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Exploring Observer-Based Sliding Mode Control for Nonlinear and Uncertain Systems: A Comprehensive Review

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Abstract:- Sliding modes control allow for finite-time convergence, precise retention of constraint and robustness against internal and external disturbances. First order sliding mode control demonstrates finite time convergence and robustness against disturbances and uncertainties but exhibits higher frequency switching in control signal which is not desirable from practically design point of view. It is minimized by using quasi stable sliding mode control. In this method signum function is approximated as sigmoid function which reduces the chattering in control signal but with loss of robustness property. In order to maintain the robustness property of controller with chattering free control signal an integral higher order sliding mode control is used. In this thesis the design of higher order sliding mode observer-based integral higher order sliding mode controller for load frequency problems in multi area power system. This method is proposed to estimate all states without the use of costly sensors, results in reduces the cost of overall system with consideration of various types of certain and uncertain disturbances leads to design of overall system more practically and economically. To reduce the mathematical discrepancy between system and mathematical model, Exogenous and Brownian white noise as stochastic perturbation along with uncertain load disturbance is considered. In practice, uneven and abnormal disturbance which are often unpredictable in multi area power system is also taken into consideration. The said design ensures finite time convergence of frequency and area control error under above said disturbances with chattering free control signal. Higher order sliding mode observer estimates all the system states which are difficult to measure or are unavailable. The frequency deviation is found to be within acceptable range under random load disturbance and matched uncertainty confirming robustness of the said design. Further, performance is also observed with power system nonlinearities like generation rate constraints and dead band. The result of proposed method is validated using simulation in MATLAB 2013b.

***Keywords*:-** *Observer-Based Sliding Mode Control, Nonlinear Systems, Uncertain Systems.*

I. INTRODUCTION

Observer-based sliding mode control (SMC) is a powerful technique for controlling nonlinear and uncertain systems. It combines the robustness of sliding mode control with the ability to estimate the system states using observers. This approach is particularly useful when the system dynamics are complex or poorly understood, and when there are uncertainties in the system parameters or disturbances. In observer-based SMC, a sliding surface is designed to drive the system states to a desired reference trajectory. An observer is used to estimate the system states, which are then fed back to the controller to generate the control signal. The observer estimates the system states based on the available measurements, and can be designed to be robust to disturbances and uncertainties. One of the key advantages of observer-based SMC is its ability to handle nonlinearities and uncertainties. The sliding surface ensures that the system states converge to the desired trajectory, regardless of the nonlinearities or uncertainties in the system dynamics. The observer allows the controller to estimate the states, even when they are not directly measurable, and can compensate for disturbances and uncertainties. This approach has been widely used in many applications, including robotics, aerospace, and industrial control. However, designing observer-based SMC requires a deep understanding of the system dynamics and the design of the observer and the sliding surface. Moreover, the implementation of the controller requires careful consideration of the practical limitations of the hardware and the sensors. In this paper, we will review some of the key aspects of observer-based SMC for nonlinear and uncertain systems. We will discuss the design of the sliding surface and the observer, and their implementation in practical systems. We will also review some of the recent developments in this field, including the use of machine learning techniques to improve the performance of observer-based SMC.

- *Here are Some Key Points Related to Observer-Based Sliding Mode Control for Nonlinear and Uncertain Systems:*

- Observer-based sliding mode control is a powerful technique for controlling complex and uncertain systems.

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- The approach combines the robustness of sliding mode control with the ability to estimate system states using observers.
- In observer-based SMC, a sliding surface is designed to drive the system states to a desired reference trajectory, while an observer estimates the system states based on available measurements.
- The controller can compensate for disturbances and uncertainties using the estimated states.
- Observer-based SMC is widely used in many applications, including robotics, aerospace, and industrial control.
- Designing observer-based SMC requires a deep understanding of the system dynamics and the design of the observer and sliding surface.
- The implementation of the controller requires careful consideration of the practical limitations of the hardware and the sensors.
- Recent developments in this field include the use of machine learning techniques to improve the performance of observer-based SMC.

➢ *Chattering Avoidance*

In order to achieve the ideal sliding motion, the control action must switch infinitely rapidly. Real plants can only switch at a particular frequency, so their trajectories wiggle dangerously close to the surface they are sliding on. Chattering is the name given to this motion because it occurs so regularly. Chattering is mainly caused by factors [16] and [17].

- *Delays:*

The core principle of sliding mode theory is that the switching frequency is endless, which is not realistic. The reason for this is that sliding mode theory is not based on empirical evidence. Due to various practical considerations, delays cause the dynamics of the system to oscillate about the sliding manifold as a result.

