Fuzzy-logic-based VAR stabiliser for power system control

P.K. Dash
S. Mishra
A.C. Liew

Indexing terms: Power system control, Fuzzy controllers

Abstract: The paper presents a new approach to the design of a robust controller for the auxiliary control loop of a static VAR system using both fuzzy logic and variable structure system (VSS) concepts. Also, the design of a simple fuzzy controller using the least number of rules for stabilisation of a synchronous generator connected to a large power system is presented. The performances of fuzzy, variable structure fuzzy and VSS stabilisers are compared with a conventional stabiliser for a variety of transient disturbances, highlighting the effectiveness of these stabilisers in providing significant damping to the system oscillations.

1 Introduction

Dynamic voltage support and reactive power compensation have long been recognised as very significant measures for improving the performance of electric power systems. The rapid advances in the power electronics area have made it both practicable and economic to design powerful thyristor-controlled reactive power compensation devices (static VAR compensators (SVCs)) [1–6]. Both theoretical analysis and field tests have proved the excellent SVC performances.

The primary application of SVCs is to maintain the busbar voltage at or near a constant level. In addition, SVCs can improve transient stability by dynamically supporting the voltage at strategic points, and steady-state stability by helping to increase swing oscillation damping. For any static VAR controller scheme, The firing angle control of the thyristor banks of the TCR-FC type SVC determines the equivalent shunt admittance presented to the power system. Once the sizing and location of each compensator has been selected, the problem still remains of adopting feasible and implementable feedback control strategies for the SVCs. The SVC is equipped with a voltage regulator that provides primarily synchronising torque. In general, the damping torque contributions from an SVC with the voltage regulator alone is small. For additional damping, auxiliary control function is necessary.

The auxiliary control of the SVC can be used to damp interarea modes and thus complements the PSS used at generating stations. The presence of a voltage regulator in the SVC, located at the midpoint of a line, helps to overcome the deleterious effect of the length of the line on system stability. With the advent of microprocessor-based controls, it is feasible to implement adaptive control of SVCs with online system identification and automatic tuning. However, this requires a good understanding of the system model, with various aspects to be considered. Another form of nonlinear control is provided by fuzzy controllers [8–10], which enable us to deal with system nonlinearities and introduce expert knowledge to control rules.

This paper presents a simple and versatile fuzzy controller based on trapezoidal membership functions for deviations in generator speed and its derivative and only four rules for the auxiliary control loop of the SVC. This fuzzy controller is equivalent to a nonlinear PI controller [8], whose gains change depending on the error and its rate. The input signals to the static VAR controller are usally the busbar voltage incremental change, along with auxiliary signals such as machine speed or busbar frequency change. In [7], a technique combining the bang-bang control of the phase angle loop and the optimal control of the voltage regulator loop has been presented. This method provides rapid damping of system oscillations for several configurations of the power systems in about 7 – 8 s.

Whenever the speed deviation signal is not available, as in the case of the SVC located at the middle of the transmission line, the busbar angle, frequency, power and current deviation signals can be used. Although the linguistic controller may be able to provide significant damping during the transient disturbances, it may not be robust for all operating conditions, system parametric changes and noisy data. Also, the stability analysis of the fuzzy-logic-based controller is not straightforward without the aid of a mathematical model of the studied system. The paper therefore presents a new approach in combining fuzzy control and variable structure system theory [11–13] to provide a robust SVC controller, which will provide significant damping to system oscillations, disturbance rejection properties etc.

To validate the effectiveness of this new control strategy, computer simulation studies for a variety of transient disturbances of a single machine connected to an

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P.K. Dash and S. Mishra are with the Regional Engineering College, Rourkela 769008, India

A.C. Liew is with the Department of Electrical Engineering, National University of Singapore, Singapore

infinite busbar were undertaken, and the results are presented in this paper. Extension to a multimachine system is straightforward, and results will be presented in the near future.

