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Attenuated-chattering global second-order sliding mode load frequency controller for multi-region linked power systems

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ABSTRACT

In this study, a new chattering-free global second-order sliding mode load frequency controller (CGSOSMLFC) is proposed for multi-region linked power systems (MRLPS). Key achievements of this paper include: i) a new CGSOSMLFC is investigated utilizing only output variables; ii) a global steadiness of the MRLPS is ensured by eliminating the hitting phase in traditional sliding mode control (TSMC), and the undesirable high-frequency vacillation marvel in the control signal is efficiently lessened by utilizing the second-order sliding mode control technique. Firstly, a novel estimator is constructed to conjecture the immeasurable state variables of the MRLPS. Then, an estimator-based CGSOSMLFC is synthesized to force the states of the controlled plant into the anticipated switching surface at an instance time and attenuate the chattering phenomenon in the control indication. Additionally, the total MRLPS's stability analysis is executed by applying the Lyapunov function theory and linear matrix inequality (LMI), confirming the practicability and reliability of the method. Lastly, simulation outcomes on a three-zone linked power system are furnished to authenticate the usefulness and advantages of the proposed technique.

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NOMENCLATURE

PS	:	Power system	A^T	:	Transpose of A matrix
MRLPS	:	Multi-region linked power system	$y(t)$	:	Output signal
WTG	:	Wind power generation	$\sigma[\hat{z}(t)]$	:	Single phase switching surface
LFC	:	Load frequency control	$\psi[\hat{z}(t)]$	:	Sliding manifold function
VSC	:	Variable structure control	$\xi(z,t)$	:	Disturbance input signal
TSMC	:	Traditional sliding mode control	$\|z(t)\|$	:	Norm of state vector $z(t)$
GSMC	:	Global sliding mode control	λ_{max}	:	Maximum eigenvalue
HOSMC	:	High-order sliding mode control	$u(t)$	:	Control signal
SOSMC	:	Second-order sliding mode control	$\varpi(t)$	:	Dynamics error of estimator
$z(t)$	:	States of the plant	$\alpha, \varepsilon, \bar{\varphi}$	:	Positive constants

1. INTRODUCTION

The operation of PS is extremely complex due to the variability of load requests and renewable generation, and especially the exchange of electricity between neighboring areas. The PS control schemes are used to maintain the system in a stable state, and LFC is an important control issue in wide-area PS operations [1]-[3]. Among control approaches, sliding mode control (SMC) is one such well-known control performance due to sturdiness, finite time convergence, insensitivity to perturbations, and uncertainties [4], [5]. The renowned SMC is a specific category of VSC, which is the newest ongoing movement in many different fields, such as hydraulic/air-filled, transmission of data, structures of satellites, robotic manipulator, and especially in the LFC of PSs [6]-[10]. Although the VSC in sliding mode has noteworthy accomplishments in LFC problems, overall, there are still two missions that should be unraveled for VSC-based LFC problems of PSs: This includes: i) Output feedback: A shortcoming of the current investigations is that all variables of the PSs have to be accessible. This is unacceptable in various practical plant controls. A new output feedback sliding mode load frequency controller (OFSMCLFC) is proposed for MRLPS employing only output information; and ii) Chattering phenomenon eradication: A new OFSMCLFC not only promises the entire steadiness of the MRLPS but also reduces the undesirable high-frequency oscillations in control indication by utilizing the SOSMC. To find the solution to the output feedback control strategy problem in the first task above, a significant number of studies have been proposed in LFC, as mentioned in Table 1.

Table 1. Summary of key works related to the first task of notable SMC-based LFC methods

Ref.	Systems	Key contributions	Approaches/techniques	Limitations
[6]	Microgrid system	Improved frequency regulation using optimized SMC	Sliding mode control law via teaching learning optimization	Traditional SMC, the chattering issue remains
[7]	Multi-region power plant with time delays and perturbations	Robust frequency regulation handling delays and perturbations	Full-order terminal sliding mode controller	Traditional SMC, robustness only in the sliding phase
[11]	Multi-area interconnected energy plants	Addressed load frequency adjustment using terminal SMC	Integral and derivative terminal sliding mode control	Requires full state measurement
[12]	Interconnected multi-field power plants	Decentralized SMC with optimized parameters	Decentralized sliding mode LFC optimized via modified PSO	Full state accessibility assumed
[13]	Interconnected power systems	Improved estimator-based SMC	Integral SMC based on state estimator	Chattering issue remains