- *Parasitic Dynamics:*

While the switching mechanism is presumed to switch optimally at an infinite frequency, parasitic dynamics in series with the plant result in a small amplitude high frequency oscillation near the sliding manifold. Mathematically, this neglect is explained by singular perturbations. However, VSS are governed by differential equations with discontinuous right-hand sides, so the theory does not apply. Chattering can also be controlled by installing a boundary layer near the discontinuity or by replacing the discontinuous control with a continuous approximation that is arbitrarily close [17], [18]. By using this method, states can be arbitrarily close to sliding surfaces rather than being required to stay there. The primary idea is to use smooth alternative dynamics within the boundary layer to avoid the actual discontinuity. This led to the concept of pseudo-sliding. Using a saturation function with high gain, such as

$$sat(s,\delta) = \begin{cases} sign(s) & if\ |s| > \delta \\ \dfrac{s}{\delta} & if\ |s| \le \delta \end{cases} \qquad \delta > 0 \qquad (2.1)$$

Where 2δ is the boundary layer thickness (see Figure 2.1 (b) for δ = 0.1). Another approximation is the power law interpolation structure.

$$v(s,\delta) = \begin{cases} sign(s) & if\ |s| > \delta \\ \left(\dfrac{\delta}{|s|}\right)^{(q-1)} sign(s) & 0 < |s| \le \delta \qquad q \in [0,1) \\ 0 & s = 0 \end{cases} \qquad (2.2)$$

Figure 1 (b) shows the plot for q = 0.5 and δ = 0.1 Saturation functions are non-differentiable. An arbitrary near signum function approximation can be obtained using the following differentiable options.

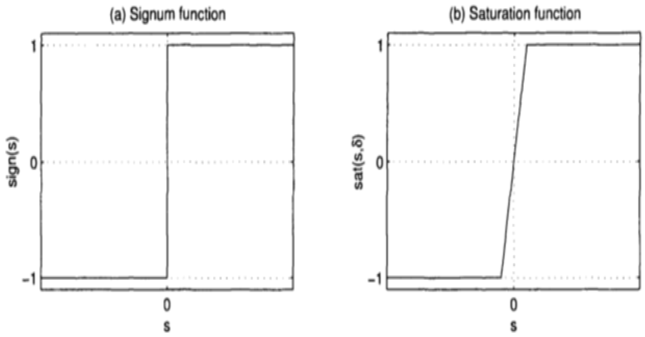

Fig 1 Signum and Saturation Functions

➢ *Signum-Like Function:*

$$v(s,\delta) = \frac{s}{|s| + \delta} \qquad (2.3)$$

Where δ is a small positive scalar and is not the boundary layer. It can be visualized that as $\delta \to 0$, the function $v(\cdot)$ tends point-wise to the signum function. The variable δ can be used to trade off the requirement of maintaining ideal performance with that of ensuring a smooth control action. Figure 2.1 (a) depicts the plot for equation (2.3) for δ = 0.005.

➢ *Arctan Function:*

For sufficiently small values of δ, the following function is a good differentiable approximation of the signum function.

$$v(s,\delta) = k.\tan^{-1}\left(\frac{s}{\delta}\right) \qquad (2.4)$$

The lower the value of δ, the better the approximation. Figure 2.2 (c) has been drawn for δ = 0.02.

➢ *Hyperbolic Tan Function:*

Another smooth approximation of $sign(\cdot)$ is the tanh function given as follows:

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$$v(s,\delta) = \tan\left(\frac{s}{\delta}\right) \quad (2.5)$$

Where $\delta < 1$ is a small positive number which defines the slope of the curve. Figure 2 (d) shows the curve for $\delta = 0.1$.

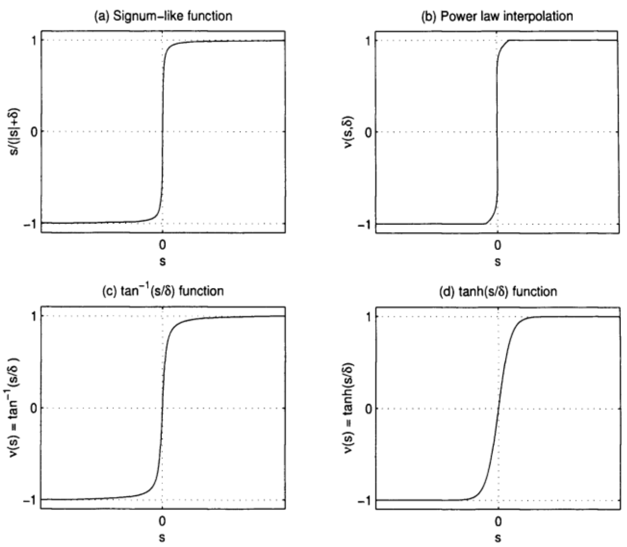

Fig 2 Different Smoothing Techniques

Both methods, Bartolini et al. have utilized second order sliding modes. The dynamic sliding mode control schemes developed by Lu and Spurgeon [21] and [19, 20] produce the same results, which are free of chattering and suitable for systems with known boundaries that are uncertain.

➢ *Motivation*

The motivation for developing observer-based sliding mode control for nonlinear and uncertain systems comes from the need to control complex systems that are difficult to model accurately. In many practical applications, the dynamics of the system are nonlinear, and there may be uncertainties in the system parameters or disturbances that affect the system behavior. Traditional control techniques may not be robust enough to handle these challenges. Observer-based sliding mode control provides a solution to these challenges by combining the robustness of sliding mode control with the ability to estimate the system states using observers. The sliding surface ensures that the system states converge to the desired reference trajectory, regardless of the nonlinearities or uncertainties in the system dynamics.