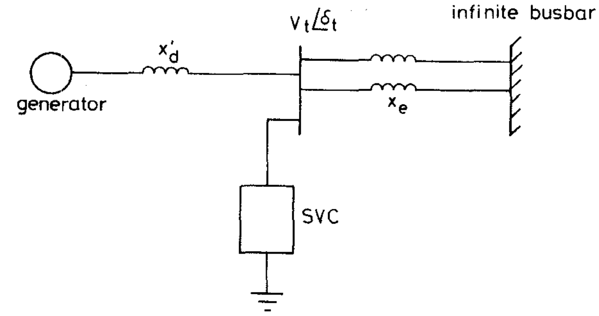

Fig. 1 *Power system configuration (SVS at the generator busbar)*

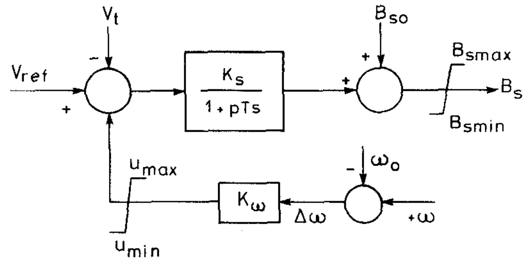

Fig. 2 *Static VAR controller*

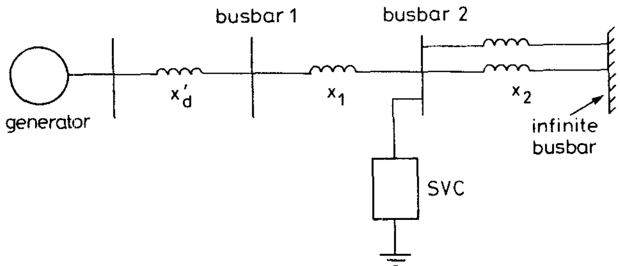

Fig. 3 *SVS at the load busbar (busbar 2)*

2 System model

Fig. 1 shows the schematic diagram of the system considered for simulation. It consists of a synchronous generator connected via a double-circuit transmission line, represented by a lumped reactance, to a large power system, represented by an infinite busbar. The synchronous generator is described by a third-order nonlinear mathematical model, represented by Park's equations. The generator is equipped with an AVR, and a static VAR compensator is located at the generator busbar to provide significant damping during transient conditions. The VAR compensator comprises a fixed capacitor and variable inductor, and its block diagram is shown in Fig. 2. The auxiliary control loop of the SVC uses stabilising signals, such as speed, frequency, phase angle difference etc., to improve the dynamic performance of the integrated system. Another alternative location of the SVC (Fig. 3) has been also considered in this paper for computer simulation.

The magnitude of the SVC inductive admittance $B_L(\alpha)$ is a function of the firing angle α and is obtained as

$$B_L(\alpha) = \frac{2\pi - 2\alpha + \sin 2\alpha}{\pi X_s} \qquad \text{for } \pi/2 \le \alpha \le \pi \qquad (1)$$

where

$$X_s = \frac{V_t^2}{Q_L}$$

V_s = SVC busbar voltage, and Q_L = MVA rating of the reactor.

As the AVR uses a fixed capacitor and variable reactor combination (TCR-FC), the effective shunt admittance is

$$B_s = \frac{1}{X_c} - B_L(\alpha) \qquad (2)$$

where X_c = capacitive reactance.

The size of the TRC-FC compensator is obtained from the maximum and minimum values of B_s and the voltage of the busbar at which the compensator is located. The SVC rating in the capacitive region is normally larger than the inductive one and can lie between 10% and 60% of the short-circuit power level of the busbar [5] at which the SVC is located. A dynamic stability analysis of the power system is done to ascertain the B_{smax} and B_{smin} values of the SVC for a wide range of operating conditions. As the paper concentrates on the development of a new auxiliary control scheme, these aspects are omitted.

The generator, AVR and static VAR compensator equations are presented in Appendix 10, and these equations, after some manipulation, yield the following dynamic equations for the single-machine infinite-busbar power system:

$$\dot{\delta} = \omega - \omega_o$$
$$\dot{\omega} = \frac{1}{M}\left[P_m - K_d\omega - \frac{E'_q V_b \sin\delta}{a_1} + \frac{(x_q - x'_d)V_b^2 \sin\delta}{2a_1 a_2}\right]$$
$$\dot{E}'_q = \frac{1}{T'_{do}}\left[E_{fd} - \frac{a'_1 E'_q V_b}{a_1} - \frac{V_b \cos\delta (x_d - x'_d)}{a_1}\right] \qquad (3)$$

where

$$a_1 = x'_d(1 - x_e B_s) + x_e$$
$$a'_1 = x_d(1 - x_e B_s) + x_e$$
$$a_2 = x_q(1 - x_e B_s) + x_e \qquad (4)$$

However, if the SVC is located at an intermediate busbar (Fig. 3), dividing the transmission line into two portions having reactances x_1 and x_2, the values of a_1, a'_1 and a_2 are

$$a_1 = (x'_d + x_1)(1 - x_2 B_s) + x_2$$
$$a'_1 = (x_d + x_1)(1 - x_2 B_s) + x_2$$
$$a_2 = (x_q + x_1)(1 - x_2 B_s) + x_2 \qquad (5)$$

This system model will be useful for deriving the variable structure fuzzy and simple sliding mode controllers. The following Section outlines the details of the fuzzy and variable structure fuzzy controllers.

3 Design of a variable structure fuzzy controller

This Section outlines the design of the rule-based fuzzy logic controller for the auxiliary control loop of the SVC.

Linguistic variables are defined through their fuzzy membership functions, and fuzzy set error $\Delta\omega$ has two sets *ep* (error positive) and *en* (error negative), and the fuzzy set rate ($\Delta\dot{\omega}$) has two members *rp* (rate positive) and *rn* (rate negative). The fuzzy set control *du* has three members *op* (output positive), *on* (output negative) and *oz* (output zero). The input and output fuzzy sets are shown in Fig. 4.

The auxiliary fuzzy controller uses the following IF-THEN rules (four for the simplest fuzzy controller):

rule 1 : If $\Delta\omega$ is *ep* and $\Delta\dot{\omega}$ is *rn*, then *du* is *oz* rule 2 : If $\Delta\omega$ is ep and $\Delta\dot{\omega}$ is rp, then du is op

rule 3 : If $\Delta\omega$ is en and $\Delta\dot{\omega}$ is rn, then du is on

rule 4 : If $\Delta\omega$ is en and $\Delta\dot{\omega}$ is rp, then du is oz (6)

