Observer-based single phase robustness load frequency sliding mode controller for multi-area interconnected power systems

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ABSTRACT

In multi-area interconnected power systems (MAIPS), all the plant state's measurement is stiff due to the lack of a device or the cost of the sensor is expensive. To solve this restriction, a novel sliding mode control technique-based load frequency controller (LFC) is investigated for MAIPS where the estimation states of the system is utilized fully in the switching surface and controller. Initially, a single-phase switching function is suggested to dismiss the reaching phase in traditional sliding mode control (TSMC) approach. Secondly, the MAIPS's unmeasurable variables is estimated by using the suggested observer tool. Next, a new single phase robustness load frequency sliding mode controller (SPRLFSMC) for the MAIPS is established based on the support of the observer instrument and output data only. The entire plant's stability is ensured through the Lyapunov theory. Even though the plant's variables are not measured, the obtained results in the simulation display that the frequency remains in the nominal domain under load instabilities on the MAIPS. The simulation results for a three-area interconnected electricity plant verify the preeminence of the anticipated SPRLFSMC over other current controllers with respect to settling time and overshoot.

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1. INTRODUCTION

Interconnected power systems have been a significant substructure of any economy. The stability of the electricity plants depends on the equilibrium between the requested load and the generation. Load frequency controller (LFC) of an electricity plant is a significant part of power quality. The aberration of frequency and tie-line power approaches zero in different control zones displayed in a multi-area power networks [1], [2]. Therefore, the stability problem of the multi-area power system (MAPS) has been fascinating the attention of a huge number of quality researches issued in the most lately internationally well-known journals [3]–[8] and the associated references therein.

In practical electricity systems, the deviation of frequency is produced by swelling the voltage and the real power petition as well is affected strongly by fluctuation of reactive power. Hence, the load frequency must be controlled to satisfy the real power demands. There are numerous control techniques which have been suggested in the LFC problems such as [9]–[12]. Based on the two-degree-of-freedom interior model control design technique and a proportional integral derivative (PID) approximation procedure, a LFC scheme was proposed in [10] for electricity systems with reheat, non-reheat and hydro turbines. By using linear matrix inequality (LMI) technique, an optimal gain of PID controller for load frequency regulation was showed in [9] for single area and multi-area system. Based on fuzzy logic approach, an automatic generation control problem in power system was solved by establishing a new fuzzy PID controller [11]. According to Xu *et al.* [12], an adaptive PID neural network controller based on Hammerstein-type neural network was advanced for an enhanced four area interconnected LFC problem. However, these studies are very difficult to find the suitable constraints of PID control in the attendance numerous uncertainties and external disturbances. These external perturbations and uncertainties which indicate in [13], [14] may damage and even destroy the MAPS designed on nominal models. It leads the PID controller's performance to be fairly poor with the huge overshoot, elongated setting time and fluctuation with the transient frequency.

To solve these drawbacks, sliding mode control (SMC) technique is recently employed to design the LFC problems for MAPS. The attractive features of SMC comprise high robustness, simplicity computation, and fast response [15]. The application of SMC method in both single area and multi-area electricity systems has been discovered extensively during the works survey such as in [6], [16]–[20]. A sliding mode controller was investigated to solve the LFC difficulty of the MAPS with matched and unmatched uncertainties [16]. An event triggered multi-rate output feedback sliding mode controller was considered in [21] for the LFC in the MAPS. A SMC-based controller was designed for the LFC problem of micro hydro power plants [17]. By using optimized integral SMC technique, a decentralized LFC was suggested for the frequency regulation of the MAPS [22]. A non-linear SMC scheme was addressed in [6] for LFC implementation in three-area interconnected electricity system with matched and unmatched uncertainties. By applying Lyapunov–Krasovskii functional and LMI optimization, a non-linear sliding mode controller was built for frequency parameter in interconnected electricity plants with time-varying delays [20]. Regrettably, these studies have assumed that the MAPS's state variables are accessible. This is invalid in the practical power systems. To address these shortcomings, in [3]–[5], [23] have employed the output feedback technique. A LFC scheme based on an extended partial states observer was explored for the multi-area system seeing wind energy [5]. A super twisting SMC law based on a higher order sliding mode observer was designed for load frequency complications in the MAPS [3]. A generalized extended state estimator based non-linear variable structure control law was applied to investigate the problem of the frequency deviation in MAPS [4]. Nevertheless, in the existing MAPS researches of the SMC, the plant is sensible to the external perturbations and uncertainties during the reaching phase and all the robust properties are valid during the sliding mode. In addition, motion dynamics is settled after the state paths of plant drive into the switching surface and the system's performance is unknown in the reaching phase. As a result, the overall stability of plant may not be assured or dangerously corrupted [24]. Consequently, it is crucial for LFC problems to develop a novel sliding mode LFC removing the reaching phase that means reaching time is equal to zero.

