International Journal of Electrical and Computer Engineering (IJECE)
Vol. 15, No. 4, August 2025, pp. 3583~3592
ISSN: 2088-8708, DOI: 10.11591/ijece.v15i4.pp3583-3592

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

Vu Tan Nguyen[1], Thinh Lam-The Tran[1], Dao Huy Tuan[1], Dinh Cong Hien[2], Vinh Phuc Nguyen[1], Van Van Huynh[3]
[1]Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam
[2]Major Projects/Field Operations/Commissioning Department, North Oil Company, Doha, Qatar
[3]Modeling Evolutionary Algorithms Simulation and Artificial Intelligence, Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam

Article Info

Article history:

Received Aug 14, 2024
Revised Mar 26, 2025
Accepted May 24, 2025

Keywords:

Integral sliding mode control
Integral sliding surface
Load frequency control
Sliding mode control
Three-area interconnected power system

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.

Corresponding Author:

Van Van Huynh
Modeling Evolutionary Algorithms Simulation and Artificial Intelligence, Faculty of Electrical and Electronics Engineering, Ton Duc Thang University
19 Nguyen Huu Tho Str., Tan Phong ward, District 7, Ho Chi Minh City, Vietnam
Email: huynhvanvan@tdtu.edu.vn

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:

$$\Delta P_{tie,1} = \Delta P_{tie,12} - \Delta P_{tie,31} \tag{1}$$

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

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

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

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

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

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:

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

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

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

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

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

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:

