

Load frequency control for integrated hydro and thermal power plant power system

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ABSTRACT

Persistent electrical supply requires the power systems to be stable and reliable. Against varying load conditions, control strategies such as load frequency control (LFC) is a key mechanism to protect its stability. Traditional control strategies for LFC often face challenges due to system uncertainties, external disturbances, and nonlinearities. This paper presents an advanced approach to control load frequency and enhancing LFC in power systems by using sliding mode control (SMC). SMC offers powerful stability and robustness versus nonlinearities and perturbation, making it a promising approach for addressing the limitations of conventional control methods. We contemporary a comprehensive analysis of the SMC approach tailored for LFC, including the strategy and employment of the control algorithm. The proposed method makes use of a sliding/gliding surface to enable the system trajectories to be continuous on this surface despite parameter variations and external disturbances. Simulation results demonstrate significant improvements in frequency stability and system performance compared to conventional proportional-integral-derivative (PID) controllers. The paper also includes a comparative analysis of SMC with other modern control techniques, highlighting its advantages in terms of robustness and adaptability.

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1. INTRODUCTION

Load frequency control (LFC) is a critical component in upholding the stability and efficiency of modern power systems (PS), particularly in the context of multi-area interconnected networks. As PS evolves to incorporate diverse energy sources, including recent advances in energy generation plants such as wind power generation, solar power generation, or even biodiesel fuel, and as the complexity of these systems increases, effective control strategies become more essential. Recent advancements in control theory have significantly enhanced the performance of LFC systems. Among these, sliding mode control (SMC) and its variations, such as greater order of SMC and observer-based methods, have garnered substantial attention for their robustness and effectiveness. These approaches are particularly valuable in managing the dynamic

challenges associated with multi-area power systems, where integration of renewable resources and varying load demands can introduce significant instability.

Sebaa *et al.* [1] applied model predictive control (MPC) for PS stability problems. MPC was applied for LFC problems [2]. Furthermore, Zheng *et al.* [3] used adaptive disturbance rejection for LFC with renewable sources. Research [4] used the same technique but based on ANFIS approach.

Research in [5] used SMC with a backstepping method for LFC. The paper of [6] used SMC with a decentralizing approach for LFC. SMC was applied for an interconnected PS with nonlinearities [7] SMC was advanced and applied to autonomous problems [8]. The work in [9] used SMC with double integral for LFC. Paper [10] used SMC for LFC of wind resources. Research of paper [11] integrated electric vehicles and wind power, then continue to use SMC for LFC of those sources. Article [12] considered SMC for LFC with communication delays. Particle swarm optimization was used in [13] to tune the gains for SMC in LFC. These works provided a deep understanding of SMC and explored its characteristics of robustness on multiple scenarios of LFC.

Since the biggest problem of SMC is its chattering effect, multiple efforts have been put into reducing its limitations. a second-order SMC was used for interconnected PS (IPS) [14] Moore-Penrose Inverse technique was applied to SMC for IPS [15] LFC problems were tackled by the use of an adaptive integral higher-order SMC in [16]. The work of [17] developed an adaptive high order SMC for LFC strategies.

But then there comes another problem knowing the exact measurements of the system states, which is almost impossible due to its complexity and expensive sensor requirements. That is why researchers like [18] developed a highly robust observer for SMC to overcome those problems. Similarly, researchers in [19] yields promising results when applying an observer to a single-phase SMC for IPS. Researchers in [20] continue to develop an advanced observer for SMC LFC problems. Furthermore, Researchers in [21] used extended state observers for three area IPS. To further exploit LFC problems, researchers have considered using unexplored territories, for example generation rate constraint (GRC) or governor dead-band (GDB) and applying meta-heuristic optimization techniques. Researchers in [22] explored the effects of GDB using the Kalman filter. Effects of GRC on LFC were demonstrated in [23]. In the work of [24], GRC is considered in PS with the amalgamations of non-reheat turbines, reheat turbines, and hydro turbines. GRC effects was researched in a highly deregulated environment of three-area PS [25].

