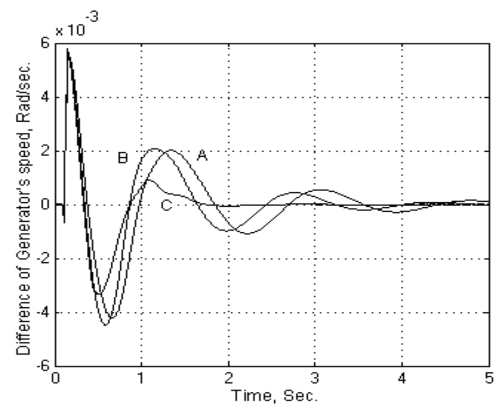

Fig. 15 : Response of the Two machine system
A: With out SVC B: Fuzzy based SVC without POD C: Fuzzy based SVC with POD

Table3: Response of Fuzzy SVC for local mode

	First peak	Settling time (s)	No. of Oscillations
With out SVC	72°	<5	<3
Fuzzy SVC	69°	4.5	2.5
Fuzzy SVC and POD	68°	1.6	1

Table 4: Response of Fuzzy SVC for inter area

	First peak(Rad./sec.)	Settling time (s)	No. of Oscillations
Without SVC	0,006	<5	<3
Fuzzy SVC	0.006	4.5	2
Fuzzy SVC and POD	0.006	1.6	1

6.4 Compare the response of the system with PI and Fuzzy based SVC

The system response for PI based SVC and Fuzzy based SVC performance is compared for primary function as well as secondary function. Fig.16 indicates that the improved voltage regulations have been achieved. The local mode of oscillations are suppressed significantly by using fuzzy based SVC with POD as compare to PI controller as shown in Fig.17. The inter area oscillations are damped by fuzzy based SVC with POD as compared to PI controller which is shown in Fig.18. The comparative analysis of results are shown in Table5 and Table6. The proposed fuzzy controller with POD significantly reduces the oscillations and settling time. The first peak is also reduced by fuzzy controller. The designed inference system is easy to adjust additional damping signal POD.

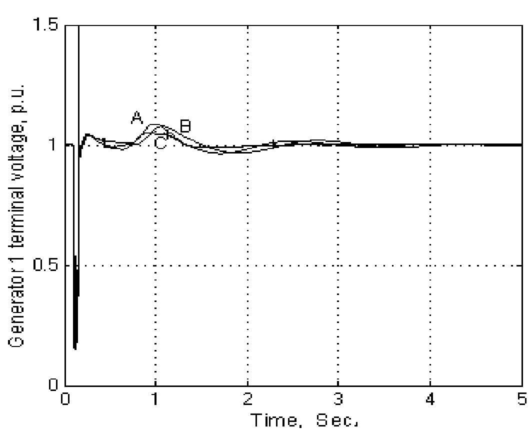

Fig.16 : Response of the Two machine system
A: With out SVC B: PI based SVC with POD
C: Fuzzy based SVC with POD

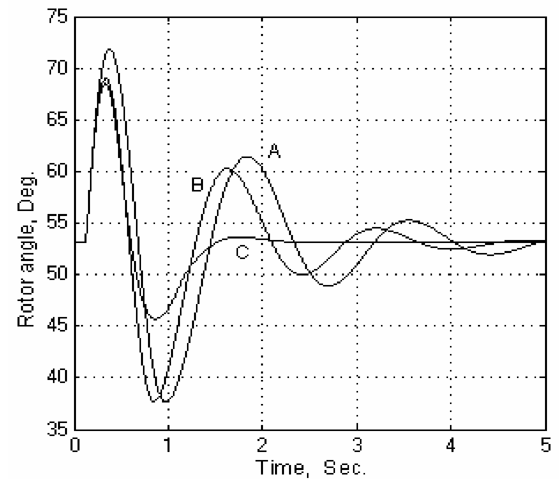

Fig.17 : Response of the Two machine system
A: With out SVC B: PI based SVC with POD
C: Fuzzy based SVC with POD