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

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

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

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

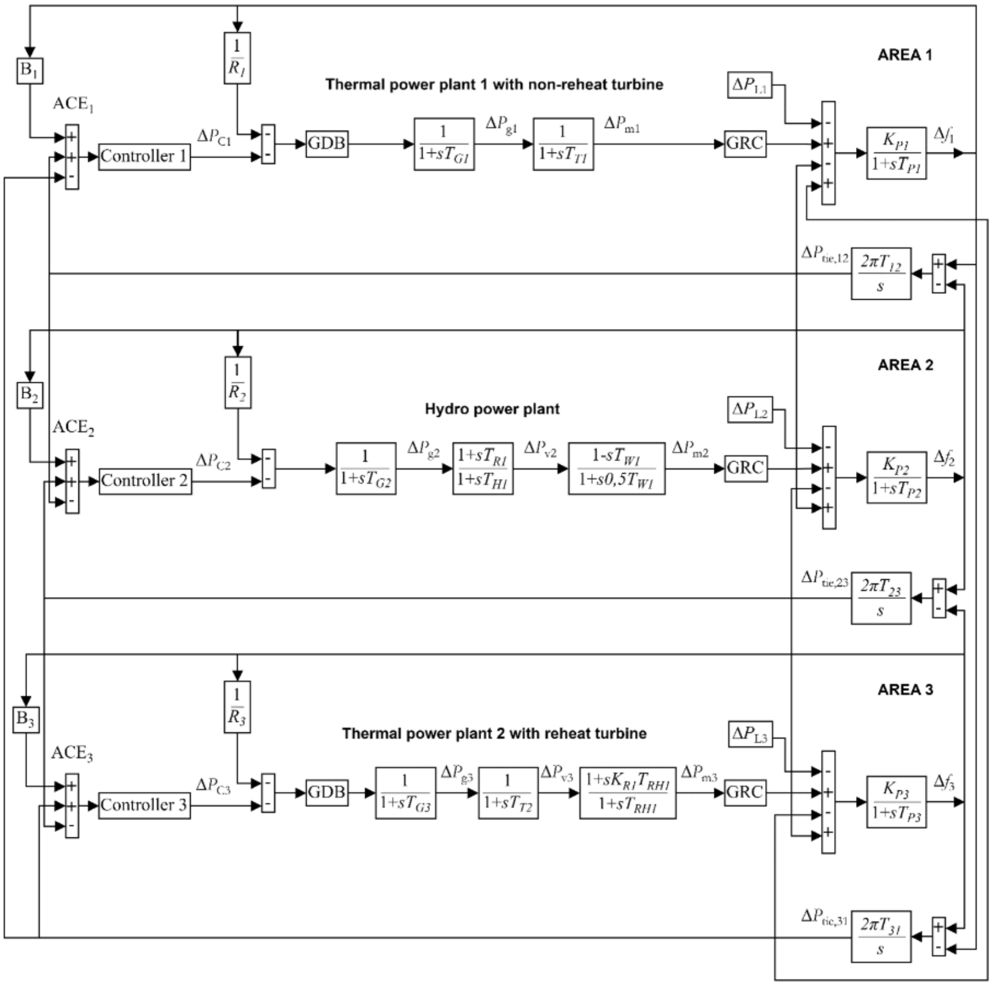

Figure 1. The single-source three-area interconnected power system block diagram

3. STATE-SPACE EQUATION OF THE OBSERVER

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

$$\begin{cases} \dot{x}_i(t) = A_i x_i(t) + B_i u_i(t) + \sum_{\substack{i=1 \\ j\neq i}}^{N} H_{ij} x_j(t) + F_i \Delta P_{Li}(t) \\ y_i(t) = C_i x_i(t) \end{cases} \quad (24)$$

With, x_i is a state vector with n state variables. Matrices A_I with dimensions of n×n. u_I is a control vector with m control variables. Matrices B_I with dimensions of n×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×g. y_I is an output vector with h output variables. Matrices C_I with dimensions of h×n.

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

$$\begin{cases} \hat{x}_i(t) = A_i x_i(t) + B_i u_i(t) + \sum_{\substack{i=1 \\ j\neq i}}^{N} H_{ij} \hat{x}_j(t) + L_i[y_i(t) - \hat{y}_i(t)] \\ \hat{y}_i(t) = C_i \hat{x}_i(t) \end{cases} \quad (25)$$

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):

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

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 $G_I = B_1^{-1}$

Taking derivative of (26) is specified underneath:

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

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

$$\begin{aligned}\dot{\sigma}_i\big[\dot{\hat{x}}_i(t)\big] &= G_i\left[A_i\hat{x}_i(t) + B_iu_i(t) + \sum_{\substack{i=1\\ j\neq i}}^{N} H_{ij}\hat{x}_j(t) + L_i[y_i(t) - \hat{y}_i(t)]\right] - G_i(A_i - B_iK_i)\hat{x}_i(t)\\ &= G_iA_i\hat{x}_i(t) + G_iB_iu_i(t) + G_i\sum_{\substack{i=1\\ j\neq i}}^{N} H_{ij}\hat{x}_j(t) + G_iL_i[y_i(t) - \hat{y}_i(t)] - G_iA_i\hat{x}_i(t) + G_iB_iK_ix_i(t)\\ &= G_iB_iu_i(t) + G_i\sum_{\substack{i=1\\ j\neq i}}^{N} H_{ij}\hat{x}_j(t) + G_iL_i[y_i(t) - \hat{y}_i(t)] + G_iB_iK_i\hat{x}_i(t)\end{aligned} \tag{28}$$

The general control signal is given below:

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

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:

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

The switching control occurs when:

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

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:

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

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:

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

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.