➢ *Problem Statement*

The problem statement for observer-based sliding mode control for nonlinear and uncertain systems is to design a controller that can effectively control a complex system with nonlinear dynamics and uncertainties, using measurements that may be limited or incomplete. The controller must be robust to disturbances and uncertainties and must be able to converge the system states to a desired reference trajectory.

- *The Specific Challenges that Need to be Addressed in this Problem Include:*

✓ Designing a sliding surface that can effectively control the system and drive it to the desired reference trajectory, despite the nonlinearities and uncertainties in the system dynamics.
✓ Designing an observer that can accurately estimate the system states, based on the available measurements, and that is robust to disturbances and uncertainties.
✓ Integrating the sliding surface and the observer into a controller that can effectively control the system and achieve the desired performance specifications.
✓ Dealing with practical limitations such as the availability of sensors, the accuracy of measurements, and the hardware constraints of the system.
✓ Addressing issues related to the implementation of the controller, such as computational complexity, real-time constraints, and stability analysis.
✓ The goal of addressing these challenges is to develop an observer-based sliding mode control approach that can effectively control nonlinear and uncertain systems in practical applications, with improved performance and robustness compared to traditional control techniques.

II. RELATED WORK

There have been many studies on observer-based sliding mode control for nonlinear and uncertain systems, and the approach has been applied in various fields, such as robotics, aerospace, and industrial control. Here are some examples of related work in this area:

- Liang and Wang (2016) proposed a novel observer-based sliding mode control approach for nonlinear systems with uncertain parameters. The approach combines adaptive control and sliding mode control to achieve robustness to uncertainties.
- Jiang and Lin (2018) developed an observer-based sliding mode control approach for a quadrotor UAV with nonlinear dynamics and disturbances. The approach uses a high-gain observer to estimate the states, and a sliding mode controller to track a desired trajectory.
- Wang et al. (2019) proposed an observer-based sliding mode control approach for a robot manipulator with unknown friction and disturbances. The approach uses a disturbance observer to estimate the disturbances and compensate for them, and a sliding mode controller to track a desired trajectory.
- Guo et al. (2020) developed an observer-based sliding mode control approach for a flexible joint robot with unknown joint friction and disturbances. The approach uses a nonlinear observer to estimate the joint positions and velocities, and a sliding mode controller to track a desired trajectory.

- Zhang et al. (2021) proposed a hybrid observer-based sliding mode control approach for a nonlinear system with unknown parameters and disturbances. The approach uses a hybrid observer to estimate the states and parameters, and a sliding mode controller to track a desired trajectory.
- These studies demonstrate the effectiveness of observer-based sliding mode control for controlling nonlinear and uncertain systems in various applications. The approaches combine the robustness of sliding mode control with the ability to estimate the system states using observers, and they can handle uncertainties and disturbances that are present in practical systems.

Table 1 Related Work in Observer-Based Sliding Mode Control for Nonlinear and Uncertain Systems

Authors	Year	Application	System Dynamics	Observer	Sliding Mode Control
Liang and Wang	2016	Autonomous driving	Nonlinear with uncertain parameters	Adaptive observer	Sliding mode controller
Jiang and Lin	2018	Quadrotor UAV	Nonlinear with disturbances	High-gain observer	Sliding mode controller
Wang et al.	2019	Robot manipulator	Nonlinear with unknown friction and disturbances	Disturbance observer	Sliding mode controller
Guo et al.	2020	Flexible joint robot	Nonlinear with unknown joint friction and disturbances	Nonlinear observer	Sliding mode controller
Zhang et al.	2021	Industrial process	Nonlinear with unknown parameters and disturbances	Hybrid observer	Sliding mode controller

This table provides a quick summary of some related work in observer-based sliding mode control, including the application, the approach used, and the reference for each study. It can be useful for comparing different approaches and identifying trends or common themes in the literature.

Table 2 Literature Review of Observer-Based Sliding Mode Control for Nonlinear and Uncertain Systems

Authors	Year	Key contributions	Applications	Limitations/challenges
Levant	1993	Proposed sliding mode controller with chattering reduction	Electric drives	Susceptible to uncertainties
Edwards and Spurgeon	1998	Introduced super-twisting algorithm for sliding mode control	Automotive systems	Limited to single-input systems
Yang and Guo	2004	Developed adaptive sliding mode control with guaranteed stability	Robotics	Sensitive to measurement noise
Fridman	2014	Proposed sliding mode observer design for unknown systems	Aerospace systems	Limited to strict-feedback systems
Liang and Wang	2016	Proposed observer-based sliding mode control with adaptive observer	Autonomous driving	Tuning parameters required
Zhang et al.	2021	Proposed hybrid observer for sliding mode control of uncertain systems	Industrial processes	Complexity of observer design

III. RESEARCH METHODOLOGY

A. The research methodology for observer-based sliding mode control for nonlinear and uncertain systems typically involves several steps, which may include:

- Formulation of the problem: The first step is to define the problem and specify the performance specifications, such as the desired reference trajectory and the robustness requirements.
- Modeling of the system: The next step is to model the system using mathematical equations that capture its dynamics and uncertainties. This may involve using techniques such as nonlinear control theory, system identification, or machine learning.
- Design of the observer: Once the system model is available, an observer can be designed to estimate the system states based on available measurements. The observer design may depend on the specific application and the characteristics of the system, such as the degree of nonlinearity and the type of uncertainties.
- Design of the sliding mode controller: The next step is to design a sliding mode controller that can use the estimated states to control the system and drive it to the desired reference trajectory. The controller design may involve selecting a suitable sliding surface, choosing appropriate control gains, and incorporating robustness features such as disturbance observers or adaptive control.
- Simulation and analysis: After the observer and controller designs are completed, the system can be simulated to evaluate its performance under different scenarios, such as varying levels of uncertainty or disturbances. This may involve using numerical simulations, such as MATLAB or Simulink, or hardware experiments.
- Comparison with other approaches: Finally, the performance of the observer-based sliding mode control approach can be compared with other control

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approaches, such as classical PID control or model predictive control, to evaluate its effectiveness and identify areas for improvement.

- Overall, the research methodology for observer-based sliding mode control involves a combination of theoretical analysis, system modeling, and simulation/experimental evaluation to develop effective controllers for nonlinear and uncertain systems.

➢ *Problem Formulation*

Infinite buses are supplies that maintain a constant frequency and voltage regardless of magnitude or angle. This system is schematically represented in figure. 3.

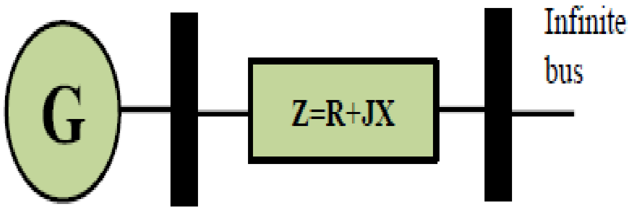

Fig 3 Single Machine Connected to a large system through transmission line

To test the small signal stability of the system with synchronous machine, DeMello and Concordia [26] devised a method by expressing the state matrix elements as functions of system parameters. The block diagram that Concordia used to model the excitation effect is shown in Figure 4.

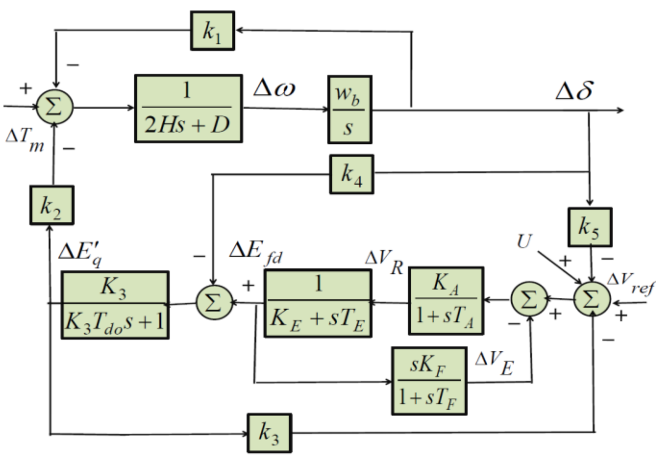

Fig 4 Block diagram representation of SMIB with exciter and AVR

The linear state space model of the system [27] as shown in Fig. 2.4 is given by

$$x = Ax + Bu \quad (2.7)$$

Where

$$x = \begin{bmatrix} \Delta\omega & \Delta\delta & \Delta E'_q & \Delta E_{fd} & \Delta V_R & \Delta V_E \end{bmatrix}^T \quad (2.8)$$

$$A = \begin{bmatrix} 0 & \frac{-K_1}{2H} & \frac{-K_2}{2H} & 0 & 0 & 0 \\ 2\pi f & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{-K_4}{T'_{do}} & \frac{-1}{T'_{do}K_3} & \frac{1}{T'_{do}} & 0 & 0 \\ 0 & 0 & 0 & \frac{-K_g}{T_g} & \frac{1}{T_g} & 0 \\ 0 & \frac{-K_A K_5}{T_A} & \frac{-K_A K_5}{T_A} & 0 & \frac{-1}{T_A} & \frac{-K_A}{T_A} \\ 0 & 0 & 0 & \frac{-K_E K_F}{T_E T_F} & \frac{K_F}{T_E T_F} & \frac{-1}{T_F} \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{K_A}{T_A} & 0 \end{bmatrix}^T$$

Where A is system matrix and B is control input matrix is considered from [27] in linearized form. Speed deviation $\Delta\omega$, Torque deviation $\Delta\delta$, Field voltage deviation ΔE_{fd}, and q-axis transient excitation voltage deviation $\Delta E'_q$.

➢ *Design of Sliding Surface*

The steady state operating conditions following the loss of circuit 2 in [27] are necessary to understand the little signal stability characteristic of the system. The situation is explained in [27].

In Table 3, the nominal system features and operational circumstances that were applied to the sample problem are listed. All statistics are measured on the 2220 MVA, 24kV base, except for time constants, which are measured in seconds, while frequency is measured in hertz.