Nevertheless, authors in Table 1 have used the TSMC technique, which only produces the wanted motion after sliding mode has occurred. The TSMC's robustness only happens in the sliding mode period. To advance the robustness of SMC, the authors in this study proposed a novel GSMC approach. It should be distinguished that GSMC has strong stability during the whole control progression, better than the TSMC [14], [15]. Recently, the design of the LFC scheme was suggested based on adaptive GSMC for a multi-region linked electricity system with immeasurable states [8]. However, most of these studies need the accessibility of the states of the plant, which cannot be warranted in practice. Preview study [16], output feedback sliding mode load frequency control law was proposed for MRLPS with external perturbations. Nevertheless, these studies could not lessen the chattering impact in the input signal. High-frequency vibration causes damage or wear to moving mechanical parts, affects control accuracy, and causes high heat in the electrical circuit [17]. To deal with this chattering phenomenon, the technique of hiding the discontinuity of the control signal in its higher derivatives was executed employing HOSMC or SOSMC. The HOSMC technique was elevated by Levant [18], then eventually it has eventually attracted a lot of attention. In addition, the theory and application of the SOSMC approach have been greatly developed in recent years. The idea of the SOSMC methodology was originally established in the 1980s by [19]. This is also the second mission of our study. To achieve chattering reduction in the second task, there are many methods to mitigate the chattering phenomenon, as shown in Table 2.

Table 2. Summary of the main findings and associated limitations regarding in the second mission

Ref.	Systems	Key contributions	Approaches/techniques	Limitations
[20]	Multi-region hydro power plants	Addressed chattering in LFC using adaptive HOSMC	Adaptive integral controller using HOSMC	Sensitivity to unmodeled dynamics, needs full state
[21]	Three-region power plant	Adaptive SMC design for improved LFC	Adaptive the HOSMC technique	Sensitivity to fast dynamics
[22]	Large-scale power plant	Robust LFC with SOSMC	Using the SOSMC approach	Full state measurability required

As shown in Tables 1 and 2, although significant progress has been made in designing advanced SMC-based LFC schemes, two major challenges remain. First, many existing methods require full state information, which is not always practically possible. Second, while various approaches have attempted to mitigate the chattering phenomenon, fully eliminating high-frequency oscillations in the control signal remains difficult. Motivated by these limitations, this paper proposes a novel chattering-free global second-order sliding mode load frequency controller (CGSOSMLFC) that employs an observer-based output feedback strategy to address both of these issues effectively. The CGSOSMLFC ensures global stability of the MRLPS from the beginning of its motion while eliminating high-frequency fluctuations in the control signal. In addition, in the sliding mode, an appropriate requirement to asymptotically alleviate the MRLPS is given by means of the renowned LMI method. To end, by mathematical example, the validity of the proposed concepts, techniques, and procedures is shown.

2. STATE SPACE FORM OF THE MULTI-REGION LINKED POWER SYSTEMS

In this part, the MRLPS contains subsystem control regions that are linked through tie-lines [7]. Figure 1 illustrates the mathematical model of i the control zone with WTG, where $i = 1,2\ldots,n$ symbolizes the number of zones, and $i \neq j$. The multi-zone electricity plant dynamics are described in Table 3.

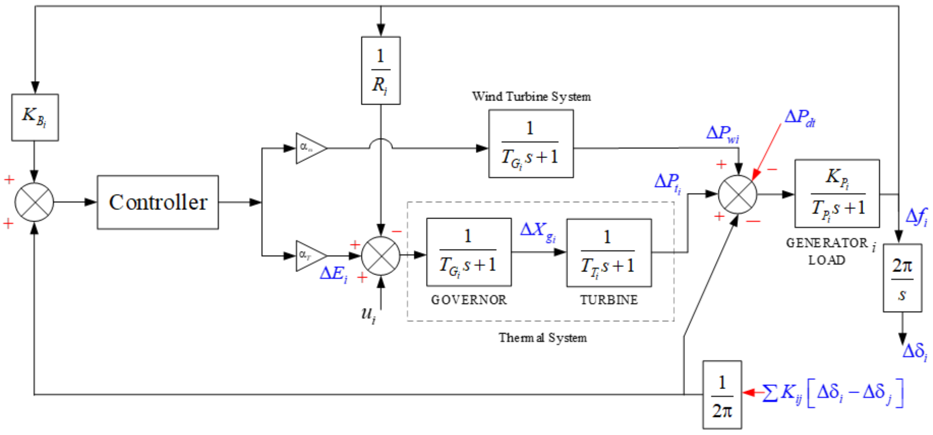


Figure 1. Block diagram of the MRLPS comprises wind and thermal units

Table 3. The interconnected multi-area power system dynamics [7]