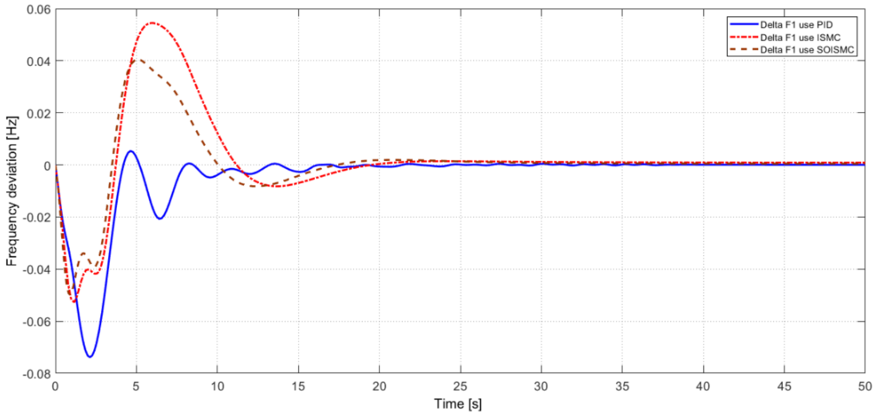

Figure 2. Area 1's change in frequency using three controllers

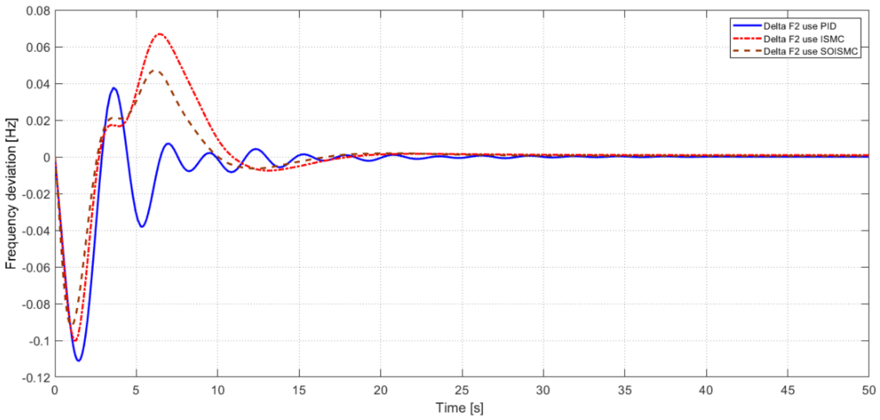

Figure 3. Area 2's change in frequency using three controllers

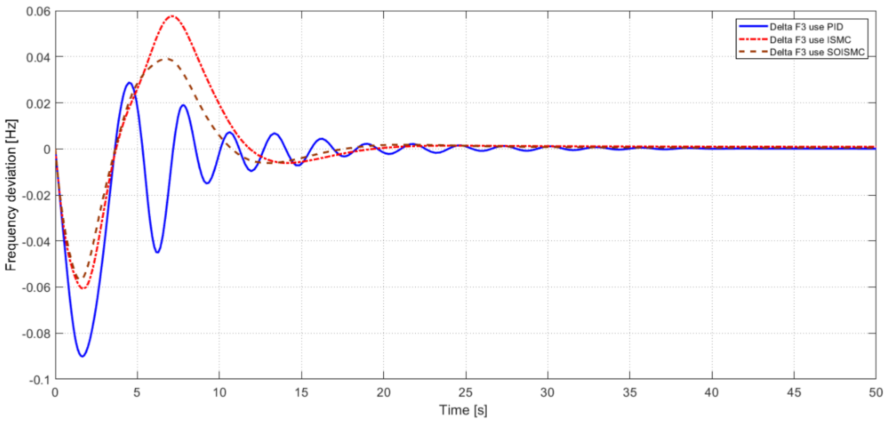

Figure 4. Area 3's change in frequency using three controllers

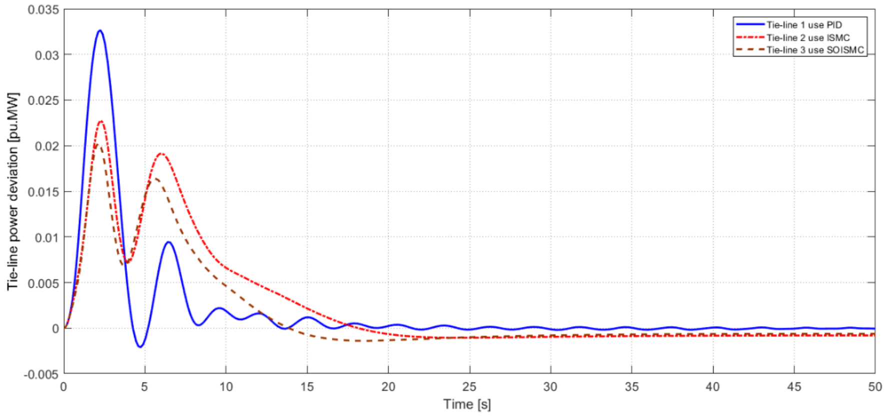

Figure 5. Area 1's change in tie-line power using three controllers

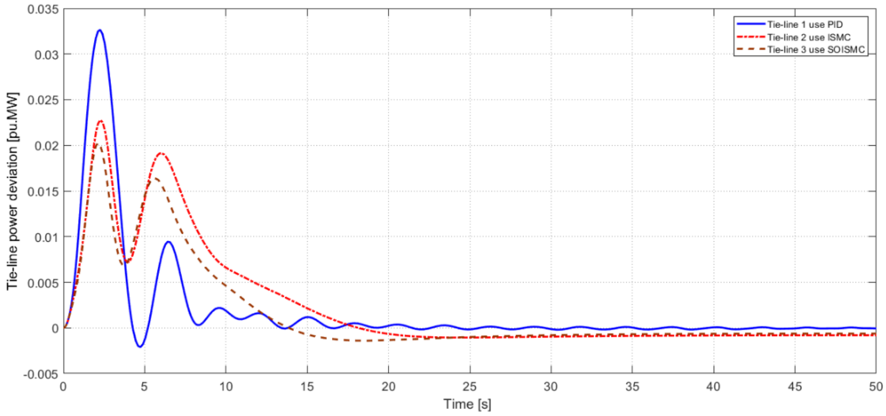

Figure 6. Area 2's change in tie-line power using three controllers

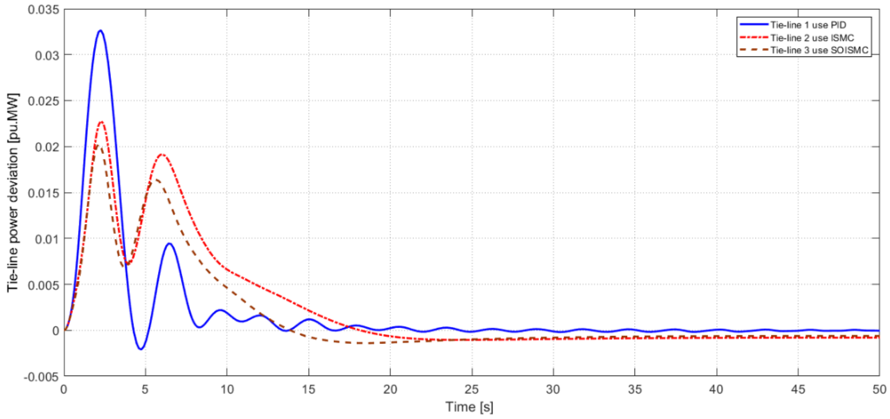

Figure 7. Area 3's change in tie-line power using three controllers

The frequency deviation of three areas follows the same pattern. As the disturbance load is artificially introduced, three types of controllers: PID, ISMC and SOISMC 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 SOISMC overshoot and undershoot only once. The steady state error of PID is more significant than that of ISMC and SOISMC. ISMC and SOISMC 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.

REFERENCES

[1] K. Sebaa, S. Moulahoum, H. Houassine, and N. Kabache, “Model predictive control to improve the power system stability,” in *2012 13th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM)*, May 2012, pp. 208–212. doi: 10.1109/OPTIM.2012.6231972.

[2] A. M. Ersdal, I. M. Cecilio, D. Fabozzi, L. Imsland, and N. F. Thornhill, “Applying model predictive control to power system frequency control,” in *IEEE PES ISGT Europe 2013*, Oct. 2013, pp. 1–5. doi: 10.1109/ISGTEurope.2013.6695306.

[3] Y. Zheng, J. Tao, Q. Sun, H. Sun, Z. Chen, and M. Sun, “Adaptive active disturbance rejection load frequency control for power system with renewable energies using the Lyapunov reward-based twin delayed deep deterministic policy gradient algorithm,” *Sustainability*, vol. 15, no. 19, p. 14452, Oct. 2023, doi: 10.3390/su151914452.

