Design of a Single Input Fuzzy Logic Controller Based SVC for Dynamic Performance Enhancement of Power Systems

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Abstract: This paper presents a design of a Single Input Fuzzy Logic Controller (SFLC) based Static VAR Compensator (SVC) for Dynamic performance enhancement of power systems. The SFLC uses only one input which is the signed distance and has the advantage of reduced number of rules. Improvement of dynamic response by the controller is illustrated in a bifurcation perspective. Bifurcation diagrams of steady state as well as periodic solutions are constructed using continuation method. From the bifurcation diagrams, the existence of various bifurcation points such as, unstable Hopf bifurcation (UHB), stable Hopf bifurcation (SHB), saddle node bifurcation (SNB) and period doubling bifurcation (PDB) are identified. With the use of tools of nonlinear dynamics, voltage collapse points, and chaotic solutions due to period doublings are unearthed. The effectiveness of the SFL controller over the conventional controller for SVC in delaying the incidence of Hopf bifurcation (HBF), SNB and hence increasing the loadability limit is illustrated for the test system.

Keywords: SFLC, SVC, voltage collapse,HBF, SNB

I. Introduction

It is recognised in the literature that system instability generally emerges from two types of events: gradual parameter variations and contingencies. This paper focusses on the analysis of power systems subject to gradual parameter variations such as load variation. This analysis can be made through local bifurcation analysis in which the system is studied by the eigen values of linearization around an equilibrium point. This analysis is suitable for problems ralated to secure power system operation and design with particular attention to stability margins and control actions required to postpone a specific type of instability.

With increasing popularity of Flexible AC transmission system (FACTS) devices and SVC being the well-understood and widely accepted FACTS device, it is worth exploring the role of SVC in improvement of dynamic stability of power systems.

L.Ji and Z. XueSong [1], presented continuation based approach for tracing equilibrium curve of a power system using differential algebraic model, analysis of parameter effect on voltage stability and effect of SVC on the occurrence of Hopf bifurcation. Effectiveness of PSS, SVC and STACOM in damping interarea oscillations from the point of view of Hopf Bifurcations using Eigen value analysis is presented by Mithulananthan. V et al.[2].

Wang . Y et al. [3] discussed voltage stability enhancement by a non-linear SVC controller designed through direct feedback linearisation technique. Gracia kasuki et al. [4] had shown the application of SVC to damp out sustained voltage oscillations for a given level of reactive power demand as well as increasing the maximum point of system's loadability using a first order delay model of SVC. Mohamed S. Sad et al [5] introduced washout aided feedback in the design of SVC to increase the range of stable operation of a power system susceptible to voltage collapse.

However, to provide an improved voltage regulation and damping system oscillations and handle parameter uncertainties and unmodeled dynamics, control methods based on fuzzy logic need to be developed. Byung – Jae Choi et al.[6], suggested a simple but powerful FLC design method using a new variable called signed distance which is equivalent to pseudo sliding mode controller. Londhe P.S et al. [7], proposed a simplified scheme to design a single input Fuzzy logic Controller for control of Advanced Heavy Water Reactor.

This paper addresses the performance of single input fuzzy logic based controller for SVC in a bifurcation perspective. Bifurcation diagrams of equilibrium as well as periodic branch are obtained from the computer implementation of the algorithm proposed by Padma Subramanian. D. et al.[8]. The improvement of dynamic response by the proposed controller is illustrated though delaying the occurrence of HBF, SNB hence an increase in loadability limit and elimination of dynamic voltage collapse.

This paper is organized as follows: Section 2 presents modeling of various power system components including SVC. A brief explanation about the single input fuzzy logic controller strategy and the design procedure for implementation of SFL controller for SVC is presented in Section 3. In Section 4, the results of implementation of the proposed SFLC for SVC are presented. The effectiveness of SFLC based SVC is illustrated in this Section by comparing the results of SFLC based SVC with the results of conventional SVC. Concluding remarks are presented in Section V.

II. Power System Description and modelling

The description of various power system models used in this study are as follows.

A. ***Power System Model***

The power system considered for investigation is shown in Fig. 1.