Expression/formula	Physical meaning/explanation
$\dot{z}_{1i}(t) = -\frac{1}{T_{Pi}}\dot{z}_{1i}(t) + \frac{K_{Pi}}{T_{Pi}}z_{2i}(t) + \frac{K_{Pi}}{T_{Pi}}\Delta P_{di}(t) - \frac{K_{Pi}}{2\pi T_{Pi}} \times \sum_{i=1,j\neq i}^{N} K_{sij}[\Delta z_{5i}(t) - \Delta z_{5j}(t) + \frac{K_{Pi}}{T_{Pi}}z_{6i}(t)]$	Frequency dynamics: $z_{1i}(t) = \Delta f_i(t)$ is frequency deviation in area i
$\dot{z}_{2i}(t) = -\frac{1}{T_{Ti}}z_{2i}(t) + \frac{1}{T_{Ti}}z_{3i}(t)$	Generator output dynamics: $z_{2i}(t) = \Delta P_{gi}(t)$ is deviation of generator output power
$\dot{z}_{3i}(t) = -\frac{1}{T_{Gi}R_i}z_{1i}(t) - \frac{1}{T_{Gi}}z_{3i}(t) - \frac{1}{T_{Gi}}z_{4i}(t) - \frac{1}{T_{Gi}}u_i$	Governor valve position dynamics: $z_{3i}(t) = \Delta X_{gi}(t)$ is governor's valve situation
$\dot{z}_{4i}(t) = K_{Ei}K_{Bi}\alpha_T z_{4i}(t) + \frac{K_{E_i\alpha_T}}{2\pi}\sum_{i=1,j\neq i}^{N}[\Delta z_{5i}(t) - \Delta z_{5j}(t)]$	Integral controller output dynamics: $z_{4i}(t) = \Delta E_i$ is output of integral controller
$\dot{z}_{5i}(t) = 2\pi z_{5i}(t)$	Rotor angle dynamics: $z_{5i}(t) = \Delta\delta_i(t)$ is the rotor angle's aberration
$\dot{z}_{6i}(t) = \frac{\alpha_\omega}{T_{\omega i}}z_{4i}(t) - \frac{1}{T_{\omega i}}z_{6i}(t)$	Wind turbine power dynamics: $z_{6i}(t) = \Delta P_{\omega i}(t)$ is the wind turbine's power

The terms T_{Pi}, T_{Ti}, and $T_{\omega i}$ are the time coefficients of the power plant, the turbine, the wind turbine, respectively; T_{Gi} indicates the governor's time constant, R_i indicates droop gain's time constant, K_{Pi} indicates power system gain's time constant, K_{Bi}indicates bias factor's time constant, K_{Ei}indicates time constant of the integral controller gain. K_{sij} is the tie-line factor between the region i and j ($i \neq j$). α_ω and α_T show the contribution coefficients of wind turbines and thermal units. Table 4 shows the interconnected electricity plant dynamics considering parameters of uncertainties.

Table 4. State-space model of the MRLPS [7]

Expression/formula	Explanation/purpose
$\dot{z}_i(t) = A_i z_i(t) + \sum_{j=1, j\neq i}^{N} G_{ij} z_j(t) + B_i u_i(t) + \xi_i(z_i, t), y_i = C_i z_i(t)$	State-space model of the i th part in MRLPS with disturbance $\xi_i(z_i, t)$.
$z_i(t) = [\Delta f_i(t)\ \Delta P_{gi}(t)\ \Delta X_{gi}(t)\ \Delta E_i\ \Delta\delta_i(t)\ \Delta P_{\omega i}(t)]^T$	Definition of the state vector $z_i(t)$.
$\xi_i(z_i, t) = \Delta A_i(z_i, t) z_i(t) + B_i \upsilon_i(z_i, t) + H_i \Delta P_{L_i}(t)$ with $\lVert\xi_i(z_i, t)\rVert \le D_{\xi_i}$	Structure of disturbance $\xi_i(z_i, t)$.