The membership functions for the error $\Delta\omega$ and its rate $\Delta\dot{\omega}$ are obtained, using trapezoidal membership characteristics, as

$$\mu_{ep}(\Delta\omega) = 0.5 + 0.5g_e\Delta\omega$$
$$\mu_{en}(\Delta\omega) = 0.5 - 0.5g_e\Delta\omega$$
$$\mu_{rp}(\Delta\dot{\omega}) = 0.5 + 0.5g_r\Delta\dot{\omega}$$
$$\mu_{rn}(\Delta\dot{\omega}) = 0.5 - 0.5g_r\Delta\dot{\omega} \quad (7)$$

The membership values for three the control outputs du_1, du_2, du_3 for the three output sets are given by

$$\mu_{op}(du_1) = du_1$$
$$\mu_{on}(du_2) = -du_2$$
$$\mu_{oz}(du_3) = 0.0 \quad (8)$$

To enable the fuzzy controller to operate for any given input, use is made of the compositional rule of inference. The control rules are evaluated using Zadeh logic for AND implication and Lukasiewicz logic for OR implication.

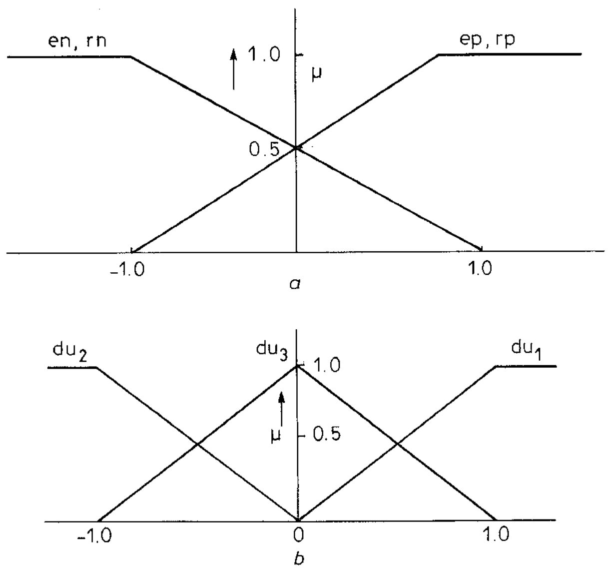

Fig. 4 *Fuzzification*
a Inputs
b Control output du

The inference engine of the fuzzy-logic-based controller matches the preconditions of the rules in the fuzzy rule base with input state linguistic terms and performs implications. For example for a given error and its rate, the firing strengths α_1, α_2, α_3 and α_4 of rules 1 – 4 are obtained as

$$\alpha_1 = \mu_{ep}(\Delta\omega) \wedge \mu_{rn}(\Delta\dot{\omega})$$
$$\alpha_2 = \mu_{ep}(\Delta\omega) \wedge \mu_{rp}(\Delta\dot{\omega})$$
$$\alpha_3 = \mu_{en}(\Delta\omega) \wedge \mu_{rn}(\Delta\dot{\omega})$$
$$\alpha_4 = \mu_{en}(\Delta\omega) \wedge \mu_{rp}(\Delta\dot{\omega}) \quad (9)$$

Here, ^ stands for the fuzzy 'and' operation and is the minimum operator.

The control output of any rule is calculated by matching the strength of its precondition to its conclusion. As rules 1 and 4 have the same output set oz, Lukasiewicz OR is used to evaluate the output decision α_0 of rules 1 and 4 as

$$\alpha_0 = \min(1, (\alpha_1 + \alpha_4)) \quad (10)$$

Using a centroid defuzzification technique, the incremental control output Δu is given by

$$\Delta u = g_u \sum_i \alpha \; du_i \Big/ \sum_i \alpha_i \quad (11)$$

where du_1, du_2 anddu_3 are the values of the control output for which the membership values in the output sets are each equal to unity. Thus

$$\Delta u = g_u(\alpha_2 - \alpha_3)/(\alpha_2 + \alpha_3 + \alpha_0) \quad (12)$$

as $du_1 = 1$, $du_2 = -1$, $du_3 = 0$.

Proceeding as outlined in [14], the nonlinear defuzzification algorithm yields the incremental control Δu as

$$\Delta u = \lambda_1 \Delta\omega + \lambda_2 \Delta\dot{\omega} \quad (13)$$

where

$$\lambda_1 = \frac{0.5g_e g_u}{2 - g_e|\Delta\omega|} \qquad \lambda_2 = \frac{0.5g_r g_u}{2 - g_e|\Delta\omega|} \quad (14)$$

for $g_r\,|\Delta\dot{\omega}| \le g_e\,|\Delta\omega| \le 1$, and

$$\lambda_1 = \frac{0.5g_e g_u}{2 - g_r|\Delta\dot{\omega}|} \qquad \lambda_2 = \frac{0.5g_r g_u}{2 - g_r|\Delta\dot{\omega}|} \quad (15)$$

for $g_e\,|\Delta\dot{\omega}| \le g_r\,|\Delta\omega| \le 1$.

The limiting rules of λ_1 and λ_2 are

$$0.25g_e g_u \le \lambda_1 \le 0.5g_e g_u$$
$$0.25g_r g_u \le \lambda_2 \le 0.5g_r g_u \quad (16)$$

The linguistic fuzzy controller presented above is a nonlinear PI controller whose gains vary with the magnitude of the speed error $\Delta\omega$ and its rate. Although this controller is expected to provide significant damping during transient disturbances of the power system, it may not be able to provide a robust control during significant changes in system operating conditions or parameters. To cope in such situations, a fuzzy controller combined with a variable structure system switching scheme is used. The variable structure switching strategy constrains the system to a special class of nonlinear system characterised by discontinued control action, which changes structure upon reaching a set of switching hyperplanes $\sigma(x) = 0$. During the sliding mode that exists on the hyperplane, the system becomes less sensitive to system parameter variations and noise disturbances.