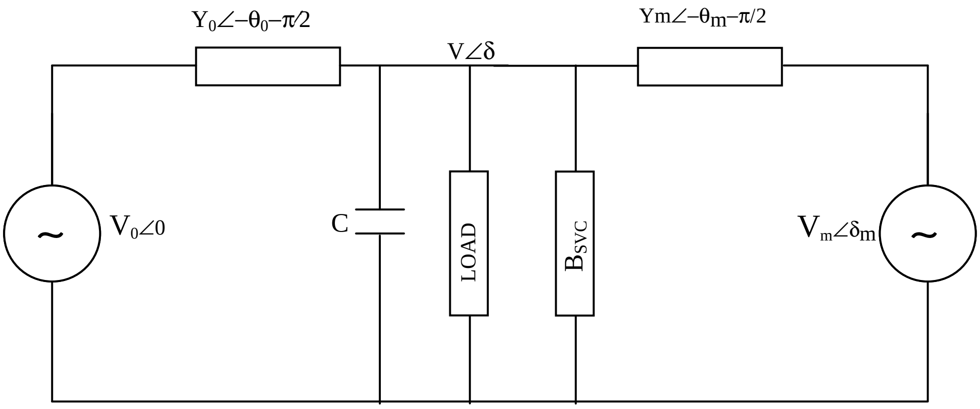

Fig. 1. A simple power system

It consists of two generator buses and a load bus. The SVC is placed at the load bus. One of the generator buses is treated as a slack bus and the other generator is described by the swing equation. The load is modelled by a simplified induction motor in parallel with constant P-Q load and constant impedance as described in Chiang. H. D et al. [9]. The induction motor model specifies the real and reactive power demands in terms of load voltage and frequency. The load model is described by

$$P = P_0 + P_1 + K_{pw}\,\dot{\delta} + K_{pv}\,(V + T\dot{V}) \tag{1}$$

$$Q = Q_0 + Q_1 + K_{qw}\,\dot{\delta} + K_{qv}\,V + K_{qv2}\,V^2 \tag{2}$$

where P_0, Q_0 are the constant real and reactive powers of the induction motor and P_1, Q_1 are the constant P-Q load and K_{pw}, K_{pv}, K_{qw}, K_{qv} and K_{qv2} are constants associated with the dynamic load. The real and reactive powers supplied to the load by the network are

$$P = -V_0' V Y_0' \sin(\delta+\Theta_0') - V_m V Y_m \sin(\delta - \delta_m + \Theta_m) + \left(Y_0' \sin\Theta_0' + Y_m \sin\Theta_m\right) V^2 \tag{3}$$

$$Q = V_0' V Y_0' \cos(\delta+\Theta_0') + V_m V Y_m \cos(\delta - \delta_m + \Theta_m) - \left(Y_0' \cos\Theta_0' + Y_m \cos\Theta_m\right) V^2 \tag{4}$$

The load bus includes a capacitor as part of its constant impedance representation in order to maintain the voltage magnitude at a nominal and reasonable value. Instead of including the capacitor in the circuit, it is convenient to account for the capacitor by adjusting V_0 and Y_0 to give Thevenin equivalent of the circuit with the capacitor. Primes are used to indicate Thevenin equivalent circuit values. The adjusted values are as given in Chiang. H. D et al [9].

$$V_0' = \frac{V_0}{\left(1 + C^2 Y_0^{-2} - 2\,C\,Y_0^{-1}\cos\Theta_0\right)^{1/2}} \tag{5}$$

$$Y_0' = Y_0\left(1 + C^2 Y_0^{-2} - 2\,C\,Y_0^{-1}\cos\Theta_0\right)^{1/2} \tag{6}$$

$$\Theta_0^{'} = \Theta_0 + \tan^{-1}\left\{\frac{C\,Y_0^{-1}\sin\Theta_0}{1-C\,Y_0^{-1}\cos\Theta_0}\right\} \quad (7)$$

B. ***Static VAR Compensator***

A simplified first order delay model of SVC, which is termed as conventional SVC in this paper, has been considered to represent the dynamics of its control action employed for delaying the dynamic bifurcations. This is shown in Fig. 2.