Here, $z_i(t)$ and $z_j(t)$ are state vectors and neighboring state vectors, respectively; $u_i(t)$ is the control signal; $y_i(t)$ is the controlled output; and D_{ξ_i} is positive constant. $B_i \upsilon_i(z_i, t)$ and $\Delta A_i(z_i, t)$ are the perturbation input signal and the uncertainty parameters, respectively. The plant matrices A_i, B_i, G_{ij} can be presented as:

$$A_i = \begin{bmatrix} -\frac{1}{T_{Pi}} & -\frac{K_{Pi}}{T_{Pi}} & 0 & 0 & \frac{K_{Pi}}{2\pi T_{Pi}} \sum_{\substack{i=1 \\ j\neq 1}}^{N} K_{sij} & \frac{K_{Pi}}{T_{\omega i}} \\ 0 & -\frac{1}{T_{Ti}} & \frac{1}{T_{Ti}} & 0 & 0 & 0 \\ -\frac{1}{T_{Gi} R_i} & 0 & -\frac{1}{T_{Gi}} & -\frac{1}{T_{Gi}} & 0 & 0 \\ K_{Ei} K_{Bi} & 0 & 0 & 0 & \frac{K_{Ei}}{2\pi} \sum_{\substack{i=1 \\ j\neq 1}}^{N} K_{sij} & 0 \\ 2\pi & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{\alpha_\omega}{T_{\omega i}} & 0 & -\frac{1}{T_{\omega i}} \end{bmatrix}, B_i = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_{G_i}} \\ 0 \\ 0 \\ 0 \end{bmatrix}, G_{ij} = \begin{bmatrix} 0 & 0 & 0 & 0 & \frac{K_{Ei}}{2\pi T_{Ti}} K_{sij} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & -\frac{K_{Ei}}{2\pi T_{Ti}} K_{sij} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}.$$

3. MAIN RESULTS

3.1. Sliding mode without reaching phase automatic load frequency control design

To establish an innovative chatter-free SOSMC law for the MRLPS, a novel state estimator is constructed to find the unmeasurable states of the MRLPS, as described in Table 5. In Table 5, $\hat{z}_i(t)$ is the estimate of $z_i(t)$, $\hat{y}_i(t)$ is the estimate of $y_i(t)$, and Ξ_i is the estimator gain matrix. Now, to generate a novel weakened-chattering single-phase SOSMC law for the MRLPS, a single-phase sliding manifold function is defined and specified in Table 6.

In Table 6, κ_i is any diagonal matrix, and α_{i1} and α_{i2} are the positive constants. F_i, L_i are the designed matrices. F_i is selected to ensure that is $(F_i B_i)$ invertible. The design matrix L_i is preferred to fulfill the inequality of the power plant: $\mathrm{Re}[\lambda i_{i_{i_{max}}}$ To get the stability of the multi-field linked electricity plant depicted in Table 4 upon the specified sliding manifold in Table 6 from the zero-attainment moment, a new CGSOSMLFC is suggested as (1). Where $\alpha_{i1}, \alpha_{i2}, \bar{\varphi}_i$ are some positive scalars.

$$\dot{u}_i(t) = -(\alpha_{i1} F_i B_i)^{-1} \{\alpha_{i1} \lVert F_i B_i L_i \rVert \lVert \dot{\hat{z}}_i(t) \rVert + \textstyle\sum_{j=1, j\neq i}^{N} \alpha_{j1} \lVert F_j G_{ji} \rVert \lVert \dot{\hat{z}}_i(t) \rVert + \alpha_{i2} \lVert F_i \Xi_i \rVert [\lVert \dot{y}_i(t) \rVert - \lVert \dot{\hat{y}}_i(t) \rVert]$$
$$+ \kappa_i \lVert \dot{\sigma}_i[\hat{z}_i(t)] \rVert + \bar{\varphi}_i \lVert \psi_i \rVert - \varepsilon_i^2 \lVert F_i \rVert \lVert \hat{z}_i(0) \rVert e^{-\varepsilon_i t}\} \mathrm{sign}(\psi_i(t)) \quad (1)$$

Table 5. The suggested state estimator for the MRLPS

Expression/formula	Explanation/purpose
$\dot{\hat{z}}_i(t) = A_i \hat{z}_i(t) + \sum_{j=1, j\neq i}^{N} G_{ij} \hat{z}_j(t) + B_i u_i(t) + \Xi_i [y_i(t) - \hat{y}_i(t)], \hat{y}_i(t) = C_i \hat{z}_i(t)$	Observer equation estimating the unmeasured states.
$\varpi_i(t) = z_i(t) - \hat{z}_i(t)$	Estimation error $\varpi_i(t)$.
$\dot{\varpi}_i(t) = [A_i - \Xi_i C_i] \varpi_i(t) + \sum_{j=1, j\neq i}^{N} G_{ij} \varpi_j(t) + \xi_i(\hat{z}_i, t)$	Dynamics of the estimation error.