To design a combined fuzzy and VSS auxiliary controller for the static VAR system, the system equations are linearised about an operating point (with the assumption that E'_q is constant and equal to its initial value E'_{q0}), to yield

$$\begin{bmatrix} \Delta\dot{\delta} \\ \Delta\dot{\omega} \\ \Delta\dot{B}_s \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ g_1 & 0 & g_2 \\ g_3 & 0 & g_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta\omega \\ \Delta B_s \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ g_5 \end{bmatrix} \Delta u \quad (17)$$

where the constants $g_1 - g$ are given in Appendix 10. The switching hyperplane is defined by the equation

$$\sigma = c_1\Delta\delta + c_2\Delta\omega + \Delta B_s \quad (18)$$

where the parameters c_1 and c_2 are chosen to achieve the desired performance. The necessary and sufficient condition for the existence of a sliding mode on the switching surface σ requires, in the vicinity $\sigma = 0$, that

$$\sigma\dot{\sigma} < 0$$

where

$$\dot{\sigma} = \frac{d\sigma}{dt} \quad (19)$$

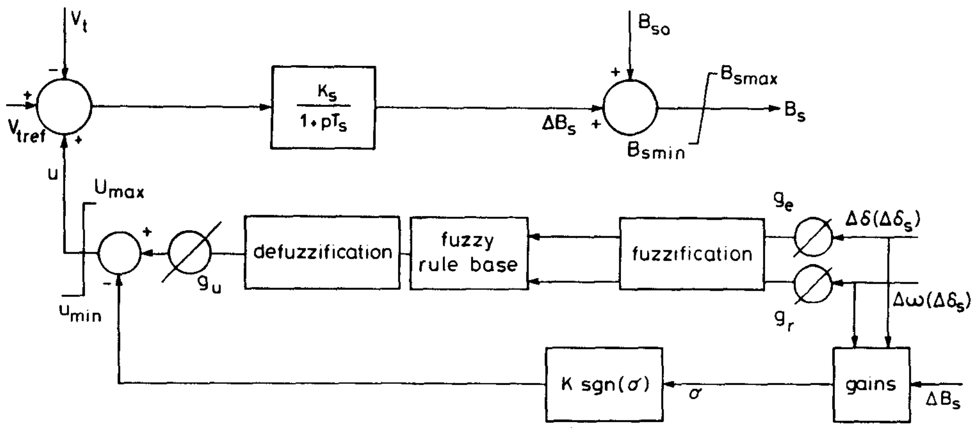

Fig. 5 *Variable structure fuzzy controller for SVC*

Eliminating ΔB_s from eqn. 18, the characteristic equation of the reduced state equation is

$$s^2 + sc_2g_2 + c_1g_2 - g_1 = 0 \qquad (20)$$

yielding two roots $-a \pm jb$, where

$$a = 0.5c_2g_2$$

$$b = \sqrt{0.25c_2^2g_2^2 - c_1g_1g_2} \qquad (21)$$

For the system to be stable,

$$c_2 = \frac{-2aMa_1}{E'_{qo}V_b \sin\delta_0 \; x'_d x_e} \qquad (22)$$

The value of $\dot{\sigma}$ is obtained as

$$\dot{\sigma} = (c_1 - c_2g_4)\Delta\omega + c_2\Delta\dot{\omega} + (g_3 - c_1g_4)\Delta\delta + g_5\Delta u \quad (23)$$

Choosing the value of c_1 as

$$c_1 = g_3/g_4 \qquad (24)$$

the value of $\dot{\sigma}$ becomes equal to

$$\dot{\sigma} = (c_1 - c_2g_4)\Delta\omega + c_2\Delta\dot{\omega} + g_5\Delta u \qquad (25)$$

The incremental control Δu is now written as

$$\Delta u = \Delta u_c - K\text{sgn}(\sigma) \qquad (26)$$

where Δu_c = incremental control output from the linguistic fuzzy controller, and the value of K is found from the reaching condition $\sigma\dot{\sigma} < 0$ in the following way:

Substituting the value of Δu in eqn. 25, the value of

$$K > \frac{F}{g_5} \qquad (27)$$

where

$$F = |(c_1 - c_2g_4)\Delta\omega_{max} + c_2\Delta\dot{\omega}| + g_5|\Delta u_c| \qquad (28)$$

Substituting the maximum value of $|\Delta u_c|$ in terms of and g_e and g_r, we obtain

$$F = |(c_1 - c_2g_5 + 0.5g_5g_e)\Delta\omega_{max} + (c_2 + 0.5g_5g_r)\Delta\dot{\omega}_{max}| \qquad (29)$$

Furthermore, the sgn (sign) function of σ can be replaced by sat (σ) using boundary layer concepts to reduce chattering problems in sliding mode control as

$$\text{sat}(\sigma) = \begin{cases} \text{sgn}(\sigma) & \text{if } |\sigma| > \epsilon \\ \sigma/\epsilon & \text{if } |\sigma| < \epsilon \end{cases} \qquad (30)$$

and ε is a chosen constant for this case.

