Single phase robustness variable structure load frequency controller for multi-region interconnected power systems with communication delays

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Article Info

Article history:

Received May 12, 2024
Revised Jun 8, 2024
Accepted Jun 16, 2024

Keywords:

Communication delay
Communication delays without reaching phase
Load frequency control
Multi-region interconnected power system
Variable structure control

ABSTRACT

This paper proposes an estimator-based single phase robustness variable structure load frequency controller (SPRVSLFC) for the multi-region interconnected power systems (MRIPS) with communication delays. The key attainments of this research consist of two missions: i) a global stability of the power systems is guaranteed by removing the reaching phase in traditional variable structure control (TVSC) technique; and ii) a novel output feedback load frequency controller is established based on the estimator tool and output information only. Initially, a single-phase switching function is constructed to disregard the reaching phase in TVSC. Then, an unmeasurable state variable of the MRIPS is estimated by using the proposed estimator tool. Next, a new SPRVSLFC for the MRIPS is suggested based on the support of the estimator tool and output data only. Furthermore, a sufficient constraint is constructed by retaining the linear matrix inequality (LMI) procedure for ensuring the robust stability of motion dynamics in sliding mode. Finally, the performance of interconnected power plant under changed multi-constraints is imitated with the novel control technique to validate the practicability of the plant.

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1. INTRODUCTION

Over the past three decades, there has been an increasing research consideration in variable structure control (VSC) implementation for power system control problems. The owing characteristics of VSC contain strong robustness in contradiction of uncertainties and perturbations, and computational easiness [1]–[3]. Owing to these benefits, VSC has been successfully implemented to solve the load frequency control (LFC) problems for the multi-region interconnected power systems (MRIPS) [4]–[7]. The LFC of a power plant is an important aspect of power quality. The frequency aberration and tie-line power aberration reach zero in changed control zones demarcated in a multi-region power networks [8], [9]. However, in practical LFC problems, time delays are common phenomena. Time delay existence can cause degradation and/or unstableness in plant performance [10]. Therefore, the time-delay electricity plant's stability has been fascinating the attention of a huge amount of value researches issued in the most newly worldwide well-known journals [5], [6], [11]–[13] and the associated references therein. In practical electricity plants, the frequency aberration is produced by swelling real power request and the voltage as well is affected strongly by the reactive power's deviation. To continue satisfying the real power requests, the load frequency desires to be regulated. There are numerous control techniques which have been suggested in establishing load frequency controllers with improved execution to keep the frequency and to maintain tie line power movements within described values such as [11], [14]–[16]. In [14], a fractional-order proportional integral (PI) controller is utilized in the control of a single zone delayed LFC plant. A novel delay-dependent robust method was investigated in [15] for investigation of proportional integral derivative (PID) type LFC designs seeing the time delays presented from the communication systems. Based on an event-triggered scheme, a T-S fuzzy controller was proposed to make certain that each subsystem was stable in the MRIPS and robust to exogenous perturbation, comprising frequency change and load variation [16]. By using the extended Kalman filter [11], a new type-2 fuzzy controller was established for the LFC in electricity plants with multi-regions, request response, battery energy storage plant, and wind farms. However, these studies are very hard to govern the acceptable parameters of PID control in the existence of various uncertainties and external disturbances. These external perturbations and uncertainties may damage and even destroy the MRIPS designed on nominal models. It makes the PID controller's dynamic performance to be moderately deprived with the large overshoot, extended setting time and fluctuation with the transient frequency.