This paper provides comprehensive research on SMC for LFC applications, with a focus on multi-area power systems incorporating classical generation resources such as thermal and hydro power. The main aids of this article are as follows:

- An integral sliding mode observer-based controller has been developed and implemented for a multi-area and multi-source power system, integrating conventional energy foundations like thermal and hydropower plants, while accounting for the GRC.
- Chattering effect of traditional SMC is considered and reduced in this advanced controller design. The simulation results demonstrate strong robustness and rapid response to non-linearities and disturbances, guaranteeing stable and efficient operation.

2. MATHEMATICAL MODEL OF THREE-AREA INTERCONNECTED POWER SYSTEM

The mathematical archetypal of a three-area interrelated power system consists of a non-reheat turbine, a hydropower plant, and a reheat turbine is presented in Figure 1. Individually area contains of the plant and its decentralized controller with a tie-line signal connecting the controllers. Area 1 and Area 3, turbines as shown in the figure, have GDB in consideration. All three areas have GRC in consideration. The mathematical state-space equations of each area are derived from the shown Figure 1 in each sub section 1 to 3.

2.1. System model of Area 1

State-space model of Area 1 is given below:

$$\Delta P_{tie,1} = \Delta P_{tie,12} - \Delta P_{tie,31} \quad (1)$$

$$\Delta \dot{f}_1 = -\frac{1}{T_{P1}} \Delta f_1 + \frac{K_{P1}}{T_{P1}} \Delta P_{m1} - \frac{K_{P1}}{T_{P1}} \Delta P_{tie,1} - \frac{K_{P1}}{T_{P1}} \Delta P_{L1} \quad (2)$$

$$\Delta \dot{P}_{m1} = -\frac{1}{T_{P1}} \Delta P_{m1} + \frac{1}{T_{T1}} \Delta P_{g1} \quad (3)$$

$$\Delta P_{g1} = -\frac{1}{T_{G1}} \Delta P_{g1} - \frac{1}{T_{G1}} \Delta P_{C1} - \frac{1}{R_1 T_{G1}} \Delta f_1 \quad (4)$$

$$A\dot{C}E_1 = \Delta P_{tie,1} + B_1 \Delta f \quad (5)$$

$$\Delta P_{tie,1} = \Delta P_{tie,12} - \Delta P_{tie,31} = 2\pi(T_{12} + T_{31})\Delta f_1 - 2\pi T_{12}\Delta f_2 - 2\pi T_{31}\Delta f_3 \quad (6)$$

2.2. System model of Area 2

State-space model of Area 2 is given below:

$$\Delta P_{tie,2} = \Delta P_{tie,23} - \Delta P_{tie,12} \quad (7)$$

$$\Delta \dot{f}_2 = -\frac{1}{T_{P2}} \Delta f_2 + \frac{K_{P2}}{T_{P2}} \Delta P_{m2} - \frac{K_{P2}}{T_{P2}} \Delta P_{tie,2} - \frac{K_{P2}}{T_{P2}} \Delta P_{L2} \quad (8)$$

$$\Delta \dot{P}_{m2} = -\frac{2}{T_{W1}} \Delta P_{m2} + \frac{2}{T_{W1}} \Delta P_{v2} - 2\Delta \dot{P}_{v2} \quad (9)$$

$$\Delta \dot{P}_{v2} = -\frac{1}{T_{H1}} \Delta P_{v2} - \frac{1}{T_{H1}} \Delta P_{g2} + \frac{T_{R1}}{T_{H1}} \Delta \dot{P}_{g2} \quad (10)$$

$$\Delta \dot{P}_{g2} = -\frac{1}{T_{G1}} \Delta P_{g2} - \frac{1}{T_{G1}} \Delta P_{C2} - \frac{1}{R_2 T_{G2}} \Delta f_2 \quad (11)$$