However, if only the sliding mode control is used, the expression for F becomes

$$F = |(c_1 - c_2g_5)\Delta\omega_{max} + c_2\Delta\dot{\omega}_{max}| \qquad (31)$$

The above control can be made robust by the proper choice of the parameter a (which is a pole of the linearised system) and the various scaling constants g_e, g_r and g_u. A simple stability criterion based on the linearised system is used to choose the values of g_e, g_r and g_u.

The closed loop matrix for the linearised system described in eqn. 17 is obtained as

$$A_F = \begin{bmatrix} 0 & 1 & 0 \\ g_1 & 0 & g_2 \\ g_3 + g_1g_5\lambda_2 & g_5\lambda_1 & g_4 + g_2g_5\lambda_2 \end{bmatrix} \qquad (32)$$

Choosing g_e and g_r as

$$g_e = 1/\Delta\omega_{max} \qquad g_r = 1/\Delta\dot{\omega}_{max} \qquad (33)$$

and λ_1, λ_2 within their limiting values, the control gain g_u can be obtained from the eigenvalue plot of the closed loop matrix A_F.

The value of a in eqn. 21 is obtained by minimising the integral squared error in the form

$$J = \int_0^t \{(\Delta V_t)^2 + (\Delta Q_s)^2\}\, dt \qquad (34)$$

where ΔV_t is the deviation in the generator terminal voltage and ΔQ_s is the change in the reactive power flow from the SVC busbar. Fig. 5 depicts a variable structure fuzzy controller for the SVC auxiliary loop.

4 Computer simulation studies

The performance of the fuzzy, sliding mode, and variable structure fuzzy controllers was tested on a synchronous generator connected to an infinite busbar and subjected to a variety of transient disturbances.

Also, the performance of the SVC control without the auxiliary signal is presented to highlight the damping properties of these controllers using an auxiliary control signal. The synchronous generator has the following parameters (p.u.):

$x_d = 2.0$; $x_q = 2.0$; $T'_{do} = 4.95$s; $H = 2.5$s; $x'_d = 0.271$

transmission line (p.u.):

$x_e = 0.2$; $x_1 = 0.2$; $x_2 = 0.2$

AVR:

$K_e = 100.0$; $T_e = 0.1$s; $-6.0 \le E_{fd} \le 6.0$

SVS (p.u.):

$B_s(\text{max}) = 0.275$; $B_s(\text{min}) = -0.275$; $B_{so} = 0.12$;

$u_c(\text{max}) = 0.1$; $u_c(\text{min}) = -0.1$; $K_s = 40.0$; $T_s = 0.1$s

Fuzzy controller:

$g_e = 0.25$; $g_r = 0.04$; $\lambda_1 = -0.5$; $\lambda_2 = -0.1$; $\epsilon = 0.01$

The following case studies were undertaken:

Case 1 : SVC at the generator terminal: Results for a 3-phase to ground fault (P = 0.4, Q = 0.2) at the infinite busbar are shown in Figs. 6–8 for conventional, fuzzy PI and variable structure fuzzy VAR stabilisers. The conventional VAR stabiliser does not use an auxiliary damping signal. From the Figures, it is quite evident that the sliding fuzzy controller produces the most significant damping to the system oscillations, and the performance of the fuzzy PI VAR controller is also quite comparable. However, the conventional stabiliser without any auxiliary control signal performs the worst in comparison with the proposed stabilisers.

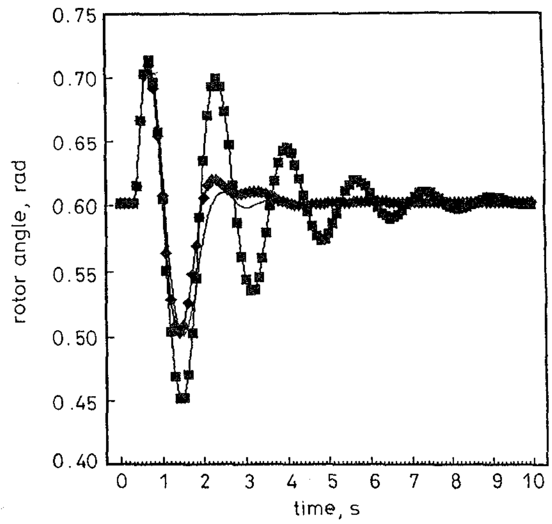

Fig. 6 *Transient performance for a 3-phase short-circuit at the infinite busbar (SVS at generator terminal) P = 0.4; Q = 0.2*

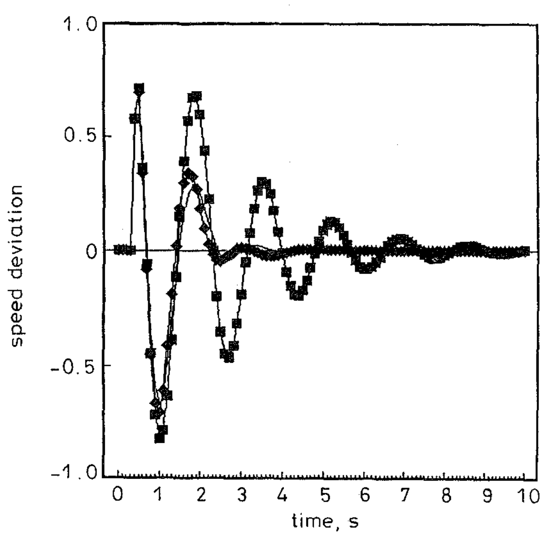

Fig. 7 *Transient performance for a 3-phase short-circuit at the infinite busbar (SVS at generator terminal) P = 0.4; Q = 0.2*