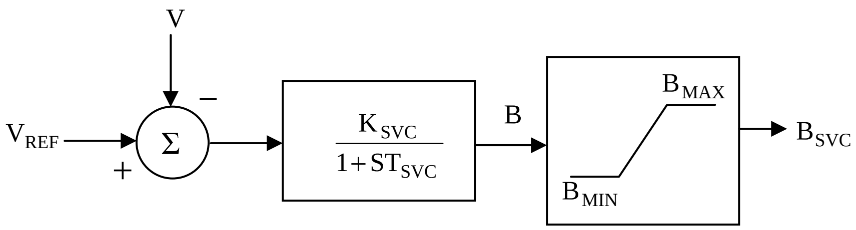

Fig.2 Block diagram representation of Static VAR compensator

From Fig. 2., the equations describing the dynamics of SVC are written as:

$$\dot{B} = \frac{K_{SVC}}{T_{SVC}}\left(V_{ref} - V\right) - \frac{B}{T_{SVC}} \quad (8)$$

$$\text{where } B_{\min} \le B \le B_{\max}$$

where B is the susceptance, K_{SVC} is the SVC gain, T_{SVC} is the time constant and V_{ref} is the reference voltage. In order to model the SVC hard limiters, a *tanh* function isemployed, such that for a susceptance B with limits ± B_{LIMIT}, the output of the limiter is given by,

$$B_{SVC} = B_{LIMIT}\tanh\left(\frac{B}{B_{LIMIT}}\right) \quad (9)$$

The net effect of the variable susceptance introduced to the system by the SVC is modelled as an additional reactive power source, $Q_{svc} = B\,V^2$.

The equations describing the dynamics of the power system model with SVC are:

$$\dot{\delta}_m = \omega_m \quad (10)$$

$$M\dot{\omega}_m = -D\omega_m + P_m + V_m V Y_m \sin(\delta - \delta_m - \Theta_m) + V_m^2 Y_m \sin\Theta_m \quad (11)$$

$$K_{qw}\dot{\delta} = -K_{qv}V - K_{qv2}V^2 + Q + Q_{svc} - Q_0 - Q_1 \quad (12)$$

$$T K_{qw} K_{pv}\dot{V} = K_{pw}K_{qv2}V^2 + \left(K_{pw}K_{qv} - K_{qw}K_{pv}\right)V + K_{pw}\left(Q_0 + Q_1 - Q - Q_{SVC}\right) - K_{qw}\left(P_0 + P_1 - P\right) \quad (13)$$

Equations (10)-(13) along with (8)-(9) describe the dynamics of the system shown in Fig. 2.

III. Design of SFLC

The SFLC is designed for fuzzy logic controllers (FLC) with skew symmetric property in the control rule table, i.e., the control inputs above and below the switching line have opposite signs as shown in Fig. 3. A new variable called a signed distance, is derived which is the distance to an actual state from the main diagonal line (or hyper plane) and is positive or negative according to the position of the actual state.

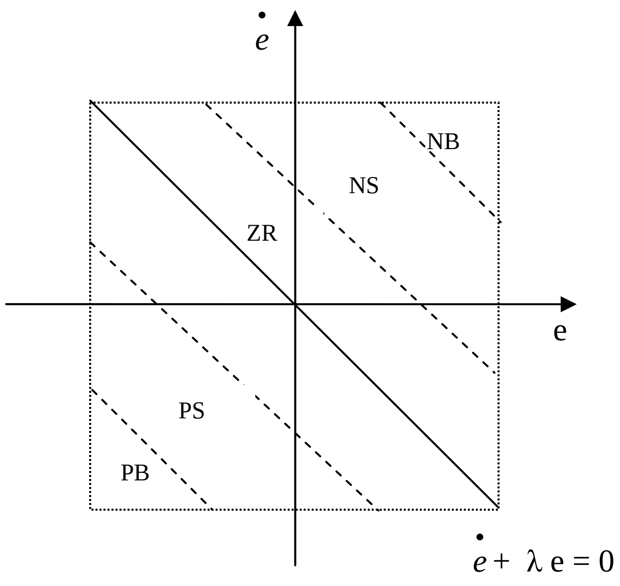

Fig. 3. Rule Table with infinitesimal quantization levels

The signed distance is used as a sole fuzzy input variable in SFLC also called Simple FLC. Magnitude |u| of the control input is proportional to the signed (d_s) from the straight line called switching line S_l:

$$S_l : \dot{e} + \lambda e = 0$$

Let $H(e, \dot{e})$ be the intersection point of the switching line and line perpendicular to the switching line from an operating point $P(e_1, \dot{e}_1)$ as illustrated in Fig. 4.