To solve these drawbacks, VSC technique is recently employed to design the load frequency controller for MRIPS. The application of VSC method in both single zone and multi-region power plants with time delays has been determined extensively during the literature survey such as in [4]–[6], [12], [17], [18]. In [17], a robust $H\infty$ sliding mode LFC law and frequency stabilization was presented for multi-region electricity plant with time delay in presence of linear matrix inequalities. In [18], a new delay dependent decentralized sliding mode controller was synthesized for the multi-region LFC electricity plant with non-linear delayed perturbations and time-varying delays by using the Lyapunov–Razumikhin approach. A switching control theory-based memoryless state-feedback control approach for the networked load frequency control in multi-region electricity plants [4]. In [5], $H\infty$ method-based sliding mode LFC law scheme by integrating an artificial delay in the controller building for MRIPS. A decentralized disturbance estimator-based sliding mode LFC scheme was considered in [6] for multi-area interlinked electricity plants with external disturbances. By employing optimized integral sliding mode control scheme, a decentralized LFC was anticipated for the frequency control of multi-region electricity plants [12]. Regrettably, the state variables of many practical power systems are not always accessible or expensive to measure all of them. Then, it is necessary that the sliding mode predominates without the measurement of all state variables. To address these shortcomings, the authors in the researches [7], [13], [19] have employed the output feedback technique. In [19], a new super twisting sliding mode control law was constructed for controlling load frequency for an interconnected multi zone electricity plants. A novel super twisting sliding mode LFC was established in [13] for multi-zone interconnected electricity plants with time delays utilizing perturbation estimator. A novel LFC problem was solved for a multi-zone interconnected electricity plant with wind energy and electric automobiles [7]. Nevertheless, the existing MRIPS research are based on the TVSC scheme which only gives the wanted motion after sliding motion has happened. As a result, the overall stability of plant may not be guaranteed or hazardously corrupted [20], [21]. Thus, it is necessary to advance a novel VSC which does not include reaching phase to stabilize MRIPS for all time.

Inspired by the above-mentioned investigation, this paper suggests a novel single phase robustness variable structure load frequency controller (SPRVSLFC) based on state estimator for the multi-region interconnected power systems (MRIPS) with communication delays. The objective of our research is to contribute to the advance of single-phase robustness variable structure control without reaching phase and performance analysis for the MRIPS. Firstly, a single-phase switching function is definitely proposed for MRIPS without reaching phase such that the robustness performance against exogenous disturbance is accurately guaranteed at the instance of moment. Secondly, a new estimator is intimated to guess the MRIPS's variables which are not measured. Thirdly, based on estimated states from the estimator, a novel SPRVSLFC is investigated for MRIPS with communication delays without reaching phase. Further, by using linear matrix inequality (LMI) technique and Razumikhin–Lyapunov approach, sufficient constraint is determined for ensuring the robust stability of motion dynamics in sliding mode. Finally, simulation example is followed through on a three-region interconnected electricity plant to validate the usefulness of the anticipated control scheme.

2. STATE SPACE FORM OF THE MULTI-REGION INTERCONNECTED POWER SYSTEM

In this section, a FLC model of the MRIPS will be discussed in the time delay. The MRIPS comprises subsystem control areas where are interconnected through tie-lines [22]. The value d_i shows the small communication delay which can fluctuate from 0.1 to 1s with deliberation of two control zones. The dynamic equations of MRIPS with the time delay are given as (1):

$$\begin{aligned}
&\Delta\dot{f}_i(t) = -\frac{1}{T_{P_i}}\Delta f_i(t) + \frac{K_{P_i}}{T_{P_i}}\Delta P_{t_i}(t) - \frac{K_{P_i}}{T_{P_i}}\Delta P_{d_i}(t) - \frac{K_{P_i}}{T_{P_i}}.\Delta P_{tie}^{ij},\\
&\Delta\dot{P}_{g_i}(t) = -\frac{1}{R_i T_{G_i}}\Delta f_i(t) - \frac{1}{T_{G_i}}.\Delta P_{g_i}(t) - \frac{1}{T_{G_i}}\Delta E_i(t-d_i) + \frac{1}{T_{G_i}}u_i(t),\\
&\Delta\dot{P}_{T_i}(t) = -\frac{1}{T_{T_i}}\Delta P_{T_i}(t) + \frac{1}{T_{T_i}}\Delta P_{g_i}(t), \Delta\dot{E}_i(t) = K_{B_i}K_{E_i}\Delta f_i(t) + K_{E_i}\Delta P_{tie}^{ij},\\
&\Delta\dot{P}_{tie}^{ij} = \textstyle\sum_{j=1,j\neq i}^{N} 2\pi T_{ij}\left[\Delta f_i(t) - \Delta f_j(t)\right], ACE_i = \Delta P_{tie_i}(t) + E_i \Delta f_i(t),
\end{aligned} \tag{1}$$

where the area control error (ACE_i) is the balance of the connected control areas. The MRIPS dynamics are determined above and it is proposed in the following state model:

$$\dot{z}_i(t) = A_i^{/} z_i(t) + A_{d_i}^{/} z_i(t-d_i) + B_i^{/} u_i(t) + \textstyle\sum_{j=1,j\neq i}^{N} G_{ij}^{/} z_j(t) + \eta_i(z_i,t), y_i = C_i^{/} z_i(t), \tag{2}$$

where $i = 1,2\ldots,N$ and N *is* symbolized as the amount of zones, the plant states are utilized as $z_i(t) = [\Delta f_i(t)\ \Delta P_{T_i}(t)\ \Delta P_{g_i}(t)\ \Delta E_i(t)\ \Delta P_{tie}^{ij}(t)]^T \in R^{n_i}$, the control signal of the plant is $u_i(t) \in R^{m_i}$, and the controlled output is $y_i(t) = ACE_i(t) \in R^{p_i}$. The lumped uncertainty $\eta_i(z_i,t) = \Delta A_i^{/}(z_i,t) z_i(t) + \Delta A_{d_i}^{/}(z_i, t-d_i) + B_i^{/}\xi_i(z_i,t) + \Omega_i \Xi_{d_i}(t)$, which is supposed to be unknown limit and to gratify the constraint $\|\eta_i(z_i,t)\| \le \gamma_i$ and $\|\dot{\eta}_i(z_i,t)\| \le \rho_i$ with γ_i, ρ_i are acknowledged coefficients and $\|.\|$ is matrix norm. The matrices $A_i^{/}, A_{d_i}^{/}, B_i^{/}$, and $G_{ij}^{/}$ are system matrices, $\Delta A_i^{/}(z_i,t)$ and $\Delta A_{d_i}^{/}(z_i,t-d_i)$ are the uncertainty parameters, and $B_i^{/}\xi_i(z_i,t)$ is the perturbation input signal. The constant matrices:

$$A_i^{/} = \begin{bmatrix} -\frac{1}{T_{P_i}} & \frac{K_{P_i}}{T_{P_i}} & 0 & 0 & -\frac{K_{P_i}}{T_{P_i}} \\ 0 & -\frac{1}{T_{T_i}} & \frac{1}{T_{T_i}} & 0 & 0 \\ -\frac{1}{R_i T_{G_i}} & 0 & -\frac{1}{T_{G_i}} & 0 & 0 \\ K_{E_i}K_{B_i} & 0 & 0 & 0 & K_{E_i} \\ \sum_{j=1,j\neq i}^{N} 2\pi T_{ij} & 0 & 0 & 0 & 0 \end{bmatrix}, A_{d_i}^{/} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -\frac{1}{T_{G_i}} & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}, B_i^{/} = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_{G_i}} \\ 0 \\ 0 \end{bmatrix},$$

$$G_{ij}^{/} = \begin{bmatrix} 0 & 0\ 0\ 0\ 0 \\ 0 & 0\ 0\ 0\ 0 \\ 0 & 0\ 0\ 0\ 0 \\ 0 & 0\ 0\ 0\ 0 \\ \sum_{j=1,j\neq i}^{N} 2\pi.T_{ij} & 0\ 0\ 0\ 0 \end{bmatrix}, \Omega_i = \left[-\frac{K_{P_i}}{T_{P_i}}\ 0\ 0\ 0\ 0\right]^T, C_i^{/} = [0\ 0\ E_i\ 1\ 0].$$

3. MAIN RESULTS

In this section, a new LFC signal will be proposed by using a novel estimator. A designed controller will keep the MRIPS's state trajectory moving along the sliding surface from the zero-reaching time as our key contribution.

3.1. Constructing an estimator-based output feedback load frequency controller

In practical power systems, several state variables cannot be measured, or the accessible measurement devices are very precious. For this reason, a dynamics estimator will be proposed for the multi-region interconnected power systems as (3).

$$\dot{\hat{z}}_i(t) = A_i^{/}\hat{z}_i(t) + B_i^{/}u_i(t) + A_{d_i}^{/}\hat{z}_i(t-d_i) + \sum_{j=1,j\neq i}^{N} G_{ij}^{/}\hat{z}_j(t) + R_i[y_i(t) - \hat{y}_i(t)], \hat{y} = C_i^{/}\hat{z}_i(t), \quad (3)$$

where $\hat{z}_i(t)$ is the approximation of $z_i(t)$, $\hat{y}_i(t)$ is the output of the estimator, $R_i \in R^{n_i \times p_i}$ is the estimator gain matrix. Now, the error between the states of real plant and estimated states are $\theta_i(t) = z_i(t) - \hat{z}_i(t)$. By relating the first (2) and the first equation of dynamics estimator (3), the leading error dynamics is pronounced by (4).