Transient response curves for a 3-phase short-circuit (P = 0.8, Q = 0.6) near the infinite busbar on one of the double-circuit transmission lines and the subsequent switching off of one of the lines are shown in Fig. 7

Figs. 9 and 10 reveal the superior performance of the variable structure fuzzy controller, although the fuzzy PI stabiliser comes very close to it. The fluctuations of the auxiliary control magnitude in the case of the variable structure stabiliser are found to be quite excessive. In comparison, the linguistic controller provides a smoother fluctuation of the auxiliary control input. The conventional controller with no auxiliary control input takes a long time to provide stability.

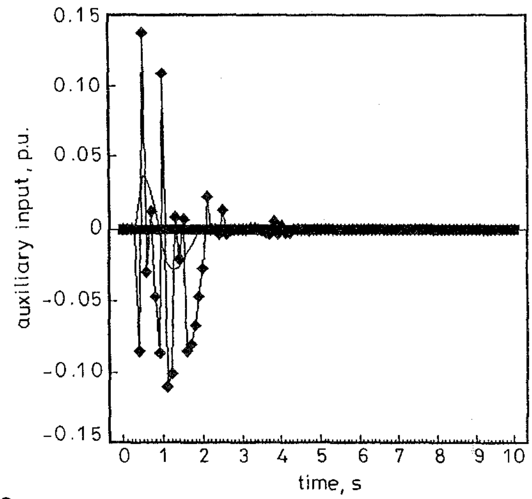

Fig. 8 *Transient performance for a 3-phase short-circuit at the infinite busbar (SVS at generator terminal) P = 0.4; Q = 0.2*

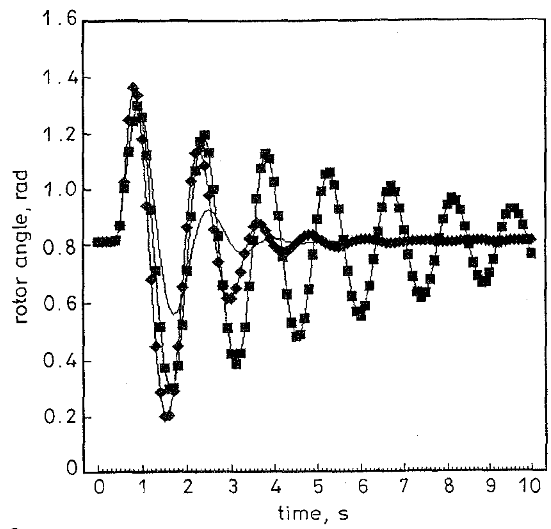

Fig. 9 *Performance for a 3-phase short-circuit and switching off one circuit (SVS at generator terminal)*
P = 0.8; Q = 0.6
—■— No control
—◆— Fuzzy PI
——— Sliding fuzzy

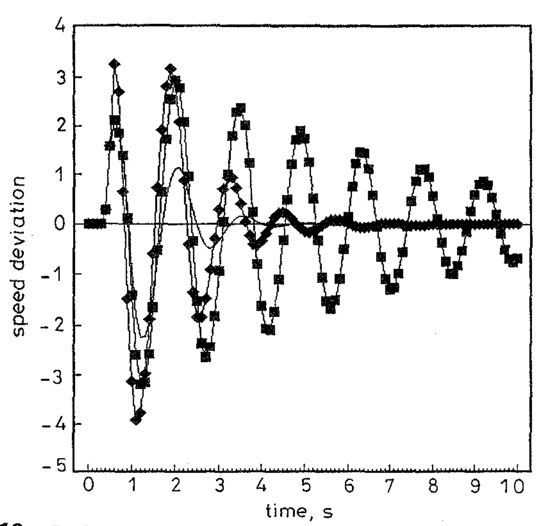

Fig. 10 *Performance for a 3-phase short-circuit and switching off one circuit (SVS at generator terminal)*
P = 0.8; Q = 0.6
—■— No control
—◆— Fuzzy PI
——— Sliding fuzzy

Case 2 : SVC located at busbar 2: When the static VAR controller is located at any busbar other than the generator terminal, the load angle and speed stabilising signals are not available for control. Instead, the busbar frequency deviations are used by the fuzzy controller to obtain the auxiliary control input to the SVC. However, for the variable structure control, a new mathematical formulation is required to provide the necessary control input. As the prime aim of this paper is to establish the efficacy of the fuzzy controllers, the results for the conventional VAR control and fuzzy control are shown in Figs. 11–14. Figs. 11 and 12

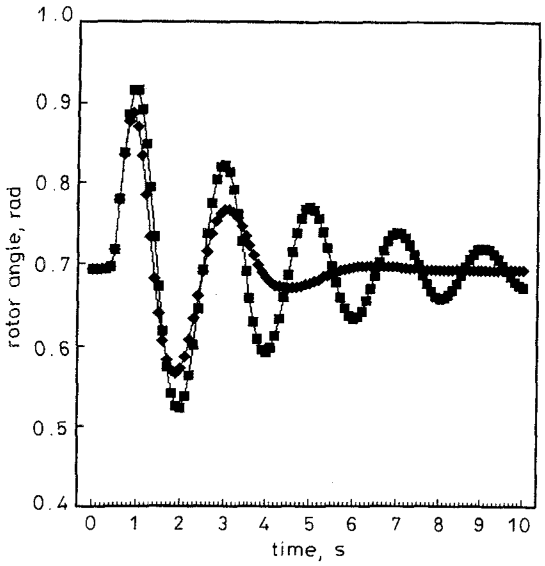

Fig. 11 *Performance for a 3-phase fault and switching off one circuit (SVC at busbar 2)*
$P = 0.4$; $Q = 0.2$
—■— No control
—◆— Fuzzy PI

