Abstract—The paper presents a new method for design of power system stabilizer based on fuzzy logic and output feedback sliding mode controller. The control objective is to enhance the stability and to improve the dynamic response of the single machine infinite bus (SMIB) system operating in different conditions. First, the control rules are constructed according to the concepts of output feedback sliding mode control, and the fuzzy sets, whose membership functions are defined. Then, hitting control, which guarantees the stability of control system, is developed. Finally, the hitting control is smoothed via the constructed heuristic control rules. We apply this output feedback fuzzy sliding mode controller to design power system stabilizer for demonstrating the availability of the proposed approach [1].

Index Terms—Fuzzy sliding mode control, power system stabilizer, multirate output feedback, robust control.

I. INTRODUCTION

Power system stabilizer (PSS) units have long been regarded as an effective way to enhance the damping of electromechanical oscillations in power system [2]. The action of PSS is to extend the angular stability limits of a power system by providing supplemental damping to the oscillation of synchronous machine rotors through the generator excitation [3]. This damping is provided by an electric torque applied to the rotor that is in phase with the speed variation. Once the oscillations are damped, the thermal limits of the tie-lines in the system may then be approached. This supplementary signal is very useful during large power transfers and line outages [4].

Over the past four decades, various control methods have been proposed for PSS design to improve overall system performance. Among these, conventional PSS of the lead-lag compensation type [2], [5], [6] have been adopted by most utility companies because of their simple structure, flexibility and ease of implementation. However, the performance of these stabilizers can be considerably degraded with the changes in the operating condition during normal operation. Since power systems are highly nonlinear, conventional fixed-parameter PSSs cannot cope with great changes in the operating conditions. There are two main approaches to stabilizing a power system over a wide range of operating conditions, namely adaptive control and robust control [7]. Adaptive control is based on the idea of continuously updating the controller parameters according to recent measurements. However, adaptive controllers have generally poor performance during the learning phase, unless they are properly initialized. Successful operating of adaptive controllers requires the measurements to satisfy strict persistent excitation conditions. Otherwise the adjustment of the controller’s parameters fails. Robust control provides an effective approach to dealing with uncertainties introduced by variations of operating conditions.

Among many techniques available in the control literature, $H_{\infty}$ and variable structure have received considerable attention in the design of PSSs. The $H_{\infty}$ approach is applied by Chen [7] to PSS design for a single machine infinite bus system. The basic idea is to carry out a search over all possible operating points to obtain a frequency bound on the system transfer function. Then a controller is designed so that the worst-case frequency response of the closed loop system lies within prespecified frequency bounds. It is noted that the $H_{\infty}$ design requires an exhaustive search and results in a high order controller. On the other hand the variable structure control is designed to drive the system to a sliding surface on which the error decays to zero [8]. Perfect performance is achieved even if parameter uncertainties are present. However, such performance is obtained at the cost of high control activities (chattering) [9].

In this paper a multirate output feedback fuzzy sliding mode control system which combines the merits of the multirate output feedback sliding mode control and the fuzzy inference mechanism is proposed. In the sliding mode controller a switching surface is designed. When the sliding mode occurs, the system dynamic behaves as a robust state feedback control system. A multirate output feedback fuzzy sliding mode controller is investigated in which a simple fuzzy inference mechanism is used to minimize the chattering. Simulations results for single machine infinite bus (SMIB) system are presented to show the effectiveness of the proposed control strategies in damping the oscillation modes.

The paper is organized as follows. Section II presents basics of power system stabilizer and power system analysis. Section III presents the review on multirate output feedback and state feedback sliding mode control. Section IV presents the proposed multirate output feedback fuzzy sliding mode control method; the same is used for PSS design of SMIB system as discussed in section V. Conclusions are drawn in Section VI. The controller is validated using non-linear

Vitthal Bandal is a Research Scholar with Systems and Control Engineering, Indian Institute of Technology Bombay, Mumbai-400076, INDIA (e-mail:vsbandal@ee.iitb.ac.in).

Prof. B. Bandyopadhyay is with Systems and Control Engineering, Indian Institute of Technology Bombay, Mumbai-400076, INDIA (e-mail:bijnan@ee.iitb.ac.in)(corresponding author).

Prof. A. M. Kulkarni is with Electrical Engineering department, Indian Institute of Technology Bombay, Mumbai-400076, INDIA (e-mail:amk@ee.iitb.ac.in).
model simulation.