- Theorem 1. Consider the MRLPS subject to exogenous disturbances as described in Table 4. Upon the implementation of the control act specified in (1), the state trajectories of the MRLPS are driven toward the switching manifold $\psi_i[\hat{z}_i(t)] = 0$ immediately from the initial moment of activation. Consequently, the asymptotic stability of the system, as represented by Table 4, is ensured.

- Proof of Theorem 1. Cogitate the applicant Lyapunov functional as $V[\hat{z}_i(t)] = \sum_{i=1}^{N}\|\psi_i[\hat{z}_i(t)]\|$, where direct differentiation of $V[\hat{z}_i(t)]$ results.

$$\dot{V}(t) \le \sum_{i=1}^{N}\Big\{\alpha_{i1}\|F_iB_iL_i\|\|\dot{\hat{z}}_i(t)\| + \sum_{j=1,j\neq i}^{N}\alpha_{j2}\|F_jG_{ji}\|\,\|\dot{\hat{z}}_i(t)\| + \frac{\psi_i^T}{\|\psi_i\|}\alpha_{i1}F_iB_i\dot{u}_i(t) + \alpha_{i1}\|F_i\Xi_i\|\big[\|\dot{y}_i(t)\| - \|\dot{\hat{y}}_i(t)\|\big] - \varepsilon_i^2\|F_i\|\|\hat{z}_i(0)\|e^{-\varepsilon_i t} + \kappa\|\dot{\sigma}_i[\hat{z}_i(t)]\|\Big\}. \quad (2)$$

Now, by substituting the output feedback control signal (1) into (2), we can appreciate that $\dot{V}[\hat{z}_i(t)] \le -\sum_{i=1}^{N}\bar{\varphi}_i\|\psi_i[\hat{z}_i(t)]\| < 0$, $\bar{\varphi}_i > 0$. Consequently, the MRLPS's state variables come in contact with the switching manifold in Table 6 from the zero-attainment moment for all $t \ge 0$.

Table 6. The new single-phase sliding manifold for supporting output feedback controller design

Expression/formula	Explanation/purpose
$\psi_i[\hat{z}_i(t)] = \dot{\sigma}_i[\hat{z}_i(t)] + \kappa_i\sigma_i[\hat{z}_i(t)]$	Single-phase sliding function
$\sigma_i[\hat{z}_i(t)] = \alpha_{i1}F_i\hat{z}_i(t) - \alpha_{i2}F_i\int_0^t(A_i - B_iL_i)\hat{z}_i(\tau)d\tau - F_i\hat{z}_i(0)e^{-\varepsilon_i t}$	Definition of $\sigma_i[\hat{z}_i(t)]$
$\dot{\sigma}_i = \alpha_{i1}F_iB_iL_i\hat{z}_i + \sum_{j=1,j\neq i}^{N}\alpha_{i1}F_iG_{ij}\hat{z}_j + \alpha_{i1}F_iB_iu_i + \alpha_{i1}F_i\Xi_iC_i\varpi_i + \varepsilon_iF_i\hat{z}_i(0)e^{-\varepsilon_i t}$	First derivative of $\sigma_i[\hat{z}_i(t)]$
$\ddot{\sigma}_i[\hat{z}_i(t)] = \alpha_{i1}F_iB_iL_i\dot{\hat{z}}_i + \sum_{j=1,j\neq i}^{N}\alpha_{i1}F_iG_{ij}\dot{\hat{z}}_j + \alpha_{i1}F_iB_i\dot{u}_i + \alpha_{i1}F_i\Xi_i[\dot{y}_i(t) - \dot{\hat{y}}_i(t)] - \varepsilon_i^2F_i\hat{z}_i(0)e^{-\varepsilon_i t}$	Second derivative of $\sigma_i[\hat{z}_i(t)]$, required for SOSMC technique
$\dot{\psi}_i[\hat{z}_i(t)] = \alpha_{i1}F_iB_iL_i\dot{\hat{z}}_i(t) + \sum_{j=1,j\neq i}^{N}\alpha_{i1}F_iG_{ij}\dot{\hat{z}}_j + \alpha_{i1}F_iB_i\dot{u}_i + \alpha_{i1}F_i\Xi_iC_i\dot{\varpi}_i - \varepsilon_i^2F_i\hat{z}_i(0)e^{-\varepsilon_i t} + \kappa\dot{\sigma}_i[\hat{z}_i(t)]$	Time derivative of the sliding manifold $\psi_i[\hat{z}_i(t)]$