[4] A. Tiguercha, A. A. Ladjici, and S. Saboune, “Multi-area optimal adaptive under-frequency load shedding control based on ANFIS approach,” *Electrical Engineering*, vol. 106, no. 3, pp. 3573–3587, Jun. 2024, doi: 10.1007/s00202-023-02156-z.

[5] J. Ansari, M. Homayounzade, and A. R. Abbasi, “Load frequency control in power systems by a robust backstepping sliding mode controller design,” *Energy Reports*, vol. 10, pp. 1287–1298, Nov. 2023, doi: 10.1016/j.egyr.2023.08.008.

[6] Y. Mi, Y. Fu, C. Wang, and P. Wang, “Decentralized sliding mode load frequency control for multi-area power systems,” *IEEE Transactions on Power Systems*, vol. 28, no. 4, pp. 4301–4309, Nov. 2013, doi: 10.1109/TPWRS.2013.2277131.

[7] J. Guo, “Sliding mode based load frequency control for an interconnected power system with nonlinearities,” Dissertation, Electrical and Computer Engineering, Cleveland State University, 2015. Accessed: Aug 14, 2024. [Online]. Available: https://etd.ohiolink.edu/acprod/odb_etd/ws/send_file/send?accession=csu1435857616&disposition=inline

[8] Y.-W. Liao, “Advanced sliding mode control and its application to autonomous vehicle at the limits of handling,” Dissertation, Mechanical Engineering, University of California, Berkeley, 2019. Accessed: Aug 14, 2024. [Online]. Available: https://escholarship.org/uc/item/3239f3hx

[9] B. Le Ngoc Minh, V. Van Huynh, T. M. Nguyen, and Y. W. Tsai, “Decentralized adaptive double integral sliding mode controller for multi-area power systems,” *Mathematical Problems in Engineering*, vol. 2018, pp. 1–11, Oct. 2018, doi: 10.1155/2018/2672436.

[10] V. Van Huynh *et al.*, “Load frequency control for multi-area power plants with integrated wind resources,” *Applied Sciences*, vol. 11, no. 7, p. 3051, Mar. 2021, doi: 10.3390/app11073051.

[11] Z. Wang, Y. Liu, Z. Yang, and W. Yang, “Load frequency control of multi-region interconnected power systems with wind power and electric vehicles based on sliding mode control,” *Energies*, vol. 14, no. 8, p. 2288, Apr. 2021, doi: 10.3390/en14082288.

[12] P.-T. Nguyen and C.-T. Nguyen, “Single phase robustness variable structure load frequency controller for multi-region interconnected power systems with communication delays,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 14, no. 5, pp. 5064-5071, Oct. 2024, doi: 10.11591/ijece.v14i5.pp5064-5071.

[13] N.-K. Nguyen, D.-T. Nguyen, and T.-M.-P. Dao, “A novel PSO-based modified SMC for designing robust load-frequency control strategies,” *Engineering, Technology & Applied Science Research*, vol. 13, no. 4, pp. 11112–11118, Aug. 2023, doi: 10.48084/etasr.5972.

[14] A.-T. Tran *et al.*, “Load frequency regulator in interconnected power system using second-order sliding mode control combined with state estimator,” *Energies*, vol. 14, no. 4, p. 863, Feb. 2021, doi: 10.3390/en14040863.

[15] P. Nguyen Van and T. Nguyen-Cong, “Chattering-free second order robustness sliding mode controller for complex interconnected systems: a Moore-Penrose inverse technique,” *Journal of Advanced Engineering and Computation*, vol. 7, no. 4, p. 210, Dec. 2023, doi: 10.55579/jaec.202374.429.

[16] A. Dev, M. K. Sarkar, P. Asthana, and D. Narzary, “Event-triggered adaptive integral higher-order sliding mode control for load frequency problems in multi-area power systems,” *Iranian Journal of Science and Technology, Transactions of Electrical Engineering*, vol. 43, no. 1, pp. 137–152, Mar. 2019, doi: 10.1007/s40998-018-0078-0.

[17] J. Guo, “The load frequency control by adaptive high order sliding mode control strategy,” *IEEE Access*, vol. 10, pp. 25392–25399, 2022, doi: 10.1109/ACCESS.2022.3152259.