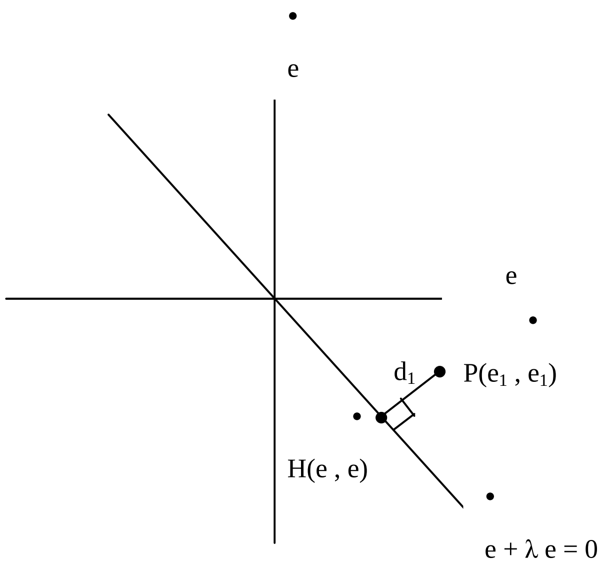

Fig. 4. Derivation of the signed distance

The distance d_1 between H(e, e) and P(e_1, e_1), can be expressed as

$$d_1 = \left[\left(e - e_1\right)^2 + \left(\dot{e} - \dot{e}_1\right)^2 \right]^{1/2} = \frac{\left|\dot{e}_1 + \lambda e_1\right|}{\sqrt{1+\lambda^2}} \qquad (14)$$

Equation (14) can be written in general for any (e, $\dot{e}$) as:

$$d = \frac{\left|\dot{e} + \lambda e\right|}{\sqrt{1+\lambda^2}} \qquad (15)$$

Then, the signed distance d_s is defined for a general point P(e, $\dot{e}$) as follows:

$$d_s = \mathrm{sgn}(S_l) \; \frac{\left|\dot{e} + \lambda e\right|}{\sqrt{1+\lambda^2}} \qquad (16)$$

$$\mathrm{sgn}(S_l) = \begin{cases} 1, \; for \; S_l > 0 \\ -1, \; for \; S_l < 0 \end{cases}$$

The sign of the control input is negative for S_l >0 and positive for S_l <0 and its absolutely magnitude is proportional to the distance from the line

S_l = 0 . Therefore $u \propto -d_s$

Then, a fuzzy rule table can be established on a 1-D space on d_s instead of the 2-D space of the phase plane for FLCs with skew- symmetric rule table. That is, the control action can be determined by d_s only. Hence the name SFLC (Single – input FLC). The rule form for the SFLC is given in Table I.

Table I
Rule Table for SFLC based SVC

ds	NB	NS	ZR	PS	PB
u	PB	PS	ZR	NS	NB

If d_s is NB then u is PB.Where NB-Big negative, NS-Small negative, NR- Zero, PS-Small positive, PB-Positive big. The parameters to be tuned are λ and gain constant K for each controller. Hence, the number of rules is greatly reduced compared to the case of the conventional FLCs. and rules can be easily modified or added for fine control.

A. ***Implementation of SFLC based SVC***

Block diagram representation of SFLC based SVC is shown in Fig 5. The signed distance is derived from the deviation of load voltage from its reference value. The controller's output is SVC susceptance, which is allowed to vary between B_{min} and B_{max} by using a wind-up limiter.

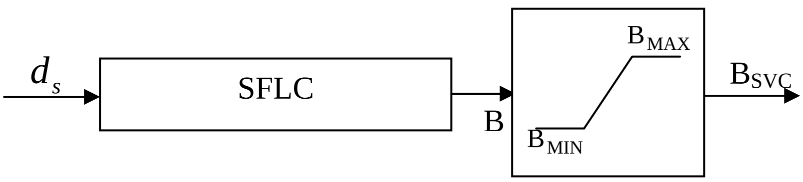

Fig. 5. Block Diagram representation of SFLC based SVC

IV. Simulation Results and Discussion

Bifurcation diagrams of equilibrium as well as periodic branch are obtained from the computer implementation of the algorithm proposed by Padma Subramanian. D. et al. [8].

A. *Bifurcation Analysis with Conventional SVC*

Fig. 6 shows the bifurcation diagram of the periodic solution branch superimposed on the stationary branch diagram.