3.2. Stability analysis of whole system in sliding mode dynamics

In this section, a appropriate requirement expressed in the form of LMI is formulated to ensure the asymptotic stability of the MRLPS, under sliding mode control. To this end, we proceed by analyzing the following LMI formulation.

$$\begin{bmatrix} \widetilde{\Lambda}_i + \sum_{\substack{j=1\\ j\neq i}}^{N}\Big[\mu_j(G_{ji} - \Gamma_jG_{ji})^T(G_{ji} - \Gamma_jG_{ji}) + \mu_j^{-1}R_jR_j\Big] & R_i\Phi & R_j & R_j\Psi_j & 0 \\ \Phi_i^TR_i & \widetilde{\Theta}_i + \sum_{\substack{j=1\\ j\neq i}}^{N}\Big[\breve{\mu}_jG_{ji}^T\Gamma_j^T\Gamma_jG_{ji} + \breve{\mu}_j^{-1}R_jR_j + \tilde{\mu}_jG_{ji}^TG_{ji} + \tilde{\mu}_j^{-1}S_jS_j\Big] & 0 & 0 & S_j \\ R_j & 0 & -\breve{\eta}_j^{-1} & 0 & 0 \\ \Psi_j^TR_j & 0 & 0 & -\tilde{\eta}_j^{-1} & 0 \\ S_j & 0 & 0 & 0 & -\tilde{\eta}_j^{-1} \end{bmatrix} < 0, \quad (3)$$

Where $\widetilde{\Lambda}_i = R_i(A_i - \Gamma_iB_iL_i) + (A_i - \Gamma_iB_iL_i)^TR_i$, $\widetilde{\Theta}_i = S_i(A_i - \Xi_iC_i) + (A_i - \Xi_iC_i)^TS_i$, R_i, S_i are any positive matrices, and $\mu_i > 0, \breve{\mu}_i > 0, \tilde{\mu}_i > 0, \breve{\eta}_i > 0, \tilde{\eta}_i > 0$. Then, we can build the following theorem:

- Theorem 2. Supposing that the sufficient condition expressed in the LMI formulation (3) admits a feasible solution $R_i > 0, S_i > 0$, and the switching manifold is demarcated as in Table 6. Then, the MRLPS subjected to exogenous perturbations, as described by Table 4, is asymptotically stable when the system trajectories evolve on the sliding manifold $\psi_i[\hat{z}_i(t)] = 0$.
- Proof of Theorem 2. Based on the defined switching manifold $\psi_i[\hat{z}_i(t)] = \dot{\psi}_i[\hat{z}_i(t)] = 0$, the equivalent control law can be derived and expressed as (4).

$$u_i^{eq}(t) = -(\alpha_{i1}F_iB_i)^{-1}\Big\{\alpha_{i1}F_iB_iL_i\hat{z}_i + \sum_{j=1,j\neq i}^{N}\alpha_{i2}F_iG_{ij}\hat{z}_j + \alpha_{i1}F_i\Xi_i[y_i(t) - \hat{y}_i(t)] + \varepsilon_iF_i\hat{z}_i(0)e^{-\varepsilon_i t}\Big\} \quad (4)$$

Now, we substitute the value of $u_i^{eq}(t)$ into the first equation of the MRIPS's state space model in Table 4 and simplify as (5).

$$\dot{z}_i(t) = [A_i - \Gamma_iB_iL_i]z_i + \Phi_i\varpi_i + \Big[\sum_{j=1,j\neq i}^{N}G_{ij} - \sum_{j=1,j\neq i}^{N}\Gamma_iG_{ij}\Big]z_j + \sum_{j=1,j\neq i}^{N}\Gamma_iG_{ij}\varpi_j + \xi_i + \Psi_ie^{-\varepsilon_i t} \quad (5)$$

Where $\Phi_i = \alpha_{i1}B_i(\alpha_{i1}F_iB_i)^{-1}F_iB_iL_i - \alpha_{i1}B_i(\alpha_{i1}F_iB_i)^{-1}F_i\Xi_iC_i, \Gamma_i = \alpha_{i1}B_i(\alpha_{i1}F_iB_i)^{-1}F_i$ and $\Psi_i = -\varepsilon_iB_i \times (\alpha_{i1}F_iB_i)^{-1}F_i\hat{z}_i(0)$. Now, to confirm the steadiness of the MRLPS dynamic, we deliberate the Lyapunov positive definition function $V[z_i(t), \varpi_j(t)] = \sum_{i=1}^{N}\begin{bmatrix} z_j(t) \\ \varpi_j(t)\end{bmatrix}^T \begin{bmatrix} R_i & 0 \\ 0 & S_i\end{bmatrix}\begin{bmatrix} z_j(t) \\ \varpi_j(t)\end{bmatrix}$, where $R_i > 0$ and $S_i > 0$ satisfy the LMI (3) for $i = 1, 2, \dots, L$. Then, taking the derivative of time, combining (5) and the dynamics of the estimation error in Table 5, and by means of Lemma 3 of work [23] and Lemma of study [24], we have