Equation (11) substitute into (10), we will have:

$$\Delta \dot{P}_{v2} = -\frac{1}{T_{H1}} \Delta P_{v2} + \left(\frac{1}{T_{H1}} - \frac{T_{R1}}{T_{H1} T_{G2}}\right) \Delta P_{g2} - \frac{T_{R1}}{T_{H1} T_{G2}} \Delta P_{C2} - \frac{T_{R1}}{R_2 T_{H1} T_{G2}} \Delta f_2 \quad (12)$$

Equation (12) substitute into (9), we will have:

$$\begin{aligned} \Delta \dot{P}_{m2} = & -\frac{2}{T_{W1}} \Delta P_{m2} + \left(\frac{2}{T_{W1}} + \frac{2}{T_{H1}}\right) \Delta P_{v2} + \left(\frac{2T_{R1}}{T_{H1} T_{G2}} - \frac{2}{T_{H1}}\right) \Delta P_{g2} + \frac{2T_{R1}}{T_{H1} T_{G2}} \Delta P_{C2} \\ & + \frac{2T_{R1}}{R_2 T_{H1} T_{G2}} \Delta f_2 \end{aligned} \quad (13)$$

$$A\dot{C}E_2 = \Delta P_{tie,2} + B_2 \Delta f_2 \quad (14)$$

$$\Delta P_{tie,2} = \Delta P_{tie,23} - \Delta P_{tie,12} = 2\pi(T_{23} + T_{12})\Delta f_2 - 2\pi T_{23}\Delta f_3 - 2\pi T_{12}\Delta f_1 \quad (15)$$

2.3. System model of Area 3

State-space model of Area 3 is given below:

$$\Delta P_{tie,3} = \Delta P_{tie,31} - \Delta P_{tie,23} \quad (16)$$

$$\Delta \dot{f}_3 = -\frac{1}{T_{P3}} \Delta f_3 + \frac{K_{P3}}{T_{P3}} \Delta P_{m3} - \frac{K_{P3}}{T_{P2}} \Delta P_{tie,3} - \frac{K_{P3}}{T_{P3}} \Delta P_{L3} \quad (17)$$

$$\Delta \dot{P}_{m3} = -\frac{1}{T_{RH1}} \Delta P_{m3} + \frac{1}{T_{RH1}} \Delta P_{v3} + K_{R1} \Delta P_{v3} \quad (18)$$

$$\Delta \dot{P}_{v3} = -\frac{1}{T_{T2}} \Delta P_{v3} - \frac{1}{T_{T2}} \Delta P_{g3} \quad (19)$$

Equation (19) substitute into (18), we will have:

$$\Delta \dot{P}_{m3} = -\frac{1}{T_{RH1}} \Delta P_{m3} + \left(\frac{1}{T_{RH1}} - \frac{K_{R1}}{T_{T2}}\right) \Delta P_{v3} + \frac{K_{R1}}{T_{T2}} \Delta P_{g3} \quad (20)$$

$$\Delta \dot{P}_{g3} = -\frac{1}{T_{G3}} \Delta P_{g3} - \frac{1}{T_{G3}} \Delta P_{C3} - \frac{1}{R_3 T_{G3}} \Delta f_3 \quad (21)$$

$$A\dot{C}E_3 = \Delta P_{tie,3} + B_3 \Delta f_3 \quad (22)$$

$$\Delta \dot{P}_{tie,3} = \Delta P_{tie,31} - \Delta P_{tie,23} = 2\pi(T_{31} + T_{23})\Delta f_3 - 2\pi T_{31}\Delta f_1 - 2\pi T_{23}\Delta f_2 \tag{23}$$