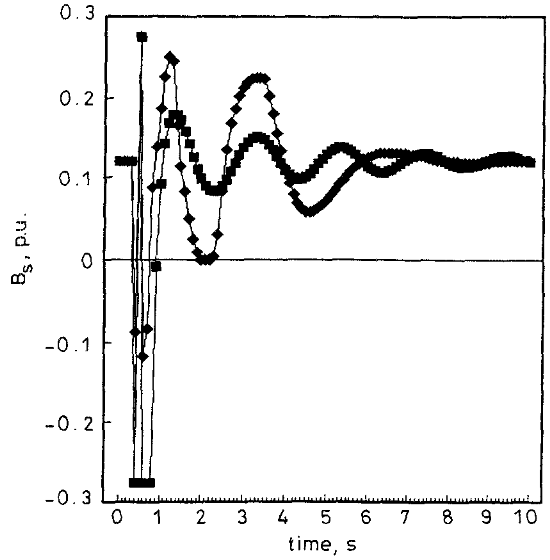

Fig. 12 *Performance for a 3-phase fault and switching off one circuit (SVC at busbar 2)*
$P = 0.4$; $Q = 0.2$
—■— No control
—◆— Fuzzy PI

depict the transient response characteristics for the sample power system for a 3-phase short-circuit near the infinite busbar cleared in 0.1s, where one of the double-circuit lines is simultaneously switched off during the short-circuit, increasing the severity of the fault. From the results, it is evident that the fuzzy PI controller provides significant damping to the system oscillations in almost 4s. These results are comparable with those presented in [8] using bang-bang control and phase angle deviation feedback.

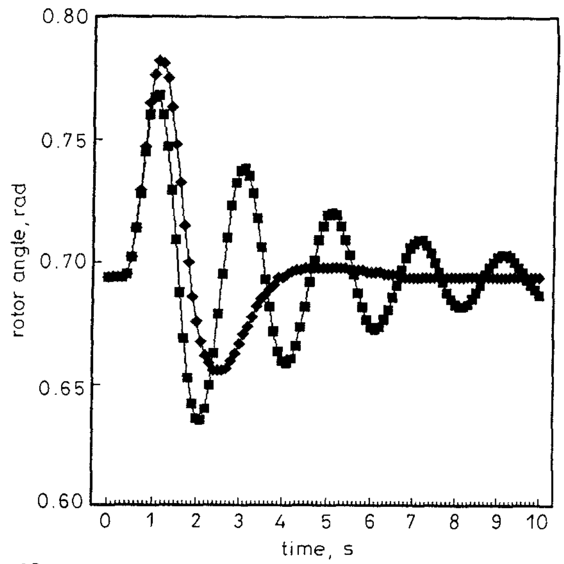

Fig. 13 *Performance for an increase in turbine input by 15% (SVC at busbar 2)*
$P = 0.4$; $Q = 0.2$
—■— No control
—◆— Fuzzy PI

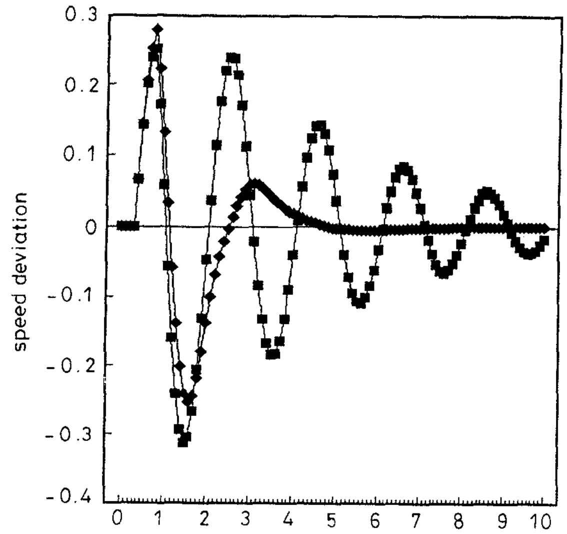

Fig. 14 *Performance for an increase in turbine input by 15% (SVC at busbar 2)*
$P = 0.4$; $Q = 0.2$
—■— No control
—◆— Fuzzy PI

Results for rotor angle, and speed changes are shown in Figs. 13 and 14 for a sudden change in the input power by 15% lasting 0.5s. The results reveal the superior performance of the fuzzy controller in damping out the system oscillations. The parameters of the fuzzy controller are not changed during this simulation, thus validating the assumption that the controller is insensitive to parameter and operating point changes. The conventional VAR stabilisers will require gain schedulings in such a case to provide effective damping.