II. POWER SYSTEM STABILIZER

A. Basic concept

The basic function of a power system stabilizer is to extend stability limits by modulating generator excitation to provide damping to the oscillation of synchronous machine rotors relative to one another. The oscillations of concern typically occur in the frequency range of approximately 0.2 to 3.0 Hz, and insufficient damping of these oscillations may limit ability to transmit power. To provide damping, the stabilizer must produce a component of electrical torque, which is in phase with the speed changes. The implementation details differ, depending upon the stabilizer input signal employed. However, for any input signal, the transfer function of the stabilizer must compensate for the gain and phase of excitation system, the generator and the power system, which collectively determines the transfer function from the stabilizer output to the component of electrical torque which can be modulated via excitation system [5].

B. Classical Stabilizer implementation procedure

Implementation of a power system stabilizer implies adjustment of its frequency characteristic and gain to produce the desired damping of the system oscillations in the frequency range of 0.2 to 3.0 Hz. The transfer function of a generic power system stabilizer may be expressed as

\[ G_p(s) = K_s \frac{T_{ws} (1 + sT_1) (1 + sT_3)}{(1 + T_u s) (1 + sT_2) (1 + sT_4)} G_f(s) \]

where \( K_s \) represents stabilizer gain and \( G_f(s) \) represents combined transfer function of torsional filter (if required) and input signal transducer. The stabilizer frequency characteristic is adjusted by varying the time constant \( T_w, T_1, T_2, T_3 \) and \( T_4 \). A torsional filter may not be necessary with signals like power or delta-P-omega signal [10].

A power system stabilizer can be most effectively applied if it is tuned with an understanding of the associated power characteristics and the function to be performed by the stabilizer. Knowledge of the modes of power system oscillation to which the stabilizer is to provide damping establishes the range of frequencies over which the stabilizer must operate. It is also desirable to establish the weak power system conditions and associated loading for which stable operation is expected, as the adequacy of the power system stabilizer application will be determined under these performance conditions. Since the limiting gain of the some stabilizers, viz., those having input signal from speed or power, occurs with a strong transmission system, it is necessary to establish the strongest credible system as the “tuning condition” for these stabilizers.

C. Power System Analysis

Analysis of practical power system involves the simultaneous solution of equations consisting of synchronous machines, associated excitation system, prime movers, interconnecting transmission network, static and dynamic (motor) loads, and other devices such as HVDC converters, static var compensator. The dynamics of the machine rotor circuits, excitation systems, prime mover and other devices are represented by differential equations. This results in the complete system model consisting of large number of ordinary differential and algebraic equations [10].

1) Generator Equations: The machine equations (for \( j^{th} \) machine) are

\[ \frac{dE_{qj}'}{dt} = -\frac{1}{T_{dqj}} [E_{qj}' - (x_{dj}' - x_{dj}' i_{dj}') - E_{f dj}], \]

\[ \frac{d\delta_j}{dt} = \omega_B (S_{mj}' - S_{m,j0}), \]

\[ \frac{dS_{mj}'}{dt} = -\frac{1}{2H} [D_j (S_{mj}' - S_{m,j0}) - P_{mj} + E_{qj}]. \]

Model 1.0 is assumed for synchronous machines by neglecting the damper windings [11].

2) State space model of single machine infinite bus (SMIB) power system: The state space model of a SMIB power system, whose block diagram is shown in Fig. 1 can be obtained using generator, transformer, network and loadflow data as given below [11],

\[ \dot{x} = Ax + B (\Delta V_{ref} + \Delta V_s), \]

\[ y = Cx, \]

where \( x \) denotes the states of the machine and are given as, \( x = [S_m, \delta, E_{f4, G}]. \)

Where \( S_m \) is machine slip, \( \delta \) is machine shaft angular displacement in degrees, \( E_{f4} \) is generator field voltage in pu and \( E_{G} \) is voltage proportional to field flux linkages of machine in p.u. Similarly, \( y \) denotes the output equation of the machine and \( C \) is the output matrix \( (C = [1, 0, 0, 0]). \)

The elements of matrix \( A \) are dependent on the operating condition.

III. REVIEW ON MULTIRATE OUTPUT FEEDBACK 
AND STATE FEEDBACK SLIDING MODE CONTROL

In the following, multirate output feedback and state feedback sliding mode control are briefly reviewed.