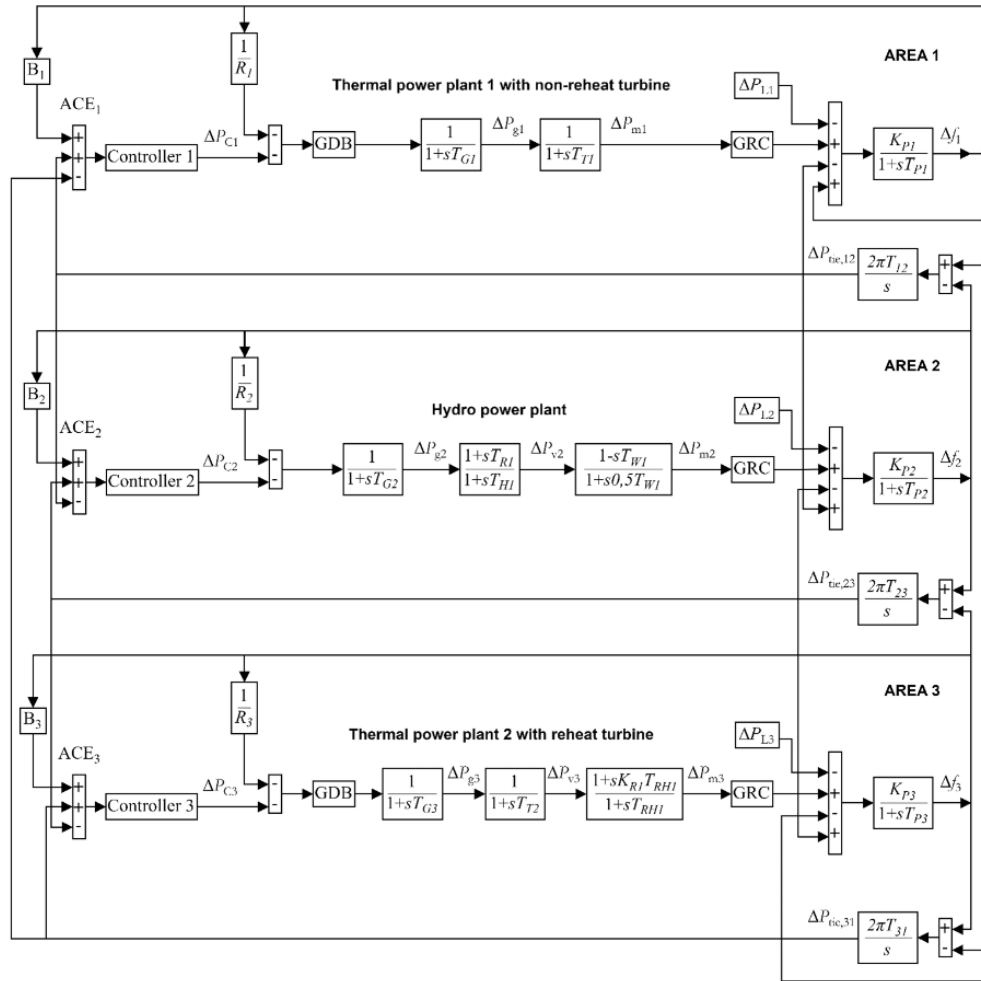


Figure 1. The single-source three-area interconnected power system block diagram

3. STATE-SPACE EQUATION OF THE OBSERVER

The state-space equation of the system is expressed as follows:

$$\begin{cases} \dot{x}_i(t) = A_i x_i(t) + B_i u_i(t) + \sum_{j \neq i}^N H_{ij} x_j(t) + F_i \Delta P_{Li}(t) \\ y_i(t) = C_i x_i(t) \end{cases} \tag{24}$$

With, x_i is a state vector with n state variables. Matrices A_i with dimensions of $n \times n$. u_i is a control vector with m control variables. Matrices B_i with dimensions of $n \times m$. x_j is a state vector connecting to another area. Matrices H_{ij} with dimensions equal to the state variable x_i . ΔP_{Li} is a load disturbance vector with g load disturbance variables. Matrices F_i with dimensions of $n \times g$. y_i is an output vector with h output variables. Matrices C_i with dimensions of $h \times n$.