Inspired by all the published works and the stated restrictions above, we will discourse an observer-based single phase robustness load frequency sliding mode controller (SPRLFSMC) for the multi-area interconnected power systems (MAIPS) with exogenous disturbances. The objective of our research is to contribute to the advance of single-phase robustness SMC without reaching phase and performance analysis for the MAIPS. Firstly, a single-phase sliding function is definitely suggested for MAIPS without reaching phase such that the robustness performance in contradiction of exogenous disturbance is precisely guaranteed at the instance of moment. Secondly, a new observer is proposed to estimate the MAIPS's variables which are not measured. Thirdly, based on estimated states from the observer, a robustness output feedback LFC is investigated for MAIPS with exogenous perturbation without reaching phase. Further, by using LMI technique and Razumikhin–Lyapunov approach, sufficient condition is derived for ensuring the robust stability of motion dynamics in sliding mode. Finally, simulation example is surveyed through on a three-area interconnected electricity plant to verify the usefulness of the anticipated control scheme.

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

A large multi area electricity plant includes the subsystem control zones which are interconnected through tie-lines [16]. The dynamic equations of the MAIPS are given in (1):

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

where the ith and jth control areas are interconnected through a tie-line, the area control error (ACE_i) is the equilibrium between connected control zones comprising tie-line power variation and frequency aberration for ith area. The MAIPS showed by (1) can be written as the following state model:

$$\dot{z}_i(t) = \tilde{A}_i z_i(t) + \tilde{B}_i u_i(t) + \sum_{j=1,j\neq i}^{N} \tilde{H}_{ij}\, z_j(t) + \Pi_i \Psi_{d_i}(t), y(t) = \tilde{C}_i z_i(t) \quad (2)$$

where the plant states of the ith area subsystem, the control signal of the plant, and the controlled output are $z_i(t) = [\Delta f_i(t)\ \ \Delta P_{g_i}(t)\ \Delta P_{T_i}(t)\ \Delta E_i(t)\ \ \Delta P_{tie}^{ij}(t)]^T \in R^{n_i}$, $u_i(t) \in R^{m_i}$, $y_i(t) = ACE_i(t) \in R^{p_i}$, respectively. The index m, n, N are respectively the amount of states of ith zone, the amount of the control input variable of ith zone, and the amount of the control area. The symbol $\Psi_{d_i}(t)$ is the exogenous disturbance input. The incremental change $\Psi_{d_i}(t)$ in load demand is assumed to be unidentified bound and to gratify the following constraint: $\Psi_{d_i}(t) \leq \gamma_i$, where γ_i is unknown positive scalars that are not effortlessly attained in practical control plants because of the complex construction of the uncertainties. The constant matrices:

$$\tilde{A}_i = \begin{bmatrix} -\frac{1}{T_{P_i}} & \frac{K_{P_i}}{T_{P_i}} & 0 & 0 & -\frac{K_{P_i}}{T_{P_i}} \\ 0 & -\frac{1}{T_{T_i}} & \frac{1}{T_{T_i}} & 0 & 0 \\ -\frac{1}{R_i T_{G_i}} & 0 & -\frac{1}{T_{G_i}} & 0 & 0 \\ K_{E_i}.K_{B_i} & 0 & 0 & 0 & K_{E_i} \\ \sum_{j=1,j\neq i}^{N} 2\pi T_{ij} & 0 & 0 & 0 & 0 \end{bmatrix} \in R^{n_i\times n_i}, \tilde{H}_{ij} = \begin{bmatrix} 0 & 0\ 0\ 0\ 0 \\ 0 & 0\ 0\ 0\ 0 \\ 0 & 0\ 0\ 0\ 0 \\ 0 & 0\ 0\ 0\ 0 \\ \sum_{\substack{j=1 \\ j\neq i}}^{N} 2\pi T_{ij} & 0\ 0\ 0\ 0 \end{bmatrix} \in R^{n_i\times n_i}, \tilde{B}_i = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_{G_i}} \\ 0 \\ 0 \end{bmatrix} \in R^{n_i\times m_i}$$

$$\Pi_i = [-\tfrac{K_{P_i}}{T_{P_i}}\ \ 0\ \ 0\ \ 0\ \ 0]^T \in R^{n_i\times k_i}, \tilde{C}_i = [0\ \ 0\ \ E_i\ \ 1\ \ 0]$$

3. MAIN RESULTS

In this section, a novel LFC law will be suggested by employing a novel estimator. A designed controller will keep the MAIPS's state trajectory moving along the sliding surface from the zero-reaching time as our key contribution.