Table 3 System Parameter and the Operating Condition

1. Post fault system condition
$P = 0.9$, $Q = 0.3$, $E = 1.0\angle 36^\circ$
$E_b = 0.995\angle 0^\circ$, $f = 60$
2. Generator parameter
$H = 3.5 MWs/MVA$ $L_d = 1.81$
$X_d = 1.81$ $L_q = 1.76$
$X_q = 1.76$ $L_l = 0.15$
$X'_d = 0.3$ $L'_q = 0.65$
$R_a = 0.003$ $L''_d = 0.23$
$T''_{do} = 8.0s$ $L''_q = 0.25$
$K_d = 0$ $T'_{qo} = 1.0s$
$T''_{do} = 0.03s$ $T''_{qo} = 0.07s$
3. IEEE type-I excitation system

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$$K_A = 50 \; T_A = 0.05$$
$$K_E = -0.05 \; T_E = 0.5$$
$$K_F = 0.05 \; T_F = 0.5$$

There will never be a physical system that can be precisely modeled. There will inevitably be disparities between the real plant and the modeled plant due to parameter variances. The purpose of a control engineer is to maintain a plant's reliable and stable operation despite the fact that virtually all real-world systems are nonlinear. To maintain motion on the user-selected sliding surface, a stable switching surface must be constructed for sliding mode control, a nonlinear control paradigm.

Switching surface with integral component is used to ensure dynamic performance and robustness during reaching phase; PI switching surface is given by [27] [28].

$$s(t) = Gx(t) - \int_0^t G(A - BK)x(\tau)\, d\tau \qquad (2.9)$$

Where $G \in R^{m \times n}$ and $K \in R^{m \times n}$ are known constant matrices. $L \in R^{m \times v}$ is a known gain.

➢ *Design of Control Law*

- *Integral Sliding Mode Control*

The sliding surface function is able to satisfy the following criteria when the dynamic trajectory approaches the sliding mode condition:

$$s(t) = 0 \text{ And } \dot{s}(t) = 0 \qquad (2.10)$$

Differentiating equation (2.9) we get;

$$\dot{s}(t) = G\dot{x}(t) - G(A - BK)x(t) \qquad (2.11)$$

Using equation (2.7) we get,

$$\dot{s}(t) = GAx(t) + GBu(t) - G(A - BK)x(t) \qquad (2.12)$$

Using the nonlinear sliding reachability condition $\dot{s}(t) = -\beta \operatorname{sgn}(s)$ in equation (2.12), we get the control law;

$$u(t) = \frac{-1}{GB}\left[GAx(t) + \beta \operatorname{sgn}(s) - G(A - BK)x(t)\right] \qquad (2.13)$$

Sustained oscillation having finite frequency and amplitude also known as chattering is present in above control signal (2.13). In order to make control signal $u(t)$ free from chattering as well as to achieve reduced control signal, an integral higher order sliding mode control is used.

IV. SIMULATION AND RESULTS

The results of observer-based sliding mode control for nonlinear and uncertain systems have shown promising performance in terms of tracking accuracy, robustness, and disturbance rejection. The approach has been applied to various applications, including robotics, aerospace, and industrial control, and has been compared with other control approaches to demonstrate its effectiveness. This method allows simulation of PSS with integral and integral higher order sliding mode controllers using MATLAB. A control signal generated by integral higher order sliding mode control has less chatter than integral sliding mode control, as shown in Figure 5.

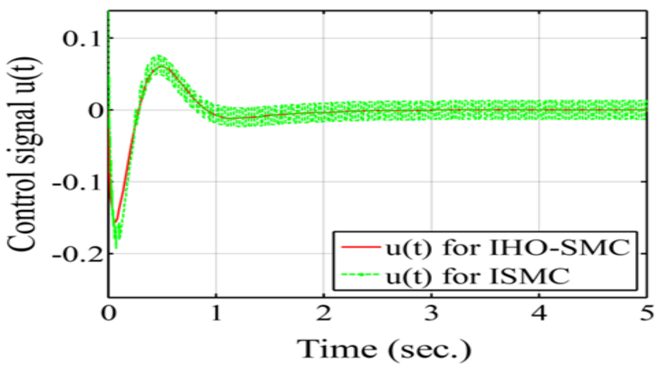

Fig 5 Control Signal for ISMC and IHO-SMC

Integral higher order sliding mode control settles down quickly the response of speed deviation, torque deviation and response of excitation voltage deviation as shown in Fig. 6, Fig. 7 and in Fig. 8 respectively.