$$\dot{\theta}_i(t) = [A_i^{/} - R_iC_i^{/}]\theta_i(t) + A_{d_i}^{/}\theta_i(t-d_i) + \sum_{j=1,j\neq i}^{N} G_{ij}^{/}\theta_j(t) + \eta_i(\hat{z}_i, t) \quad (4)$$

Now, to design a variable structure controller, a novel load frequency controller using output information only is designed for the MRIPS. To do this, a new single phase sliding surface is built as (5).

$$\sigma_i(t) = B_i^{/+}\hat{z}_i(t) - B_i^{/+}\int_0^t (A_i^{/} - B_i^{/}S_i)\hat{z}_i(\tau)d\tau - B_i^{/+}\hat{z}_i(0)e^{-\varepsilon_i t}, \quad (5)$$

where $B_i^{/+} = (B_i^{/T}B_i^{/})^{-1}B_i^{/T} \in R^{m_i \times n_i}$ is the Moore-Penrose pseudoinverse of the matrix $B_i^{/}$, $\hat{z}_i(0)$ is the initial condition of the estimator tool, and ε_i is the positive constant. The design matrix $S_i \in R^{m_i \times n_i}$ is chosen to gratify the inequality of the electricity plant: $Re[\lambda_{max}(A_i^{/} - B_i^{/}S_i) < 0]$. The time derivative of (5) with respect time and combine with the estimator (3) are calculated as (6).

$$\dot{\sigma}_i(t) = B_i^{/+}B_i^{/}S_i\hat{z}_i(t) + B_i^{/+}.B_i^{/}u_i(t) + B_i^{/+}A_{d_i}^{/}\hat{z}_i(t-d_i) + \sum_{j=1,j\neq i}^{N} B_i^{/+}G_{ij}^{/}\hat{z}_j(t)$$
$$+ B_i^{/+}R_i[y_i(t) - \hat{y}_i(t)] + \varepsilon_i B_i^{/+}\hat{z}_i(0)e^{-\varepsilon_i t}. \quad (6)$$

To attain the stability of the multi-region electricity plants described in (2), a new single phase load frequency control signal is constructed as (7):

$$u_i(t) = -(B_i^{/+}B_i^{/})^{-1}\Big\{\Big[\|B_i^{/+}B_i^{/}S_i\| + q_i\left\|B_i^{/+}A_{d_i}^{/}\right\|\Big]\|\hat{z}_i(t)\| + \sum_{j=1,j\neq i}^{N}\|B_j^{/+}G_{ji}^{/}\|\,\|\hat{z}_i(t)\|$$
$$+ \|B_i^{/+}R_i\|[\|y_i(t)\| - \|\hat{y}_i(t)\|] + \alpha_i\|\sigma_i(t)\| + \varepsilon_i B_i^{/+}\hat{z}_i(0)e^{-\varepsilon_i t}\Big\}sign(\sigma_i(t)), \quad (7)$$

where α_i are some positive scalars.

Theorem 1. Regard the multi-region power systems with exogenous perturbations (2). Then, the MRIPS's state variables will approach to the switching surface $\sigma_i(t) = 0$ from the instant process under the controller signal (7). The asymptotic stability of the multi-are electricity plant is ensured.

Proof of Theorem 1. Consider the candidate Lyapunov functional as $V(t) = \sum_{i=1}^{N}\|\sigma_i(t)\|$, where direct differentiation of $V(t)$ results

$$\dot{V}(t) \le \sum_{i=1}^{N}\Big[\|B_i^{/+}B_i^{/}S_i\|\|\hat{z}_i(t)\| + \frac{\sigma^T{}_i(t)}{\|\sigma_i(t)\|}B_i^{/+}.B_i^{/}u_i(t) + \left\|B_i^{/+}A_{d_i}^{/}\right\|\,\|\hat{z}_i(t-d_i)\|$$
$$+ \sum_{j=1,j\neq i}^{N}\|B_i^{/+}G_{ij}^{/}\|\,\|\hat{z}_j(t)\| + \|B_i^{/+}R_i\|[\|y_i(t)\| - \|\hat{y}_i(t)\|] + \varepsilon_i B_i^{/+}\hat{z}_i(0)e^{-\varepsilon_i t}\Big]. \quad (8)$$