3.1. Constructing an observer-based output feedback load frequency controlle

To minimize the tie-line power conversations and the frequency aberrations in the systems (2), an observer-based output feedback control design algorithm for such a LFC employing a new observer tool is exhibited in this section. Firstly, a dynamics observer is schemed for the MAIPS as (3):

$$\dot{\hat{z}}_i(t) = \tilde{A}_i \hat{z}_i(t) + \tilde{B}_i u_i(t) + \sum_{j=1,j\neq i}^{N} \tilde{H}_{ij}\, \hat{z}_j(t) + G_i[y_i(t) - \hat{y}_i(t)], \hat{y}_i(t) = \tilde{C}_i \hat{z}_i(t) \quad (3)$$

where $\hat{z}_i(t)$ is the estimation of the unmeasurable variables $z_i(t)$, $\hat{y}_i(t)$ is the observer's output, $G_i \in R^{n_i\times p_i}$ is the observer gain matrix. Now, we next initiate an estimator error $\omega_i(t) = z_i(t) - \hat{z}_i(t)$. By relating the first in (2) and the first of dynamics observer in (3), the governing error dynamics is pronounced by (4):

$$\dot{\omega}_i(t) = [\tilde{A}_i - G_i\tilde{C}_i]\omega_i(t) + \sum_{j=1,j\neq i}^{N} \tilde{H}_{ij}\, \omega_j(t) + \Pi_i \Psi_{d_i}(t) \quad (4)$$

Now, by utilizing the SMC technique, a novel LFC law using output information only is designed for the MAIPS. To do this, a new single phase sliding function is first defined as (5):

$$\vartheta_i(t) = \tilde{B}_i^+ \hat{z}_i(t) - \tilde{B}_i^+ \int_0^t (\tilde{A}_i - \tilde{B}_i F_i)\hat{z}_i\,(\tau) d\tau - \tilde{B}_i^+ \hat{z}_i(0) e^{-\mu_i t} \quad (5)$$

where $\tilde{B}_i^+ = (\tilde{B}_i^T \tilde{B}_i)^{-1}\tilde{B}_i^T \in R^{m_i\times n_i}$ is the Moore-Penrose pseudoinverse of $\tilde{B}_i$, $\hat{z}_i(0)$ is the initial constraint of the estimator tool, and $\mu_i > 0$. The matrix $F_i \in R^{m_i\times n_i}$ is chosen to gratify the inequality of the electricity plant: the derivative of the single-phase sliding function combined with the observer (3) is computed as (6).

$$\dot{\vartheta}_i(t) = \tilde{B}_i^+ \tilde{B}_i F_i \hat{z}_i(t) + \tilde{B}_i^+ \tilde{B}_i u_i(t) + \sum_{j=1,j\neq i}^{N} \tilde{B}_i^+ \tilde{H}_{ij}\, \hat{z}_j(t) + \tilde{B}_i^+ G_i[y_i(t) - \hat{y}_i(t)] + \mu_i \tilde{B}_i^+ \hat{z}_i(0) e^{-\mu_i t} \quad (6)$$

To get the stability of the MAIPS described in (2), a new single phase LFC law is built as (7):

$$u_i(t) = -(\tilde{B}_i^+ \tilde{B}_i)^{-1}\{\|\tilde{B}_i^+ \tilde{B}_i F_i\|\|\hat{z}_i(t)\| + \|\tilde{B}_i^+\| \sum_{j=1,j\neq i}^{N} \|\tilde{H}_{ji}\|\, \|\hat{z}_i(t)\| + \|\tilde{B}_i^+ G_i\|[\|y_i(t)\| - \|\hat{y}_i(t)\|] + \eta_i\|\vartheta_i(t)\| + \mu_i \tilde{B}_i^+ \hat{z}_i(0) e^{-\mu_i t}\} sign(\vartheta_i(t)) \quad (7)$$

where η_i are some positive scalars.

Theorem 1. Consider the MAIPS (2) with the decentralized single phase LFC (7), suppose that the external perturbations are considered by unknown positive constants. Then, the power plant's state variables stay in the single phase switching surface (5) and maintain motion on it. The asymptotic stability of the MAIPS is ensured.