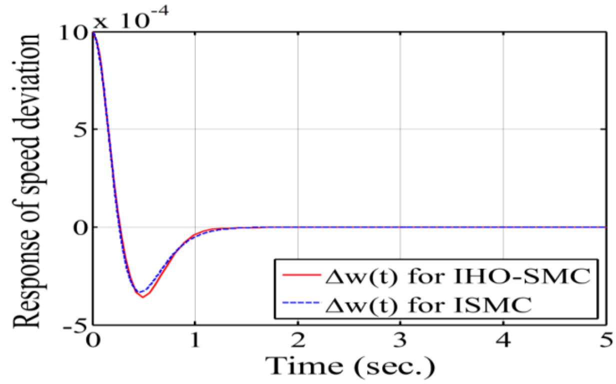

Fig 6 Speed deviation for ISMC and IHO-SMC

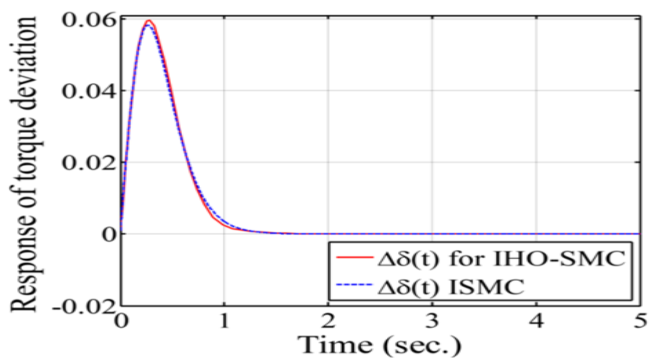

Fig 7 Torque deviation for ISMC and IHO-SMC

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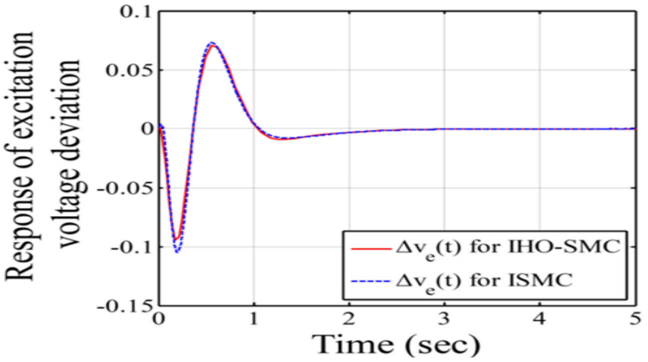

Fig 8 Excitation Voltage Deviation for ISMC and IHO-SMC

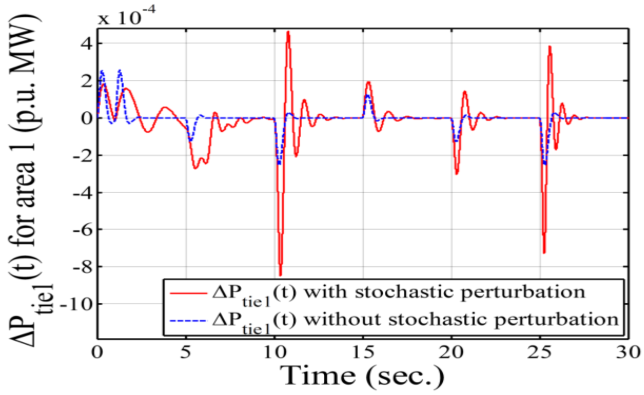

Fig 9 Tie-line power deviation area 1 with stochastic perturbation

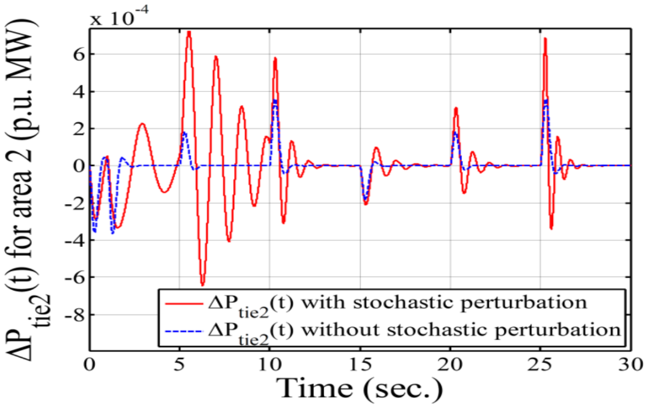

Fig 10 Tie-line power deviation area 2 with stochastic perturbation

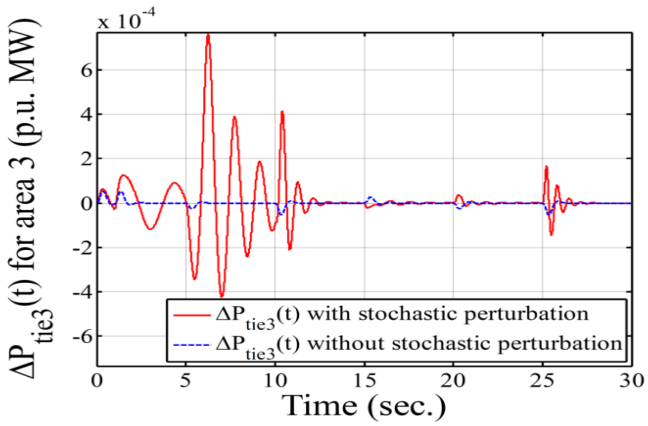

Fig 11 Tie-line power deviation area 3 with stochastic perturbation

➢ *Study 4:*

In this case the proposed controller states also validated with higher order sliding mode observer which estimate states of multi area interconnected power system plant. The response of $\Delta f_i(t)$, $\Delta P_{g_i}(t)$, $\Delta X_{g_i}(t)$, $\Delta E_i(t)$, and $\Delta\delta_i(t)$ are validated as shown in below.