The state-space equation of the observer is expressed as (25):

$$\begin{cases} \dot{\hat{x}}_i(t) = A_i \hat{x}_i(t) + B_i u_i(t) + \sum_{j \neq i}^N H_{ij} \hat{x}_j(t) + L_i [y_i(t) - \hat{y}_i(t)] \\ \hat{y}_i(t) = C_i \hat{x}_i(t) \end{cases} \tag{25}$$

With, $\hat{x}_i(t)$ is the predictable state of $x_i(t)$. $\hat{y}_i(t)$ is the estimated state output of $y_i(t)$. L_i is the observer gain which can be determined through pole placement technique.

4. INTEGRAL SLIDING MODE CONTROL WITH STATE ESTIMATOR

Integral sliding mode control (ISMC) with a state estimator is a robust control method to enhance the stability and performance of PS. First step is to determine the integral sliding surface (ISS). The next step is the construction of a corresponding control law and a switch law. Finally, stability analysis of the control signal.

The ISS with estimated state is given as (26):

$$\sigma_i[\hat{x}_i(t)] = G_i\hat{x}_i(t) - \int_0^t G_i(A_i - B_iK_i)\hat{x}_i(\tau)d\tau \quad (26)$$

With, matrices G_i is chosen accordingly to confirm that the matrix G_iB_i is nonsingular or invertible. Therefore, matrix G_i can be chosen as $G_i = B_i^{-1}$

Taking derivative of (26) is specified underneath:

$$\dot{\sigma}_i[\hat{x}_i(t)] = G_i\dot{\hat{x}}_i(t) - G_i(A_i - B_iK_i)\hat{x}_i(t) \quad (27)$$

Substitute (24) into (27), we will have:

$$\begin{aligned} \dot{\sigma}_i[\hat{x}_i(t)] &= G_i \left[A_i\hat{x}_i(t) + B_iu_i(t) + \sum_{j \neq i}^N H_{ij}\hat{x}_j(t) + L_i[y_i(t) - \hat{y}_i(t)] \right] - G_i(A_i - B_iK_i)\hat{x}_i(t) \\ &= G_iA_i\hat{x}_i(t) + G_iB_iu_i(t) + G_i \sum_{j \neq i}^N H_{ij}\hat{x}_j(t) + G_iL_i[y_i(t) - \hat{y}_i(t)] - G_iA_i\hat{x}_i(t) + G_iB_iK_i\hat{x}_i(t) \\ &= G_iB_iu_i(t) + G_i \sum_{j \neq i}^N H_{ij}\hat{x}_j(t) + G_iL_i[y_i(t) - \hat{y}_i(t)] + G_iB_iK_i\hat{x}_i(t) \end{aligned} \quad (28)$$

The general control signal is given below:

$$u_i(t) = u_i^{eq}(t) + u_i^{sw}(t) \quad (29)$$

With, $u_i^{eq}(t)$ is the equivalent control equation (ECE) to certify that the system is in the sliding surface and $u_i^{sw}(t)$ is the switching control equation that ensures the system will head towards and remains on the sliding surface.

From (28) when $\sigma_i(t) = \dot{\sigma}_i(t) = 0$, the ECE becomes:

$$u_i^{eq}(t) = -(G_iB_i)^{-1} \left[G_i \sum_{j \neq i}^N H_{ij}\hat{x}_j(t) + G_iL_i[y_i(t) - \hat{y}_i(t)] + G_iB_iK_i\hat{x}_i(t) \right] \quad (30)$$

The switching control occurs when:

$$\dot{\sigma}[\hat{x}_i(t)] = -\alpha_i \text{sat}[\sigma_i[\hat{x}_i(t)]] \quad (31)$$