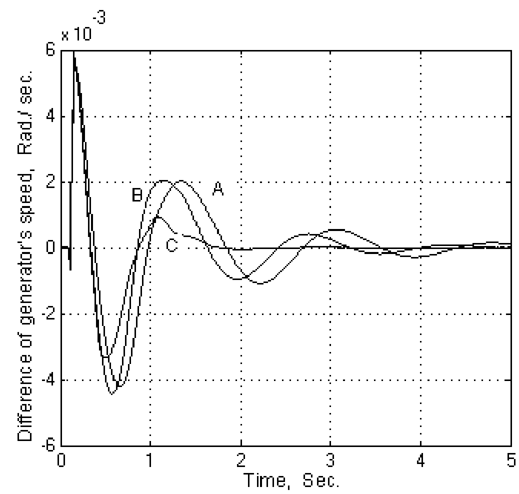

Fig. 18 : Response of the Two machine system
A: With out SVC B: PI based SVC with POD
C: Fuzzy based SVC with POD

Table 5: Comparison on local mode of oscillations

	First Peak	Settling time(S)	No. of Oscillations
PI with POD	68°	4.4	2.5
Fuzzy with POD	67.5°	1.6	1

Table 6: Comparison on inter area oscillations

	First Peak(Rad./sec.)	Settling time (s)	No. of Oscillations
PI with POD	0.006	4.4	2.5
Fuzzy with POD	0.006	1.6	1

7 Conclusion

A fuzzy logic based controller for SVC has been proposed to improve damping of oscillations and voltage regulation of the power system. The fuzzy rules have been designed to minimize oscillations, maximize real power flow and smooth voltage regulation. Simulation results show that the coordinated fuzzy logic controller for SVC with POD provides a system performance that meets the main objective and the results at different operating conditions demonstrate the robustness of the controller. The comparative study of proposed controllers of SVC indicates that fuzzy based controller performance is better than PI based controller. The simplicity of the design is the most attractive feature of fuzzy based control scheme and feed back signal are based on local measurable components. The additional damping signal derived by using POD significantly improved the dynamic performance of the system. The study revealed that the SVC device performance can be maximize by applying intelligent controller and additional damping signal POD to voltage control loop.

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Appendix I System data

Reference Voltage : 1.006 pu.
Base Voltage : 500Kv
Base MVA : 100
M/C-I : 1000MVA, 13.8Kv, 60 c/s, H(s)=3.7, Xd=1.305,Xd'=0.296,Xd"=0.252,Xq=0.474 ,Xq"= 0.242, Xl=0.18pu
M/C-II : 5000MVA, 13.8Kv, 60 c/s, H(s)=3.7, Xd=1.305,Xd'=0.296,Xd"=0.252,Xq=0.474, Xq"= 0.243, Xl=0.18pu
Transformer I: 1000MVA,60 c/s, 13.8Kv/500 Kv
Transformer II: 5000 MVA, 60 c/s, 500Kv/13.8Kv
T.Line 1 & T.Line 2: R= 0.01755 ohm/km, L= 0.0008737 H/km, C= 13.33 e-9 F/km, length = 350 km.
Shunt Transformer III : 500MVA, 60c/s, 500Kv / 13.8 Kv, 60 c/s.
Reactive power limits: Q: 0 to 500 MVAR ,
PI : K = 20, Kp=5, Ki=2
POD : Kpod=50, T1=0.05sec. , T2= 0.03 sec., T3= 3 sec. , T4= 5.4 sec.

Appendix II

A. Modeling of Power System

The generator is represented by 6th order differential equations given below:

$$\frac{d\delta_j}{dt} = \omega_j - \omega_0 \tag{4}$$

$$\frac{d\omega_j}{dt} = \frac{1}{M}(P_{mj} + K_d\omega_j - P_{ej}) \tag{5}$$

$$\frac{dE'_{dj}}{dt} = \frac{1}{T'_{q0}}(-E'_{dj} + (x'_{qj} - x_{qj})i_{qj}) \tag{6}$$

$$\frac{dE'_{qj}}{dt} = \frac{1}{T'_{d0}}(E_{fj} - E'_{qj} + (x_{dj} - x'_{dj})i_{dj}) \tag{7}$$

$$\frac{dE''_{qj}}{dt} = \frac{1}{T''_{d0}}(E'_{qj} + (x'_{dj} - x''_{dj})i_{dj} - E''_{qj}) \tag{8}$$

$$\frac{dE''_{dj}}{dt} = \frac{1}{T''_{q0}}(E'_{dj} - (x'_{qj} - x''_{qj})i_{qj} - E''_{dj}) \tag{09}$$