7 Discussion

Results given in Figs. 6–14 clearly show that the system response with the fuzzy controller is, in general, better than the conventional SVS regulator. Even for the SVS located at a busbar, other than the generator busbar, the fuzzy controller produces excellent performance and damping in comparison with those described in one of the latest references [8] on VAR control. The incorporation of the concept of a sliding surface to the fuzzy controller increases the tuning property of the fuzzy controller and provides a better performance. As the prime purpose of the paper is to design a robust nonlinear controller using the linguistic properties of fuzzy logic, for static VAR systems there has been no attempt to provide a comparison between machine excitation control and static VAR control for improving the system stability.

8 Conclusions

The paper presents the applications of a fuzzy-logic-based control scheme to the stabilising loop of a static VAR compensator for improving system damping during transient disturbances. The performance of this fuzzy PI controller is compared with that of a variable structure fuzzy controller and conventional VAR stabiliser without auxiliary control for a variety of transient disturbances. The performances of both the fuzzy and variable structure fuzzy controllers are found to be superior in comparison with the conventional controller. The fuzzy variable structure controller provides better system damping in comparison with a traditional fuzzy controller during transient disturbances. However, an accurate mathematical model of the system and computational overhead are factors that will require consideration for any specific application. The simplest fuzzy controller with minimum number of rules is highly effective in providing an auxiliary damping signal to the conventional VAR stabilisers.

9 References

1 HAMMAD, A.E., and EL-SADEK, M.: 'Applications of a thyristor controller VAR compensator for damping subsynchronous oscillations in power system', *IEEE Trans.*, 1985, **PAS–103**, (1), pp. 198–212

2 HIYAMA, T.: 'Effective application of static VAR compensator to damp oscillations', *IEEE Trans.*, 1985, **PAS–104**, (6), pp. 1405–1412

3 KAPOOR, S.C.: 'Dynamic stability of static compensator synchronous generator combination', *IEEE Trans.*, 1985, **PAS–100**, (4), pp. 1694–1702

4 BRIEN, M.O.: 'Static reactive power compensator controls for improved system stability', *IEE Proc. C*, 1987, **134**, (1), pp. 38–42

5 RAMOS, A.J.P., and TYLL, H.: 'Dynamic performance of a radial weak power system with multiple static VAR compensators', *IEEE Trans.*, 1989, **4**, (4), pp. 1316–1325

6 HSU, Y., and CHENG, C.: 'Design of static VAR compensator using model reference adaptive control', *Electr. Power Syst. Res.*, 1987, (13) pp. 129–138

7 LARCH EDWIN, N., PORH, D., and XU, L.: 'Advanced SVC control for damping power system oscillations', *IEEE Trans.*, 1991, **PWRS–6**, (2), pp. 524–535

8 YING, H.: 'General analytical structure of typical fuzzy controllers and their limiting structure theorems', *Automatica*, 1993, **29**, pp. 1139–1143

9 HASSAN, M.A.M., MALIK, O.P., and HOPE, G.S.: 'A fuzzy logic based stabiliser for a synchronous machine', *IEEE Trans.*, 1991, **EC–6**, (3), pp. 407–414

10 HSU, Y., and CHENG, C.: 'Design of fuzzy power system stabilisers for multimachine power systems', *IEE Proc. C*, 1990, **137**, (2), pp. 233–238

11 DAS, D., KOTHARI, M.L., KOTHARI, D.P., and NANDA, J.: 'Variable structure control strategy, to automatic generation control of interconnected reheat thermal systems', *IEE Proc. C*, 1991, **138**, (6), pp. 579–585

12 DASH, P.K., SAHOO, N.C., and DORAISWAMI, R.: 'A variable structure VAR stabiliser for power systems control', *Electr. Power Syst. Res.*, 1993, **26**, pp. 127–136

13 DASH, P.K., and SAHOO, N.C.: 'A new control strategy for static VAR compensators', *IE(I) Journal-EL*, 1994, **75**, pp. 107–114

10 Appendix

The following set of equations describes a single synchronous generator connected to a large system through a double-circuit transmission line.

Generator:

$$\begin{aligned}
\dot{\delta} &= \omega - \omega_0 \\
\omega &= (P_m - E_q i_q)/M \\
E'_q &= (E_{fdo} + \Delta E_{fd} - (x_d - x'_d)i_d - E'_q)/\tau'_{do} \\
V_d &= x_q i_q \\
V_q &= E'_q - x'_d i_d \\
E_q &= E'_q + (x_q - x'_d) i_d
\end{aligned} \qquad (35)$$

V_d, V_q = d-axis and q-axis voltages; I_d, I_q = d-axis, and q-axis currents.

For the static VAR compensator connected at the generator busbar, the voltage equations of the transmission line are

$$\begin{aligned}
V_d &= a_0 V_b \sin\delta - a_0 x_e i_q \\
V_q &= a_0 V_b \cos\delta + a_0 x_e i_d
\end{aligned} \qquad (36)$$

and

$$a_0 = \frac{1}{1 - x_e B_s}$$

AVR:

$$\begin{aligned}
E_{fd} &= E_{fdo} + \Delta E_{fd} \\
\Delta\dot{E}_{fd} &= \frac{K_e}{T_e}(V_{ref} - V_t) - \frac{\Delta E_{fd}}{T_e}
\end{aligned} \qquad (37)$$

SVC:

$$B_s = \frac{B_s - B_{so}}{T_s} + \frac{K_s}{T_s}(V_{ref} - V_t) + \frac{K_s}{T_s} u_s \qquad (38)$$