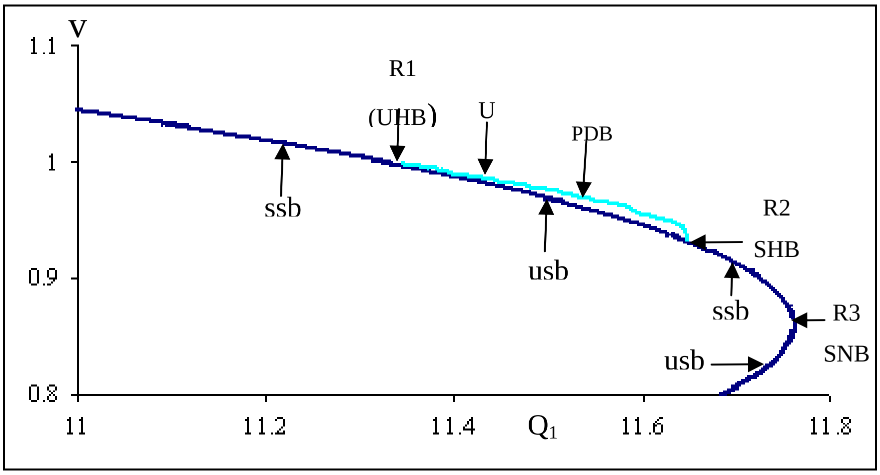

Fig. 6. Bifurcation diagram of load voltage magnitude with conventional SVC

S-stable periodic branch, U- unstable periodic branch, ssb-stable stationary branch, usb- unstable stationary branch.

Three critical points R1, R2, and R3 are observed. At Q_1 = 11.32109, i.e., at point R1, there is a UHB with the emergence of an unstable limit cycle. At Q_1 =11.5579 , there is a SHB. The loci of Floquet multipliers shown in Fig. 7. confirm the occurrence of SHB. The frequency and period of stable oscillation at SHB point are 0.6035 Hz, 1.6567 s respectively.

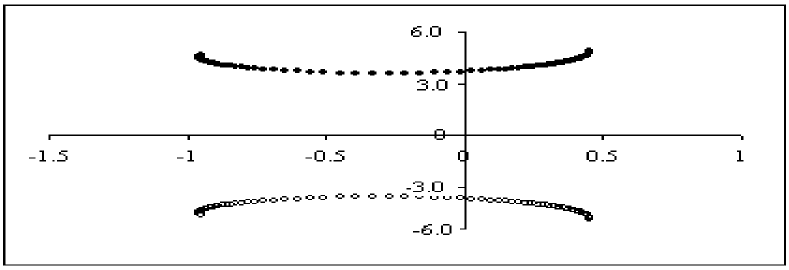

Fig. 7. Movement of complex conjugate eigenvalues in the vicinity of SHB.

The period doubling route to chaos with conventional SVC (point PDB in Fig. 6.) is demonstrated using three-dimensional plots, Fig. 8.