![Fig. 1. Block diagram of a Single Machine Infinite Bus (SMIB) system](image-url)
A. Multirate Output Feedback

Multirate Output Feedback (MROF) is the concept of sampling the control input and sensor output of a system at different rates. It was found that multirate output feedback can guarantee closed loop stability, a feature not assured by static output feedback [12] while retaining the structural simplicity of static output feedback. Much research has been performed in this field [13]–[17]. In multirate output feedback, the control input [15], [17] or the sensor output [16] is sampled at a faster rate than the other. In this paper, the term multirate output feedback is used to refer the situation wherein the system output is sampled at a faster rate as compared to the control input.

It was found that state based control laws of any structure may be realized by the use of multirate output feedback, by representing the system states in terms of the past control inputs and multirate sampled system output [18], [19].

B. State feedback sliding mode control

Consider a SISO plant described by a continuous time linear model

\[ \dot{x} = Ax + Bu, \]
\[ y = Cx. \]

Where \( x \in \mathbb{R}^n \), \( u \in \mathbb{R} \), \( y \in \mathbb{R} \) and the matrices \( A, B \) and \( C \) are of appropriate dimensions.

Let \((\Phi_\tau, \Gamma_\tau, C)\) be the system given by Eqn.(6) sampled at sampling interval \( \tau \) seconds and is represented as,

\[ x(k+1) = \Phi_\tau x(k) + \Gamma_\tau u(k), \]
\[ y(k) = Cx(k). \]

Using the reaching law for discrete time sliding mode control as given by Gao [20], the state feedback based discrete sliding mode control law is given by [20],

\[ u(k) = Fx(k) + \gamma \text{sgn}(s(k)) \]

Where

\[ F = -(c^T \Gamma_\tau)^{-1} [c^T \Phi_\tau - c^T I + q \tau c^T], \]
\[ \gamma = -(c^T \Gamma_\tau)^{-1} \varepsilon \tau \]

IV. MULTIRATE OUTPUT FEEDBACK FUZZY SLIDING MODE CONTROL

A. Output feedback sliding mode controller design

A generalized expression for the state feedback based discrete sliding mode control has been derived and is as given by Eqn. (9).

The control algorithm as derived in [19], the expression for switching plane and control law based on output feedback sliding mode control technique is given by,

\[ s(k) = c^T \Phi_\tau C_0^{-1} y_k + c^T [\Gamma_\tau - \Phi_\tau C_0^{-1} D_0] u(k-1), \]
\[ u(k) = F \Phi_\tau C_0^{-1} y_k + F [\Gamma_\tau - \Phi_\tau C_0^{-1} D_0] u(k-1) + \gamma \text{sgn}(s(k)). \]

Thus, it can be seen from the Eqsns. (11) and (12) that the states of the system are needed neither for switching function evaluation nor for the feedback purpose.

B. Multirate output feedback fuzzy sliding mode controller design

Fuzzy logic control (FLC) is a method utilizing those fuzzy experimental and for experimental rules to decide control actions [21]. In past years, FLC has found many successful applications in industry. However, traditional fuzzy controller lacks formal synthesis techniques and all the decision rules are experience oriented. In other words, the FLC is human dependent.
Sliding mode control (SMC) is a particular type of variable structure control systems that is designed to drive and then constrain the system to lie within the neighborhood of switching function. There are two main advantages of this approach. Firstly, the dynamic behavior of the system may be tailored by the particular choice of switching functions. Secondly, the closed loop response becomes totally insensitive to a particular class of uncertainty and external disturbances [22]. In addition, the ability to specify performance directly makes sliding mode control attractive from the design perspective. This design approach consists of two components. The first, involves the design of a switching function so that the sliding motion satisfies design specifications. The second is concerned with the selection of a control law, which will make the system state attractive to the switching function.

The fuzzy sliding mode control (FSMC) technique, which is an integration of variable structure control and FLC, provides a simple way to design FLC systematically. The main advantage of FSMC is that the control method achieves asymptotic stability of the system. Another feature is that the method can minimize the set of FLC and provide robustness against model uncertainties and external disturbances. In addition, the method is capable of handling the chattering problem that is arisen in traditional sliding mode control. Therefore a output feedback fuzzy sliding mode controller is proposed in which fuzzy inference mechanism is used to estimate the upper bound of the lumped uncertainty. The fuzzy inference mechanism uses prior expert knowledge to accomplish control objective more efficiently.

The conventional sliding mode control will make the system converge to the sliding surface at a rate proportional to $\gamma$, however on convergence to the surface the chattering present in the system would also be proportional to the $\gamma$.