α_i : positive constant ($\alpha_i > 0$). This factor helps to adjust the conjunction rapidity of the system. The saturation condition that helps reduce the chattering effect is given below:

$$\text{sat}[\sigma_i[\hat{x}_i(t)]] = \begin{cases} -1 & \text{if } \sigma_i[\hat{x}_i(t)] < -1 \\ \sigma_i[\hat{x}_i(t)] & \text{if } -1 < \sigma_i[\hat{x}_i(t)] < 1 \\ 1 & \text{if } \sigma_i[\hat{x}_i(t)] > 1 \end{cases} \quad (32)$$

From (31) we will have $[\sigma_i(t) \dot{\sigma}_i(t) < 0]$. Substitute (30) and (31) into (29), and the general control sign is as:

$$u_i(t) = -(G_iB_i)^{-1} \left[G_i \sum_{j \neq i}^N H_{ij}\hat{x}_j(t) + G_iL_i[y_i(t) - \hat{y}_i(t)] + G_iB_iK_i\hat{x}_i(t) + \alpha_i \text{sat}[\sigma_i[\hat{x}_i(t)]] \right] \quad (33)$$

Remark 1: The condition above will ensure that the value of $\sigma_i(t)$ will decrease over time, thereby ensuring that the sliding motion will be asymptotically stable over time.

Remark 2: The controller is based on a state-observer, which effectively reduces the use of costly sensors as the full-state feedback from [6].

5. SIMULATION RESULTS AND DISCUSSION

For simulation, the proposed ISS-observer-based controller is compared against the proportional-integral-derivative (PID) controller and Integral SMC (ISMC). A load disturbance of 1% is introduced in three areas of generation. Figures 2, 3 and 4 show the comprehensive comparison of frequency deviation of three controllers respective to Area 1, 2 and 3 and Figure 5 as Figures 6 and 7 demonstrates their modification in tie-line power.