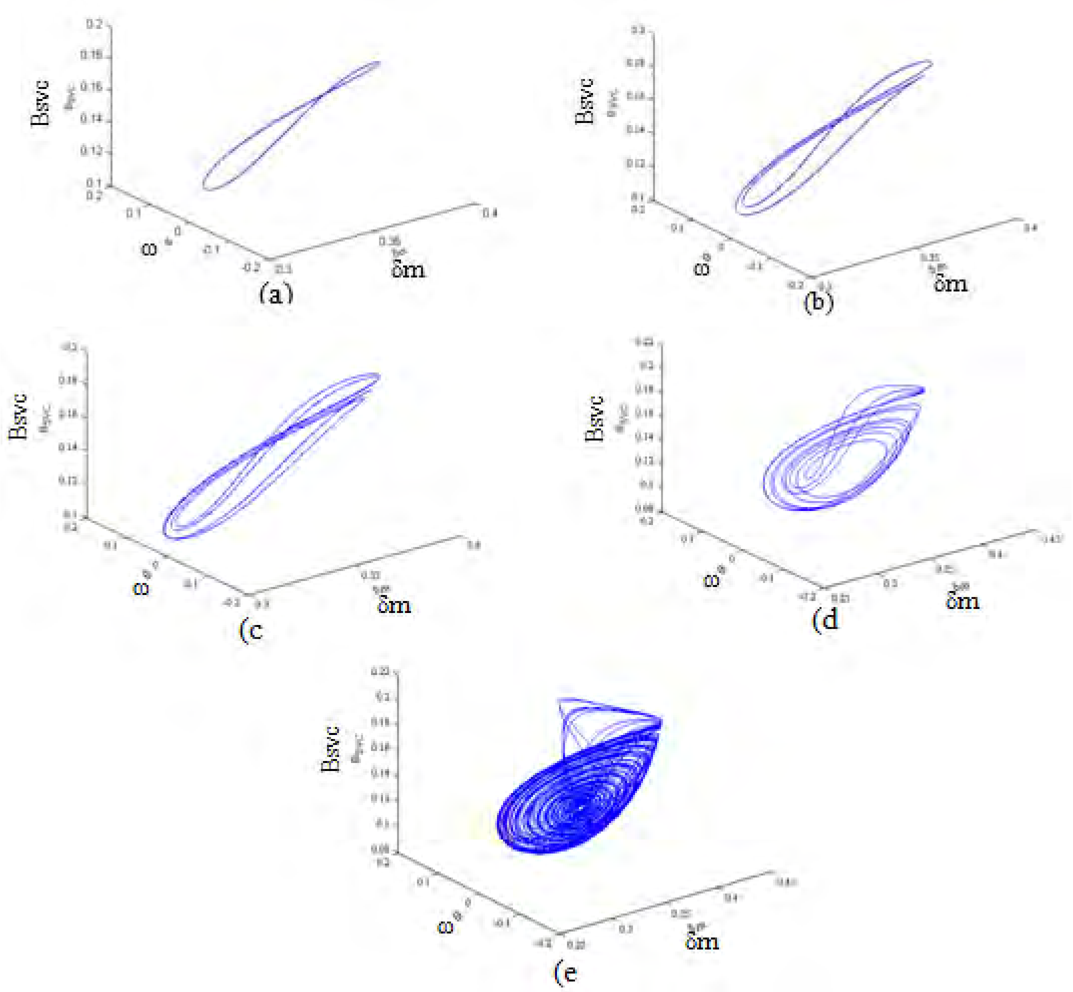

Fig. 8. Cascade of period doubling with conventional SVCe

Period Doubling Bifurcation occurs with the following details:

(a) P1 oscillation at Q_1 = 11.517934, (b) P2 oscillation at Q_1 = 11.520969

(c) P4 oscillation at Q_1 = 11.522001, (d) P8 oscillation at Q1 = 11.523342

(e) Chaos at Q_1 = 11.524958

Voltage collapse point occur at Q_1 = 11.5521. Time response plot of voltage collapse is shown in Fig. 9.

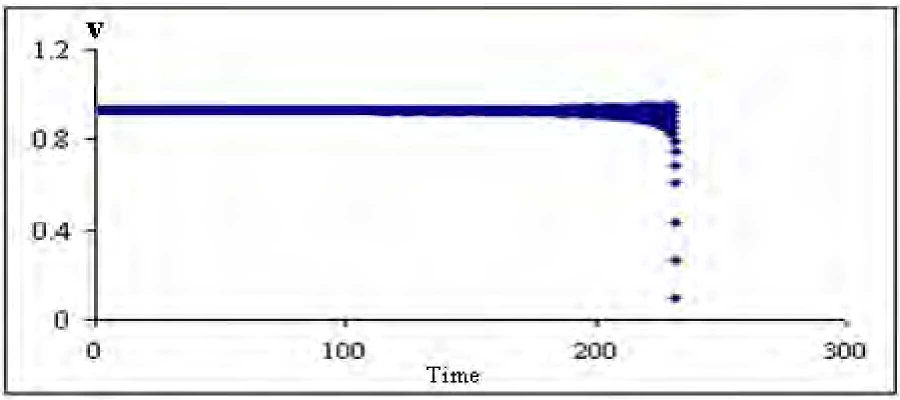

Fig. 9. Voltage collapse at Q_1 = 11.5521

B. *Bifurcation Analysis with SFLC Based SVC*

Single input fuzzy logic controller as explained in Section III is employed for improving the performance of SVC. Bifurcation diagrams are plotted with SFLC based SVC. In Fig. 10 bifurcation diagram of the periodic solution branch is superimposed on the stationary branch diagram.