Since $\sum_{j=1,j\neq i}^{N}\|B_i^{/+}G_{ij}^{/}\|\,\|\hat{z}_j(t)\| = \sum_{j=1,j\neq i}^{N}\|B_j^{/+}G_{ji}^{/}\|\,\|\hat{z}_i(t)\|$. By exploiting the Lemma 3 of the study [23], we get $\hat{z}_i(t-d_i) \le q_i\hat{z}_i(t)$, where $q_i > 1$. From the (8), we can rewrite as

$$\dot{V}(t) \le \sum_{i=1}^{N}\Big[\|B_i^{/+}B_i^{/}S_i\|\|\hat{z}_i(t)\| + \frac{\sigma^T{}_i(t)}{\|\sigma_i(t)\|}B_i^{/+}B_i^{/}u_i(t) + q_i\left\|B_i^{/+}A_{d_i}^{/}\right\|\,\|\hat{z}_i(t)\|$$
$$+ \sum_{j=1,j\neq i}^{N}\|B_j^{/+}G_{ji}^{/}\|\,\|\hat{z}_i(t)\| + \|B_i^{/+}R_i\|[\|y_i(t)\| - \|\hat{y}_i(t)\|] + \varepsilon_i B_i^{/+}.\hat{z}_i(0)e^{-\varepsilon_i t}\Big]. \quad (9)$$

Now, by replacing the control law (7) into (9), we can realize that $\dot{V}(t) \le -\sum_{i=1}^{N}\alpha_i.\|\sigma_i(t)\| < 0$, α_i is positive constant. Consequently, the MRIPS's state variables reach the sliding surface from the zero-reaching time for all $t \ge 0$. Proof of Theorem 1 is ended.

3.2. Power system stability analysis in single phase sliding mode

In this part, the overall MRIPS's asymptotic stability in the sliding mode will be confirmed by means of the renowned LMI approach, Schur complement method, and the Lyapunov function.

Theorem 2. Regard the multi-region electricity plants with exogenous perturbations (2) and the switching surface $\sigma_i(t) = 0$. If there exist symmetric matrix

$$\begin{bmatrix} \bar{\Xi}_i + q_i\bar{\Xi}_{d_i} + \sum_{j=1,j\neq i}^{N}[\beta_j(G_{ji}^{/} - \Gamma_j G_{ji}^{/})^T(G_{ji}^{/} - \Gamma_j G_{ji}^{/}) + \bar{\gamma}_i P_i P_i] & P_i\Phi_i + q_i P_i \Gamma_i A_{d_i}^{/} & P_i & P_i\Psi_i & 0 \\ \Phi_i^T P_i + q_i(\Gamma_i A_{d_i}^{/})^T & P_i\bar{\Psi}_i + q_i\bar{\Psi}_{d_i} + \sum_{j=1,j\neq i}^{N}[\bar{\beta}_j G_{ji}^{/T}\Gamma_j^T\Gamma_j G_{ji}^{/} + \tilde{\beta}_j G_{ji}^{/T}G_{ji}^{/} + \tilde{\beta}_i^{-1}Q_iQ_i] & 0 & 0 & Q_i \\ P_i & 0 & -\bar{\mu}_i^{-1} & 0 & 0 \\ \Psi_i^T P_i & 0 & 0 & -\tilde{\mu}_i^{-1} & 0 \\ Q_i & 0 & 0 & 0 & -\mu_i^{-1} \end{bmatrix} < 0 \quad (10)$$

where $\bar{\Xi}_i = P_i(A_i^{/} - B_i^{/}S_i) + (A_i^{/} - B_i^{/}S_i)^T P_i, \bar{\Psi}_i = Q_i(A_i^{/} - R_iC_i^{/}) + (A_i^{/} - R_iC_i^{/})^T Q_i$, $\bar{\Xi}_{d_i} = P_i(A_{d_i}^{/} - \Gamma_i A_{d_i}^{/}) + (A_{d_i}^{/} - \Gamma_i A_{d_i}^{/})^T P_i$, $\bar{\Psi}_{d_i} = Q_iA_{d_i}^{/} + (\Gamma_i A_{d_i}^{/})^T Q_i$, the scalars $\bar{\gamma}_i = \beta_i^{-1} + \bar{\beta}_i^{-1} > 0$, $\tilde{\gamma}_i = \mu_i^{-1} + \bar{\mu}_i^{-1} > 0$, and P_i, Q_i are any positive matrices, then the multi-region power system (2) guarantees the asymptotical stability.