The system algebraic equations are given as follows :

$$i_{dj} = G_{jj}E''_{dj} + B_{jj}E''_{qj} + \sum_{\substack{k=1\\k\neq j}}^{n}\left\{\begin{matrix}\left[E''_{dk}(G_{jk}\cos\delta_{jk} + B_{jk}\sin\delta_{jk})\right] + \\ \left[E''_{qk}(B_{jk}\cos\delta_{jk} - G_{jk}\sin\delta_{jk})\right]\end{matrix}\right\} \tag{10}$$

$$i_{dj} = G_{jj}E''_{qj} - B_{jj}E''_{qj} + \sum_{\substack{k=1\\k\neq j}}^{n}\left\{\begin{matrix}\left[E''_{qk}(G_{jk}\cos\delta_{jk} + B_{jk}\sin\delta_{jk})\right] - \\ \left[E''_{dk}(B_{jk}\cos\delta_{jk} - G_{jk}\sin\delta_{jk})\right]\end{matrix}\right\} \tag{11}$$

$$V_{dj} = E''_{dj} - r_j i_{dj} - x''_{qj} i_{qj} \tag{12}$$

$$V_{qj} = E''_{qj} - r_j i_{dj} + x''_{dj} i_{dj} \tag{13}$$

$$V_j = \sqrt{V_{dj}^2 + V_{qj}^2} \tag{14}$$

$$P_{ej} = E''_{dj} i_{dj} + E''_{qj} i_{qj} + (x''_{dj} - x''_{qj}) i_{dj} i_{qj} \tag{15}$$

Where
δ = Rotor angle in degree
ω = angular speed in rad/sec
M = inertia constant
T'_{do} = d-axis open circuit transient time constant
T''_{do} = d-axis open circuit sub transient time constant
T'_{qo} = q-axis open circuit sub transient time constant
T''_{qo} = q-axis open circuit sub transient time constant
P_m = Mechanical power
K_d = Damping constant of the generator
x_d, x_q = Direct & quadrature axis reactance of the generator in p.u.
E_d, E_q = Direct & quadrature axis voltage behind the transient reactance in p.u.
P_e = Electrical power delivered in p.u.

B. Exciter and PSS

The block diagram representing IEEE type 1 DC exciter and power system stabilizer (PSS) accommodated with the generator is shown in Fig.19 which is modeled with the following equations

$$E_{fd} = \frac{K_A}{T_A}(V_{ref} - V_t + U_{PSS}) - \frac{E_{fd}}{T_A} \quad (16)$$

$$P_e = v_d i_d + v_q i_q \quad (17)$$

and

$$V_t = (v_d^2 + v_q^2)^{1/2} \quad (18)$$

with

$v_d = E \sin \delta - (x_q i_q) D_s$ and

$v_q = E_q^{'} - x_d^{'} i_d$

$$G = (K_{G1} + \frac{K_{G2}}{1 + sT_G})\dot{\delta} \quad (19)$$

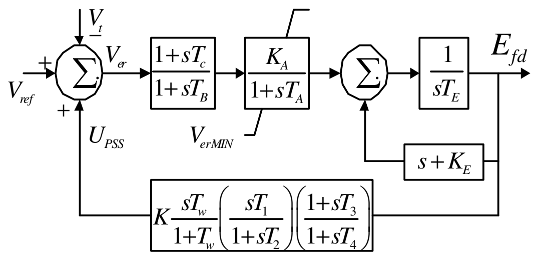

Fig.19. IEEE type DC1 exciter

$$U_{PSS} = -\frac{1}{K_p}\left(\frac{sT_1}{1 + sT_2}\right)\left(\frac{1 + sT_3}{1 + sT_4}\right)\dot{\delta} \quad (20)$$

Where

K_A and T_A = gain and time constants of the exciter

V_{ref} = reference voltage in p.u

V_t = Terminal voltage in p.u.

E_{fd} = Field voltage of the generator in p.u.

K_{G1}, K_{G2} = Gain constants of the governor

K_p =Gain of the PSS

T_1, T_2, T_3 and T_4 = Time constant of the PSS

D_s = Damping coefficient of PSS

U_{PSS} = Output of PSS in p.u.