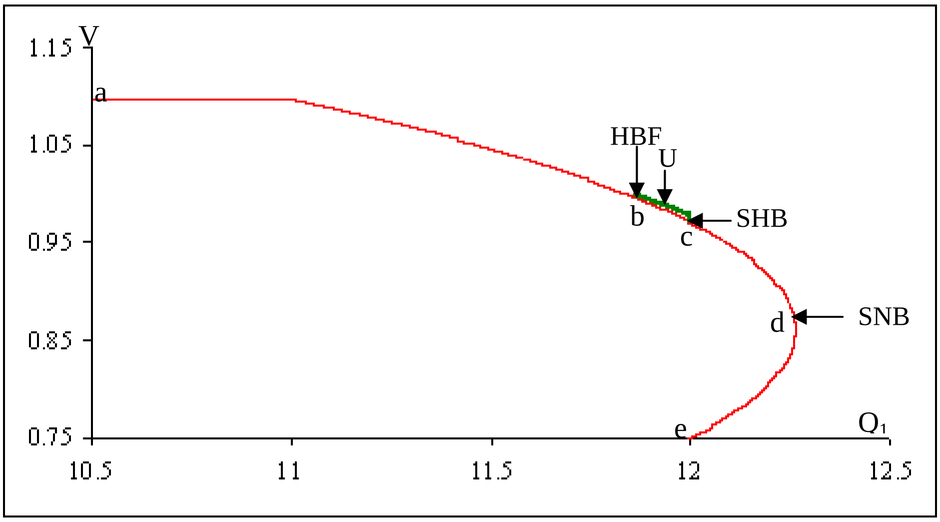

Fig. 10. Bifurcation diagram with SFLC based SVC

a-b: ssb, b-c: usb, c-d: ssb, d-e: usb, U: unstable periodic branch

ssb-stable stationary branch, usb-unstable stationary branch

Extensive time domain analysis along with observation of evolution of Floquet multipliers have been carried out with each set of solutions in the periodic branch. It is found that with SFLC based SVC, there are no period doublings and hence chaos. Moreover, there is a ramarkable level of constriction in the periodic solutions branch. Load voltage remains constant until Q_1 is incremented upto 11p.u. Table II summarizes the various Q_1 values at which bifurcations occur in Fig. 6 and 10.

TABLE II
Summrization of Bifurcation Points in Figs. 6 and 10

Type	With conventional SVC	With SFL based SVC
	Q_1	Q_1
UHB	11.32109	11.83485
PDB	11.517934	-
SHB	11.6279	12.02317
SNB	11.7711	12.29014

From Table II, it can be observed that single input fuzzy logic controller for SVC delays the occreence of HBF, SNB, and hence increases the loadabilyt limit. It also eliminates dynamic voltage collapse. The proposed controller maintais the load voltage at a constant value until Q_1 is incremented upto 11p.u.

V. Conclusion

A single input Fuzzy Logic based Static VAR Compensator is designed to improve dynamic performance of a sample power system. The SFLC uses only one input which is the signed distance and has the advantage of reduced number of rules.The signed distance is derived from the deviation of load voltage from its reference value. The proposed controller for SVC is effectve in delaying the HBF, SNB, and hence increasing the loadability limit. The controller is effective in eliminating the dynamic voltage collapse which otherwise occurred with conventional SVC. Moreover, the proposed controller has the advantage of maintaining constant voltage at the load bus for higher loading level. Tracing of stable and unstable steady state equilibrium as well as periodic solution branches is performed by a numerical algorithm, based on continuation technique. From bifurcation diagrams, existence of various critical points is identified with the help of eigen value analysis. Simulation results prove the effectiveness of the designed Single Input Fuzzy logic Controller based SVC in improving the dynamic performance of the sample power system.

Appendix

The parameters considered for simulation, except those for SVC are taken from Chiang. H. D et al. (1990) and are given below for easy reference. All the parameter values are in p.u. except angles which are in electrical degrees.

Network parameters:

$$Y_0 = 20.0, \quad \Theta_0 = -5.0, \quad V_0 = 1.0, \quad Y_m = 5.0, \quad \Theta_m = -0.08726.$$

Generator parameters:

$$V_m = 1.0, \quad P_m = 1.0, \quad M = 0.3, \quad D = 0.05$$

Load parameters:

$$K_{pw} = 0.4, \quad K_{pv} = 0.3, \quad K_{qw} = -0.03, \quad K_{qv} = -2.8, \quad K_{qv2} = 2.1, \quad T = 8.5, \quad P_0 = 0.6,$$
$$Q_0 = 1.3, \quad P_1 = 0$$

SVC parameters:

$K_{SVC} = 2.0$, $T_{SVC} = 0.01$, $B_{LIMIT} = 1.0$

SFLC parameters:

$\lambda = 2$, $K = 4$

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