Proof of Theorem 2. By utilizing the switching surface, $\sigma_i(t) = 0, \dot{\sigma}_i(t) = 0$, we can realize that the equivalent control is showed as (11).

$$u_i^{eq}(t) = -\left(B_i^{/+}B_i^{/}\right)^{-1}\Big\{B_i^{/+}B_i^{/}S_i\hat{z}_i(t) + B_i^{/+}A_{d_i}^{/}\hat{z}_i(t-d_i) + \sum_{j=1,j\neq i}^{N} B_i^{/+}G_{ij}^{/}\hat{z}_j(t) + B_i^{/+}R_i[y_i(t) - \hat{y}_i(t)] + \varepsilon_i B_i^{/+}\hat{z}_i(0)e^{-\varepsilon_i t}\Big\}. \quad (11)$$

By replacing (11) into the first equation of the electricity system (2), we have (12),

$$\dot{z}_i(t) = [A_i^{/} - B_i^{/}S_i]z_i(t) + \Phi_i.\theta_i(t) + \left[A_{d_i}^{/} - \Gamma_i A_{d_i}^{/}\right]z_i(t-d_i) + \Gamma_i A_{d_i}^{/}\theta_i(t-d_i) + \sum_{j=1,j\neq i}^{N}\Gamma_i G_{ij}^{/}\theta_j(t) + \sum_{j=1,j\neq i}^{N}\left(G_{ij}^{/} - \Gamma_i G_{ij}^{/}\right)z_j(t) + \Psi_i e^{-\varepsilon_i t} + \eta_i(z_i,t), \quad (12)$$

where $\Phi_i = B_i^{/}S_i - B_i^{/}(B_i^{/+}B_i^{/})^{-1}B_i^{/+}R_iC_i, \Gamma_i = B_i^{/}(B_i^{/+}B_i^{/})^{-1}B_i^{/+}$, and $\Psi_i = -\varepsilon_i B_i^{/}(B_i^{/+}B_i^{/})^{-1}B_i^{/+}\hat{z}_i(0)$. The eigenvalue of $(A_i^{/} - B_i^{/}S_i)$ is used to control the estimated system variables into the sliding surface (5). The sliding motion dynamics can be represented as (13).

$$\begin{bmatrix}\dot{z}_i(t)\\ \dot{\theta}_i(t)\end{bmatrix} = \begin{bmatrix}A_i^{/} - B_i^{/}S_i & \Phi_i\\ 0 & A_i^{/} - R_iC_i^{/}\end{bmatrix}\begin{bmatrix}z_i(t)\\ \theta_i(t)\end{bmatrix} + \begin{bmatrix}A_{d_i}^{/} - \Gamma_i A_{d_i}^{/} & \Gamma_i A_{d_i}^{/}\\ 0 & A_{d_i}^{/}\end{bmatrix}\begin{bmatrix}z_i(t-d_i)\\ \theta_i(t-d_i)\end{bmatrix} + \sum_{j=1,j\neq i}^{N}\begin{bmatrix}G_{ij}^{/} - \Gamma_i G_{ij}^{/} & \Gamma_i G_{ij}^{/}\\ 0 & G_{ij}^{/}\end{bmatrix}\begin{bmatrix}z_j(t)\\ \theta_j(t)\end{bmatrix} + \begin{bmatrix}I_i & \Psi_i\\ I_i & 0\end{bmatrix}\begin{bmatrix}\eta(z_i,t)\\ e^{-\varepsilon_i t}\end{bmatrix}. \quad (13)$$