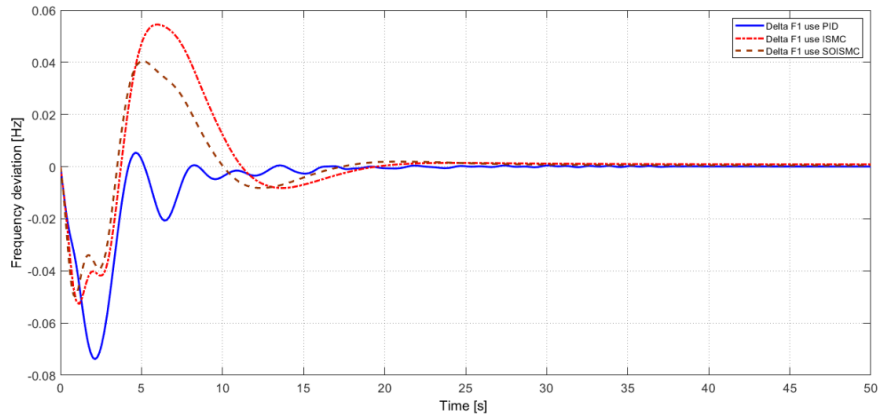


Figure 2. Area 1’s change in frequency using three controllers

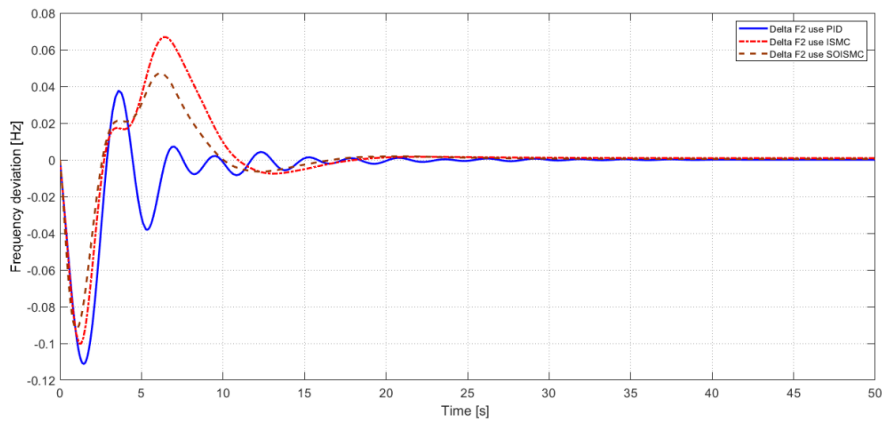


Figure 3. Area 2’s change in frequency using three controllers

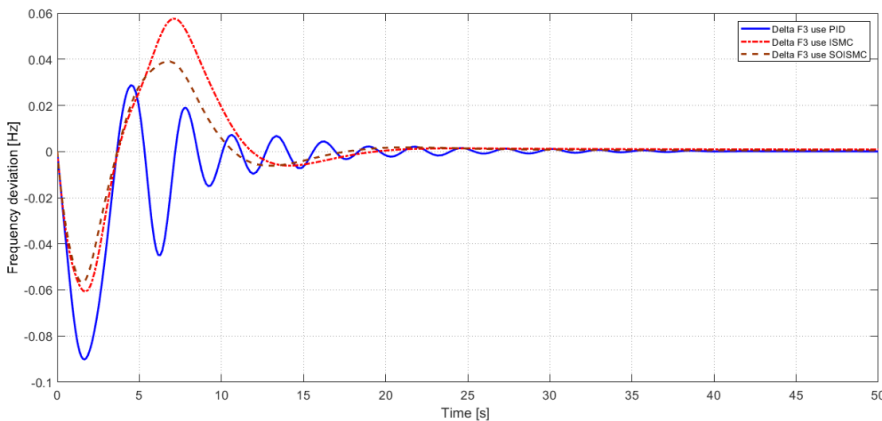


Figure 4. Area 3’s change in frequency using three controllers

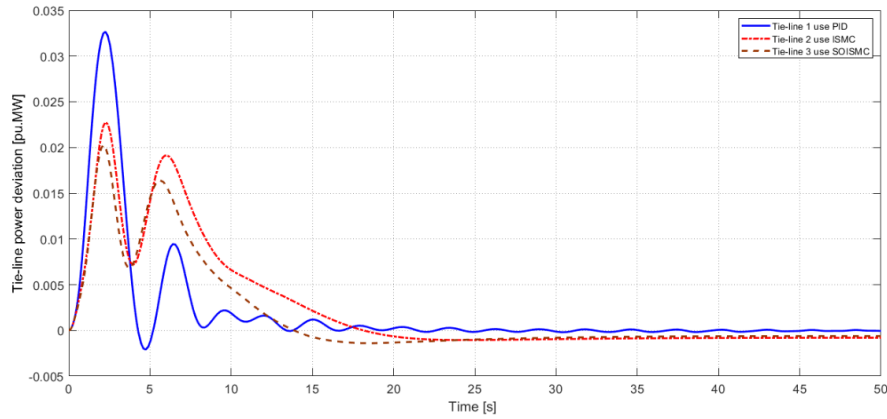


Figure 5. Area 1's change in tie-line power using three controllers

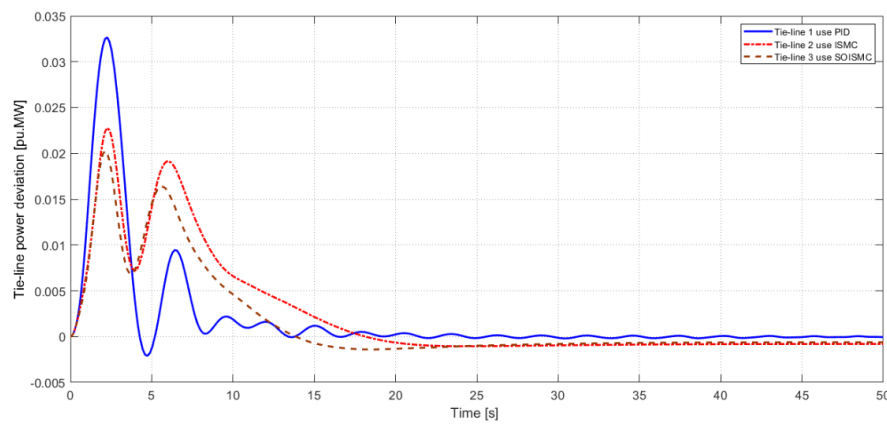


Figure 6. Area 2's change in tie-line power using three controllers

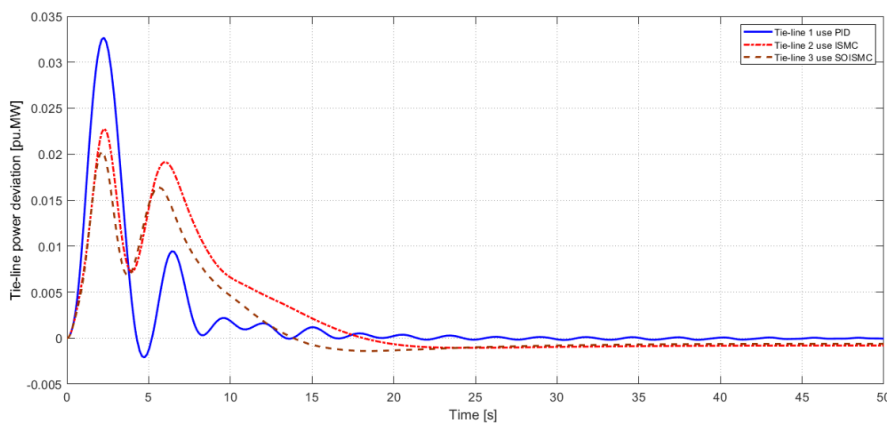


Figure 7. Area 3's change in tie-line power using three controllers

The frequency deviation of three areas follows the same pattern. As the disturbance load is artificially introduced, three types of controllers: PID, ISMC and SOISMIC react with those changes almost instantaneously and at the same rate of about 2s from start to peak. After reaching the peak and returning to zero, the controllers' characteristics are exhibited distinctly. PID continues to oscillate multiple times converging to zero while ISMC and SOISMIC overshoot and undershoot only once. The steady state error of PID is more significant than that of ISMC and SOISMIC. ISMC and SOISMIC are identical in waveform but are distinguishable by their magnitude (Area 1 for example: 0.05 Hz peak, 0.04 Hz overshoot for ISMC;

0.052 Hz peak, 0.055 Hz overshoot for SOISMC). All controllers reach convergence in approximately 30 seconds, with SOISMC and ISMC slightly faster. By qualitative and quantitative comparisons, SOISMC is proven to be more superior than its alternatives.

Remark 3: The proposed controller exhibits outstanding effectiveness in handling the variability and uncertainty associated with GRC. By successfully reducing frequency deviations and achieving fast stabilization, it highlights its robustness and adaptability, positioning itself as an advanced solution for integrating various power sources within a multi-area hybrid power system.

6. CONCLUSION

A multi-area and multi-source hybrid power system utilizing conventional energy sources such as thermal and hydropower plants have been equipped with a newly developed ISS-observer-based. This advanced design not only accounts for the GRC but also addresses and mitigates the chattering effect typically associated with traditional SMC. Precise simulations demonstrate that the planned controller outperforms conventional methods in robustly maintaining frequency stability, achieving fast response, effectively mitigating deviations under varying loads and disturbances, and ensures seamless integration of hydro and thermal plants compared to other methods, by all quantitative and qualitative means. Further implementation of the proposed controller should be attempted in real-time as soon as we have access to and acquire deep understanding of Hardware-in-the-loop systems.




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