$$\dot{V}[z_i(t), \varpi_j(t)] \le \begin{bmatrix} z_i \\ \varpi_i \end{bmatrix}^T \sum_{i=1}^{N}\begin{bmatrix} \widetilde{\Lambda}_i + \sum_{j=1, j\neq i}^{N}\left[\mu_j\left(G_{ji} - \Gamma_jG_{ji}\right)^T\left(G_{ji} - \Gamma_jG_{ji}\right) + \mu_j^{-1}R_jR_j\right] + \breve{\eta}_jR_jR_j + \tilde{\eta}_jR_j\Psi_j\Psi_j^TR_j & R_i\Phi \\ \Phi_i^TR_i & \widetilde{\Theta}_i + \sum_{j=1, j\neq i}^{N}\left[\breve{\mu}_jG_{ji}^T\Gamma_j^T\Gamma_jG_{ji} + \breve{\mu}_j^{-1}R_jR_j + \tilde{\mu}_jG_{ji}^TG_{ji} + \tilde{\mu}_j^{-1}S_jS_j\right] + \eta_jS_jS_j \end{bmatrix} \times [z_i(t)\ \ \varpi_i(t)]^T + \sum_{i=1}^{N}\left[\tilde{\gamma}_i\theta_i^2 + \lambda_i(t)\right] \quad (6)$$

Where $\widetilde{\Lambda}_i = R_i(A_i - \Gamma_iB_iL_i) + (A_i - \Gamma_iB_iL_i)^TR_i, \widetilde{\Theta}_i = S_i(A_i - \Xi_iC_i) + (A_i - \Xi_iC_i)^TS_i, \tilde{\gamma}_i = \eta_j^{-1} + \breve{\eta}_j^{-1}$, $\theta_i(t) = \left\|\xi_j(z_i, t)\right\|$, and $\lambda_i(t) = \tilde{\eta}_j^{-1}(e^{-\varepsilon_i t})^Te^{-\varepsilon_i t}$. Then, employing well-known LMI approach [25] to inequality (3), we attain

$$\breve{\Xi}_i = -\begin{bmatrix} \widetilde{\Lambda}_i + \sum_{j=1, j\neq i}^{N}\left[\mu_j\left(G_{ji} - \Gamma_jG_{ji}\right)^T\left(G_{ji} - \Gamma_jG_{ji}\right) + \mu_j^{-1}R_jR_j\right] + \breve{\eta}_jR_jR_j + \tilde{\eta}_jR_j\Psi_j\Psi_j^TR_j & R_i\Phi \\ \Phi_i^TR_i & \widetilde{\Theta}_i + \sum_{j=1, j\neq i}^{N}\left[\breve{\mu}_jG_{ji}^T\Gamma_j^T\Gamma_jG_{ji} + \breve{\mu}_j^{-1}R_jR_j + \tilde{\mu}_jG_{ji}^TG_{ji} + \tilde{\mu}_j^{-1}S_jS_j\right] + \eta_jS_jS_j \end{bmatrix} > 0 \quad (7)$$

Based on (6) and (7), it can be seen that $V \le \sum_{i=1}^{\dot{N}}[-\lambda_{min}(\Xi_i)||\hat{z}_i(t)||^2 + \gamma_i\theta_i^2 + \lambda_i(t)]$, when the term $\lambda_i(t)$ will tend to zero in the infinity time. We can be represented as $\dot{V} \le \sum_{i=1}^{N\Sigma}\left[-\lambda(\breve{\Xi}_i)||\widehat{z_1(t)}||^2{}_{i_i}{}^{2}{}_{min}[]\right]$ where the constant value $\tilde{\gamma}_i\theta_i(t) = \tilde{\gamma}_i\left\|\xi_j(z_i, t)\right\|$ and the eigenvalue $\lambda_{min\,(\Xi_i) > 0}$. Hence, $\dot{V} < 0$ is derived with $||\hat{z}_i(t)|| > \sqrt{\gamma_i\theta_i^2 / \lambda_{min}(\Xi_i)}$ which shows that the MRLPS is asymptotically stable.