Now, to validate the stability of the electricity system dynamics, we regard the Lyapunov positive definition function $V[z_i(t),\theta_i(t)] = \sum_{i=1}^{N}\begin{bmatrix}z_i(t)\\ \theta_i(t)\end{bmatrix}^T\begin{bmatrix}P_i & 0\\ 0 & Q_i\end{bmatrix}\begin{bmatrix}z_i(t)\\ \theta_i(t)\end{bmatrix}$, where the positive matrices P_i and Q_i are defined by LMI (10). Then, by executing the derivative of $V[z_i(t),\theta_i(t)]$, combining (13), and using Lemma 3 of paper [23] and Lemma of work [24], we attain

$$\dot{V}[z_i(t),\theta_i(t)] \le \sum_{i=1}^{N}\begin{bmatrix}z_i(t)\\ \theta_i(t)\end{bmatrix}^T\begin{bmatrix}\Lambda_{1ij} + \bar{\mu}_i P_i P_i + \tilde{\mu}_i P_i \Psi\Psi_i^T P_i & P_i\Phi_i + q_i P_i\Gamma_i A_{d_i}^{/}\\ \Phi_i^T P_i + q_i\left(\Gamma_i A_{d_i}^{/}\right)^T P_i & \Lambda_{2ij} + \mu_i Q_i Q\end{bmatrix}\begin{bmatrix}z_i(t)\\ \theta_i(t)\end{bmatrix} + \sum_{i=1}^{N}[\tilde{\gamma}_i\tilde{\varphi}_i^2 + \tilde{\chi}_i(t)], \quad (14)$$

where $\Lambda_{1ij} = \bar{\Xi}_i + q_i\bar{\Xi}_{d_i} + \sum_{j=1,j\neq i}^{N}[\beta_j(G_{ji}^{/} - \Gamma_j G_{ji}^{/})^T(G_{ji}^{/} - \Gamma_j G_{ji}^{/}) + \bar{\gamma}_i P_i P_i]$, $\Lambda_{2ij} = \bar{\Psi}_i + q_i\bar{\Psi}_{d_i} + \sum_{j=1,j\neq i}^{N}[\bar{\beta}_j G_{ji}^{/T}\Gamma_j^T\Gamma_j G_{ji}^{/} + \tilde{\beta}_j G_{ji}^{/T}G_{ji}^{/} + \tilde{\beta}_i^{-1}Q_iQ_i]$, $\tilde{\varphi}_i = \|\eta_i(z_i,t)\|$, and $\tilde{\chi}_i(t) = \tilde{\mu}_i^{-1}(e^{-\varepsilon_i t})^T e^{-\varepsilon_i t}$. Then, applying well-known LMI technique [25] to inequality (14), we achieve

$$\tilde{\Upsilon}_i = -\begin{bmatrix} \Lambda_{1ij} + \bar{\mu}_i P_i P_i + \tilde{\mu}_i P_i.\Psi\Psi_i^T P_i & P_i\Phi_i + q_i P_i.\Gamma_i A_{d_i}^{/} \\ \Phi_i^T P_i + q_i\left(\Gamma_i A_{d_i}^{/}\right)^T P_i & \Lambda_{2ij} + \mu_i Q_i Q_i \end{bmatrix} > 0. \quad (15)$$

According to the (14), (15), it can be seen that

$$\dot{V}\left[z_i(t),\ \theta_i(t)\right] \le \sum_{i=1}^{N}\left[-\lambda_{\min}\left(\tilde{\Upsilon}_i\right)\left\|\hat{z}_i(t)\right\|^2 + \tilde{\gamma}_i\tilde{\varphi}_i^2 + \tilde{\chi}_i(t)\right]. \quad (16)$$

The term $\tilde{\chi}_i(t)$ in (16) will hit zero when the time reaches infinity. The equation (16) can be represented as $\dot{V}[z_i(t),\theta_i(t)] \le \sum_{i=1}^{N}[-\lambda_{\min}(\tilde{\Upsilon}_i).\|\hat{z}_i(t)\|^2 + \tilde{\gamma}_i.\tilde{\varphi}_i^2]$, where the constant value $\tilde{\gamma}_i\tilde{\varphi}_i = \tilde{\gamma}_i\|\eta_i(z_i,t)\|$ and the eigenvalue $\lambda_{\min}(\tilde{\Upsilon}_i) > 0$. Consequently, $\dot{V}[z_i(t),\theta_i(t)] < 0$ is attained with $\|\hat{z}_i(t)\| > \sqrt{\tilde{\gamma}_i\tilde{\varphi}_i^2 / \lambda_{\min}(\tilde{\Upsilon}_i)}$. From now, the sliding motion dynamics (13) is asymptotically stable.