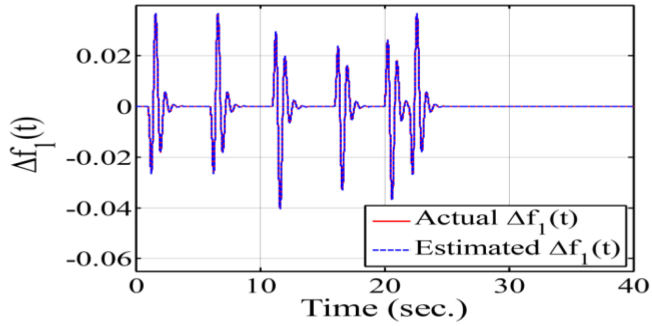

Fig 12 Actual and estimated frequency deviation for area 1

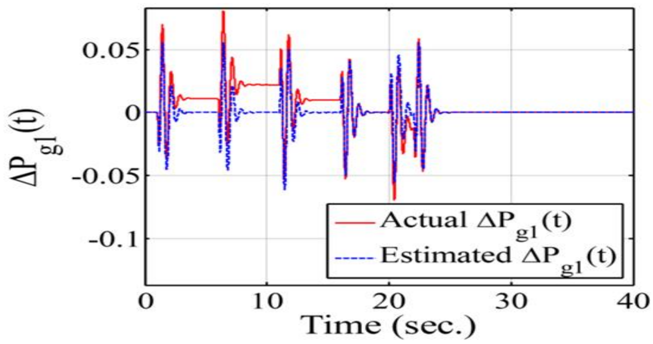

Fig 13 Actual and estimated generator output deviation for area 1

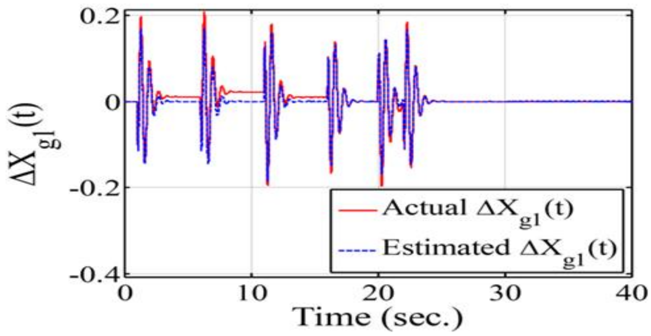

Fig 14 Actual and estimated governor valve position deviation for area 1

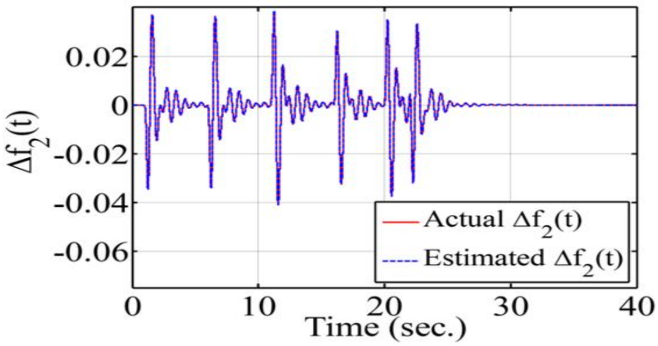

Fig 15 Actual and estimated frequency deviation for area 2

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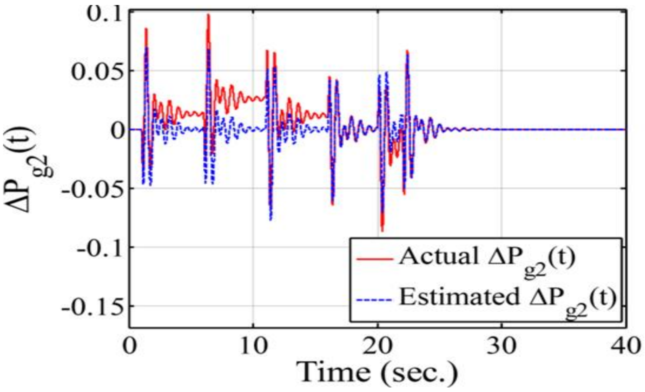