[18] V. Van Huynh, B. L. N. Minh, E. N. Amaefule, A.-T. Tran, and P. T. Tran, “Highly robust observer sliding mode based frequency control for multi area power systems with renewable power plants,” *Electronics*, vol. 10, no. 3, p. 274, Jan. 2021, doi: 10.3390/electronics10030274.

[19] C.-T. Nguyen, C. Trong Hien, and V.-D. Phan, "Observer-based single phase robustness load frequency sliding mode controller for multi-area interconnected power systems," *Bulletin of Electrical Engineering and Informatics*, vol. 13, no. 5, pp. 3147–3154, Oct. 2024, doi: 10.11591/eei.v13i5.7893.

[20] V. Van Huynh, P. T. Tran, T. M. Nguyen, V.-D. Phan, and V.-T. Pham, "Advanced sliding mode observer design for load frequency control of multiarea multisource power systems," *International Transactions on Electrical Energy Systems*, vol. 2022, pp. 1–21, Mar. 2022, doi: 10.1155/2022/6587194.

[21] V. Van Huynh, P. T. Tran, T. A. Tran, D. H. Tuan, and V.-D. Phan, "Extended state observer based load frequency controller for three area interconnected power system," *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, vol. 19, no. 3, pp. 1001-1009, Jun. 2021, doi: 10.12928/telkomnika.v19i3.18777.

[22] P. Bhui, N. Senroy, A. K. Singh, and B. C. Pal, "Estimation of inherent governor dead-band and regulation using unscented Kalman filter," *IEEE Transactions on Power Systems*, vol. 33, no. 4, pp. 3546–3558, Jul. 2018, doi: 10.1109/TPWRS.2017.2765692.

[23] N. Kumari and A. N. Jha, "Effect of generation rate constraint on load frequency control of multi area interconnected thermal systems," *Journal of Electrical and Electronics Engineering Research*, vol. 5, no. 3, pp. 44–49, 2013, doi: 10.5897/JEEER12.107.

[24] K. P. S. Parmar, "State space based load frequency control of multi-area power systems," PhD Theses, Electronics and Electrical Engineering, IIT Gandhinagar, India, 2013.

[25] A. Pant, "Load frequency control of multi area hybrid power system under deregulated environment," Masters Theses, Department of Electrical & Instrumentation Engineering, Thapar Institute of Engineering and Technology, India, 2018.

BIOGRAPHIES OF AUTHORS

Vu Tan Nguyen was born in Tay Ninh City, Vietnam. Currently, he is B.Eng. student in electrical engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam. His research topics include load frequency control, sliding mode control and optimal control.

Thinh Lam-The Tran was born in Ca Mau City, Vietnam. Currently, he is B.Eng. student in electrical engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam. His research topics include load frequency control, sliding mode control and optimal control. He can be contacted at email: 42000133@student.tdtu.edu.vn.

Dao Huy Tuan received the master's degree in thermal engineering from Vietnam University of Technology, in 2013. He is currently pursuing the Ph.D. degree in electrical engineering with Ton Duc Thang University. His research interests include power systems and control systems. He can be contacted at email: daohuytuan@tdtu.edu.vn.

Dinh Cong Hien received an B.Eng. in controls and informatics in technical systems from Tomsk Polytechnique University. He is currently working as ICSS/INS Commissioning Lead at North Oil Company Qatar.

Vinh Phuc Nguyen was born in Vung Tau City, Vietnam. Currently, he is B.Eng. student in electrical engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam. His research topics voltage stabilization in power systems, wind power generation forecast, solar power generation forecast.

Van Van Huynh received the Ph.D. degree in mechanical and automation engineering from Da- Yeh University, Changhua, Taiwan, in 2015. He is currently a Lecturer with the Faculty of Electrical and Electronics Engineering, Ton Duc Thang University, Ho Chi Minh City, Vietnam. His current research interests include sliding mode control, variable structure control, and power system control. He can be contacted at email: huynhvanvan@tdtu.edu.vn.