Hence, in order to get maximum advantage of the controller structure, $\gamma$ should be tuned to be of high magnitude when the state is approaching the sliding surface, thus helping for faster convergence and when the state is in sliding mode, $\gamma$ should be tuned to be of low magnitude in order to reduce chattering.

The control law given by Eqn. (12) can also be expressed as

$$u(k) = Fx(k) + \gamma \text{sgn}(c^T x(k)),$$  \hspace{1cm} (13)

where

$$x(k) = \Phi_r c^{-1} y_h + [I_r - \Phi_r c^{-1} D_0] u(k-1).$$

and $\gamma$ is tuned by fuzzy inference mechanism. The membership function for the fuzzy sets corresponding to switching surface $s = c^T x(k)$ and $\gamma$ are defined in the Fig. 3 and Fig. 4 respectively.

The $i^{th}$ rule for a output feedback fuzzy sliding mode controller is expressed as follows:

$$R^i = \text{if } s = A_i \text{ then } \gamma = B_i,$$

where $A_i$ and $B_i$ are the labels of fuzzy sets representing the linguistic values of $s$ and $\gamma$ respectively, which are characterized by their membership functions as shown in Fig. 3 and Fig. 4 respectively. The fuzzy inference mechanism contains seven rules. The rule base for fuzzy sliding mode controller relating $|s|$ and $\gamma$ is given in table (I).

The membership functions for fuzzy sets $A_i$ and $B_i$ are chosen to be triangular membership functions and min-max methodology is used for the fuzzification. The defuzzification methodology used in the above problem is of centroid type [1]. The basic configuration of an output feedback fuzzy sliding mode controller is shown in Fig.2.

V. CASE STUDY

A. Linearization of power system

The Nonlinear differential equations governing the behavior power system can be linearized about a particular operating point to obtain a linear model which represents the small signal oscillatory response of a power system. A SIMULINK based block diagram including all the nonlinear blocks can also be used to generate the linear state space model of the system is obtained. This linear model is then discretized with the sampling time $\tau = 0.05$ sec.
B. Classical power system stabilizer design for a power system

The classical power system stabilizer (PSS) is designed in the following way.

The eigenvalues analysis of single machine infinite bus (SMIB) system is carried out and the participation ratio towards instability in the network is estimated. Power system stabilizer using phase compensation technique is designed according to the participation ratio towards instability till satisfactory closed loop performance of the power system is achieved. The above design of classical power system stabilizer is iterative and optimal tuning of parameters is based on experience. If the power characteristics of the system change, then the whole procedure has to be repeated. So, design of classical power system stabilizers cannot be considered as robust in nature for all operating points.

The proposed output feedback fuzzy sliding mode control technique based power system stabilizer is robust in nature and is not iterative.

C. PSS design by output feedback fuzzy sliding mode control technique for Single Machine Connected to Infinite Bus

The single machine infinite bus power system data is considered for designing decentralized output feedback fuzzy sliding mode control technique based power system stabilizer. The block diagram of the system is shown in Fig. 1.

The following parameters are used for simulation of the single machine infinite bus system model [11]:

\[ H = 5 \text{ sec.}, \quad T_{do} = 6 \text{ sec.}, \quad K_E = 100, \quad T_E = 0.02 \text{ sec.}, \quad \text{and} \quad x_e = 0.2 \text{ p.u.} \]

D. Simulation with Non-linear model

The slip of the machine is taken as output. This output signal with decentralized fuzzy sliding mode controller and a limiter is added to \( V_{ref} \) signal. This is used to damp out the small signal disturbances via modulating the generator excitation. The disturbance considered here is a self clearing fault which is cleared after 0.1 second. The limits of PSS output are taken as \( \pm 0.1 \). All PSSs can be applied simultaneously to the respective machines. Simulation results for all generators are shown in Fig. 5 to Fig. 12 with fuzzy sliding mode controller and classical controller.
As shown in plots, the proposed controller is able to damp out the oscillations in 1 to 2 seconds after clearing the fault.

**VI. CONCLUSION**

This paper proposes, the design of PSS for SMIB power system based on fuzzy logic and output feedback sliding mode controller. The slip signal is taken as output and output feedback fuzzy sliding mode control is applied at an appropriate sampling rate. It is found that designed controller provides good damping enhancement. The conventional power system stabilizer is dynamic in nature and is required to be tuned according to power characteristics where as, the proposed controller is non-dynamic in nature and a single controller structure is able to damp out the oscillations for all models.

**REFERENCES**