4. SIMULATION TEST

To attempt the usefulness and robustness of the suggested control approach, simulations are executed to verify the performance. In this section, the proposed suggestion has been carried out the three-region electricity systems gotten from [22]. The subsystem parameters are represented in Table 1. The external perturbations of three areas are respectively assumed as Ξ_{d1} = 0.01, Ξ_{d1} = 0.015, Ξ_{d1} = 0.02. The performance of the controller in these power systems are illustrated in Figure 1.

Table 1. Parameters of three-region interconnected electricity plant

Area	T_{p_i}	T_{G_i}	K_{E_i}	T_{T_i}	K_{p_i}	$K_{T_{ij}}$	R_i	K_{B_i}
1	0.2×10^2	0.08	0.1×10^2	0.3	1.2×10^2	0.55	0.024×10^2	0.41
2	0.25×10^2	0.072	0.09×10^2	0.33	11.25×10^2	0.65	0.027×10^2	0.37
3	0.2×10^2	0.07	0.071×10^2	0.35	11.5×10^2	0.545	0.0025×10^2	0.4

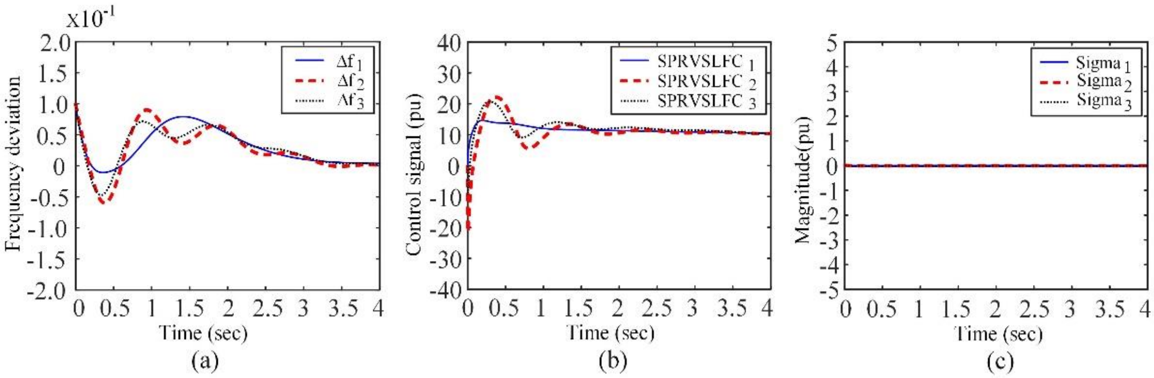

Figure 1. Time response of (a) the frequency deviations, (b) the load frequency controllers, and (c) the single-phase sliding surfaces of three-area power systems with external disturbances

From the aforementioned investigation of the achieved imitation results, it is clear to observe that the sliding mode occurs from the opening time moment (t = 0). Additionally, it can be specified that the improved robustness and the desired dynamic response of the MRIPS are attained by canning reaching phase that has reduced the limitations required in other studies [4], [7], [13]. Moreover, unlike the recent studies [5], [6], [12], the constructed technique does not require the accessibility of the state variables of the MRIPS. Consequently, this approach is very valuable and more realistic, since it can be effortlessly executed in many practical MRIPSs.

5. CONCLUSION

This paper represents the novel estimator-based single phase robustness variable structure load frequency controller, which eliminates entirely the reaching phase and utilizes output data only, for the multi-region interconnected power systems with communication delays. We have suggested the new single phase sliding function such that the reaching time is equivalent to zero and the MRIPS is insensitive the external perturbations. The estimator has been designed to estimate the immeasurable states for helping the load frequency controller strategy. The new SPRVSLFC for the MRIPS has been proposed by using the estimator tool and output information only. Improved robustness and the wanted dynamic response are achieved by the removal of the reaching phase that has reduced the limitations required in other study. Additionally, the sufficient condition has been given by using the LMI method such that the motion dynamics in sliding mode possess the possessions of asymptotical stability. Lastly, the simulated results of the three- region interconnected power system validate practicability, usefulness and robustness of the anticipated control scheme even in the existence of the external disturbances and the communication delays.

ACKNOWLEDGEMENTS

This research was supported by Ho Chi Minh City University of Technology and Education, Ho Chi Minh City, Vietnam under grant number T2024-156.

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