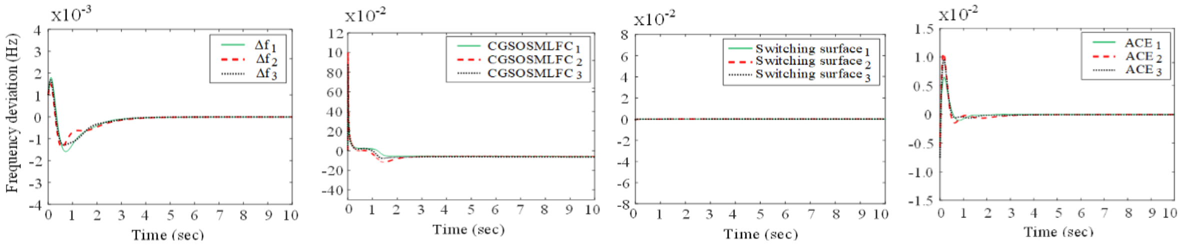
4. SIMULATION RESULTS

In this section, the parameters of a three-region linked electricity plant with WTGs, which are itemized in [7], is simulated by MATLAB software to validate the feasible solution of the suggested LFC approach. The external disturbances of the three regions are respectively supposed as $\xi_1 = 0.04$, $\xi_2 = 0.022$, $\xi_1 = 0.06$. The obtained results of these electricity plants are exemplified in Figure 2.

- Remark

The performance of the proposed CGSOSMLFC (1) in the MRLPS integrated with WTGs is shown in Figure 2. In Figure 2(a), the frequency deviations Δf_1, Δf_2, and Δf_3 respond rapidly immediately after the initial disturbance. Although slight oscillations occur within the first 0 - 2 seconds, all frequency curves of three areas converge to a stable value in 3,5 seconds, with under shoot are $-1{,}2 \times 10^{-3}$ (pu MW) and -1.7×10^{-3} (pu MW). Figure 2(b) shows the control signals for the three areas. It is remarkable that the proposed method exhibits no chattering and does not require access to the state variables of the MRLPS, which is a clear advantage over recent studies [6]-[8]. This verifies that the suggested CGSOSMLFC (1) successfully dismisses undesirable high-frequency switching. Figure 2(c) plots the switching surfaces of the three areas rapidly converging to zero without oscillations from the initial instant of system motion. It can be stated that the enhanced robustness and the anticipated dynamic response of the MRLPS are conquered by sacking the reaching phase in the TSMC approach, that has condensed the restrictions required in other studies [13], [16], [21], [22]. Figure 2(d) demonstrates that the area control errors decline quickly and approach zero within approximately 3 seconds, reflecting precise frequency and power regulation. Overall, the simulation results prove that the CGSOSMLFC (1) not only provides high-performance frequency regulation with fast response, global system stability, and small steady-state error, but also completely eliminates chattering.

From above obtained achievements, the anticipated method does not necessarily the accessibility of the state variables. We can conclude that the proposed method not only efficiently solves the stabilization problem but also reduces the chattering for the MRLPS integrated with WTGs. Subsequently, this technique is highly appreciated and more realistic, since it can be easily instigated in practical systems.



(a) (b) (c) (d)

Figure 2. Time history of (a) the frequency aberrations, (b) the load frequency controllers, (c) the single-phase sliding surfaces, and (d) the area control error of three-area power plants with WTGs

5. CONCLUSION

In this paper, a new chattering-free global second order sliding mode load frequency controller (CGSOSMLFC) has been developed for multi-region linked power systems (MRLPS) subjected to external perturbations. To resolve the unmeasurable state variables problem, a novel observer has been projected for guessing the unmeasurable state variables. A newly formulated one-phase switching manifold function has been systematically formulated for SMC such that all states trajectories of the system begin at the surface at an initial time moment which makes it highly robust for applications. The novel CGSOSMLFC is systematically designed to suppress high-frequency chattering phenomena and to robustly stabilize the MRLPS under the influence of external perturbations. Furthermore, the steadiness of the MRLPS is promised via the LMI method which is extracted based on Lyapunov steadiness theory. Ultimately, the experimental replications are applied to a three-area interconnected power network to validate the enhanced usefulness of the planned controller in suppressing chattering and outperforming existing sliding mode control methodologies. In future work, we will examine the robustness of the proposed approach with complex power systems, including various renewable energy sources and energy storage systems.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Cong-Trang Nguyen	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓		

C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo: **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Each author in this work agrees to declare that we have no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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