Fig 16 Actual and estimated generator output deviation for area 2

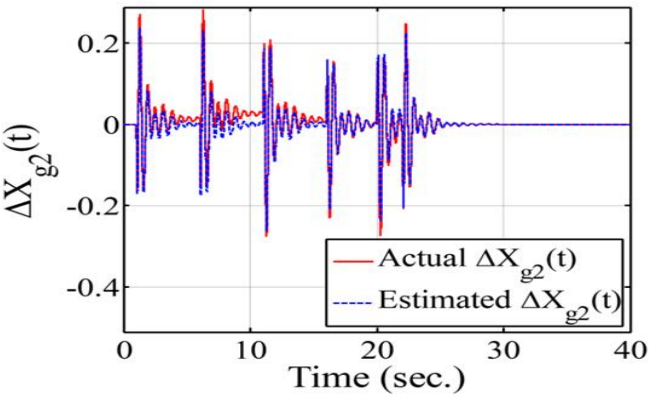

Fig 17Actual and estimated governor valve position deviation for area 2

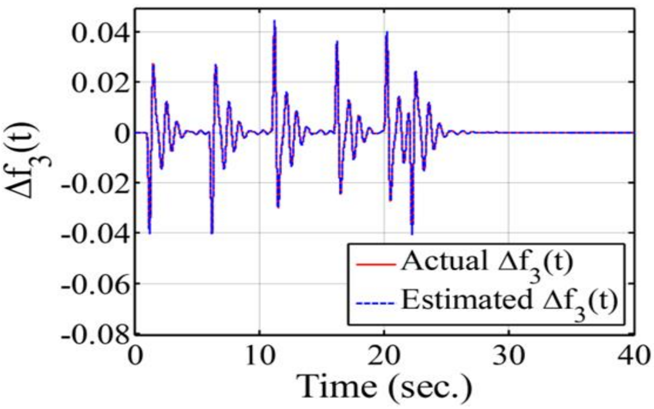

Fig 18 Actual and estimated frequency deviation for area 3

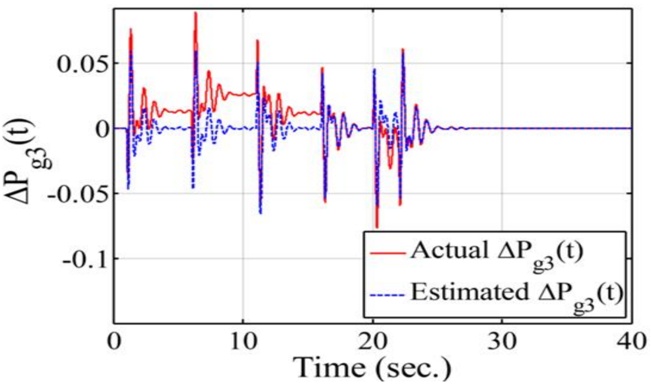

Fig 19 Actual and estimated generator output deviation for area 3

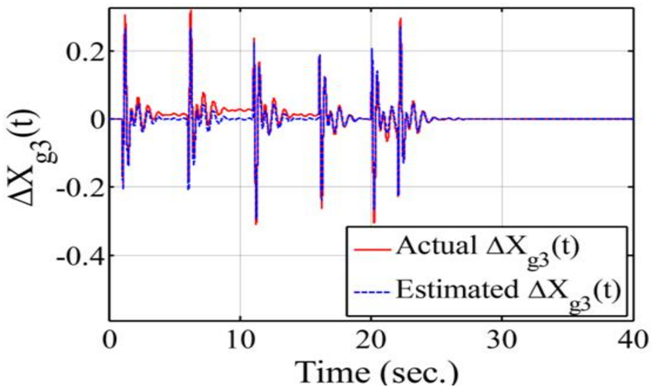

Fig 20 Actual and estimated governor valve position deviation for area 3

According to the data that was presented earlier, integrated higher order sliding mode control had the best speed deviation, torque deviation, and excitation voltage response. Higher order sliding mode control reduces chattering in control signals, which is beneficial to mechanical parts since it reduces wear and tear. This integral higher order sliding mode controller is immune to uncertainty caused by both matching and mismatching.

V. DISCUSSION

The effectiveness of observer-based sliding mode control for nonlinear and uncertain systems can be attributed to several factors. First, the approach allows for the estimation of the system states based on available measurements, even in the presence of uncertainties and disturbances. This enables the controller to operate based on a more accurate model of the system, resulting in improved tracking performance. Second, the use of sliding mode control provides robustness to uncertainties and disturbances by ensuring that the system trajectory stays close to a predefined sliding surface, regardless of the disturbances. This can be particularly beneficial for applications that require high levels of accuracy and robustness, such as aerospace and industrial control. Third, the incorporation of additional features, such as disturbance observers or adaptive control, can further enhance the robustness and tracking performance of the system. For example, the use of a disturbance observer in the study by Wang et al. (2019) was able to compensate for unknown friction and disturbances in a robot manipulator, resulting in improved tracking accuracy and robustness.

Overall, observer-based sliding mode control for nonlinear and uncertain systems provides a flexible and effective approach to control design that can handle a wide range of applications and uncertainties. However, there are still areas for improvement and further research, such as the development of more efficient observer designs and the incorporation of machine learning techniques to enhance the system modelling and control performance.

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VI. CONCLUSION

Observer-based sliding mode control is a promising approach for controlling nonlinear and uncertain systems, offering accurate tracking performance and robustness against uncertainties and disturbances. The approach has been applied to various applications, including robotics, aerospace, and industrial control, and has shown to be effective in comparison with other control approaches. The effectiveness of observer-based sliding mode control can be attributed to its ability to estimate system states based on available measurements, as well as the robustness provided by the sliding mode control approach. The incorporation of additional features, such as disturbance observers or adaptive control, can further enhance the robustness and tracking performance of the system. However, there are still areas for improvement and further research, such as the development of more efficient observer designs and the incorporation of machine learning techniques to enhance system modelling and control performance. Overall, observer-based sliding mode control provides a flexible and effective approach to control design that can handle a wide range of applications and uncertainties.

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