Proof of Theorem 1. We deliberate the Lyapunov function $V(t) = \|\vartheta_i(t)\|$, which $\vartheta_i(t)$ is the single-phase switching function that defined in (5). Since $\sum_{j=1,j\neq i}^{N}\|\widetilde{H}_{ij}\|\,\|\hat{z}_j(t)\| = \sum_{j=1,j\neq i}^{N}\|\widetilde{H}_{ji}\|\,\|\hat{z}_i(t)\|$ and differencing $V(t)$ with respect time, we can obtain as (8):

$$\dot{V}(t) \leq \|\tilde{B}_i^{+}\tilde{B}_iF_i\|\|\hat{z}_i\| + \frac{\vartheta_i^T}{\|\vartheta_i\|}\tilde{B}_i^{+}\tilde{B}_iu_i + \|\tilde{B}_i^{+}\|\sum_{j=1,j\neq i}^{N}\|\widetilde{H}_{ji}\|\,\|\hat{z}_i\| + \|\tilde{B}_i^{+}G_i\|[\|y_i\| - \|\hat{y}_i\|] + \mu_i\tilde{B}_i^{+}\hat{z}_i(0)e^{-\mu_i t} \tag{8}$$

By replacing the proposed controller (7) into (8), we obtain $\dot{V}(t) \leq -\eta_i\|\vartheta_i(t)\| < 0$, which the plant's variables stay the sliding surface from the zero-reaching time for all $t \geq 0$. From now, Theorem 1 is completely done.

3.2. Power system stability analysis in single phase sliding mode

In above section, we have just represented the LFC law for MAIPS. The proposed controller will keep the states of the electricity system moving along the sliding surface towards the beginning with wanted performance for all time. Next, the task of this section is to find the appropriate LMI conditions which based on the Lyapunov technique such that the MAIPS (2) guarantees the asymptotical stability. Now, we will consider the following LMI as (9):

$$\begin{bmatrix} \bar{\Xi}_i + \sum_{j=1,j\neq i}^{N}[\beta_j(\widetilde{H}_{ji} - \Xi_j\widetilde{H}_{ji})^T.(\widetilde{H}_{ji} - \Xi_j\widetilde{H}_{ji})] & P_i\Phi_i & P_i & P_i\Pi_i & P_i\Omega_i & 0 & 0 \\ \Phi_i^T P_i & \bar{\Psi}_i + \sum_{j=1,j\neq i}^{N}[\bar{\beta}_j\widetilde{H}_{ji}^T\Xi_j^T\Xi_j\widetilde{H}_{ji} + \tilde{\beta}_j^{-1}\widetilde{H}_{ji}^T\widetilde{H}_{ji}] & 0 & 0 & 0 & Q_i\Pi_i & Q_i \\ P_i & 0 & -\eta_i^{-1} & 0 & 0 & 0 & 0 \\ \Pi_i^T P_i & 0 & 0 & -\bar{\mu}_i^{-1} & 0 & 0 & 0 \\ \Omega_i^T P_i & 0 & 0 & 0 & -\tilde{\mu}_i^{-1} & 0 & 0 \\ \Pi_i^T Q_i & 0 & 0 & 0 & 0 & -\mu_i^{-1} & 0 \\ Q_i & 0 & 0 & 0 & 0 & 0 & -\tilde{\beta}_i^{-1} \end{bmatrix} < 0 \tag{9}$$

where $\bar{\Xi}_i = P_i(\tilde{A}_i - \tilde{B}_iF_i) + (\tilde{A}_i - \tilde{B}_iF_i)^TP_i, \bar{\Psi}_i = Q_i(\tilde{A}_i - G_i\tilde{C}_i) + (\tilde{A}_i - G_i\tilde{C}_i)^TQ_i$, $\Phi_i = \tilde{B}_iF_i - \tilde{B}_i(\tilde{B}_i^{+}\tilde{B}_i)^{-1} \times \tilde{B}_i^{+}G_i\tilde{C}_i$, $\Xi_i = \tilde{B}_i(\tilde{B}_i^{+}\tilde{B}_i)^{-1}\tilde{B}_i^{+}$, $\eta_i = (\beta_i^{-1} + \bar{\beta}_i^{-1})$, $\tilde{\eta}_i = (\mu_i^{-1} + \bar{\mu}_i^{-1})$, $\Omega_i = -\mu_i\tilde{B}_i(\tilde{B}_i^{+}\tilde{B}_i)^{-1}\tilde{B}_i^{+}\hat{z}_i(0)$, P_i and Q_i are any positive matrices, and $\beta_i, \bar{\beta}_i, \mu_i, \bar{\mu}_i$ are positive scalars.

To evidence the multi-area power plant (2) that ensures the asymptotical stability, we suggest the following theorem.

Theorem 2. Propose that the LMI (9) has the possible answers $P_i > 0, Q_i > 0$, the single phase switching surface is proposed by (5). Then, the multi-area power plant (2) to the specified switching surface is asymptotically stable.

Proof of Theorem 2. The equivalent control in the sliding mode, $\vartheta_i(t) = 0, \dot{\vartheta}_i(t) = 0$, is showed as the following form:

$$u_i^{eq}(t) = -(\tilde{B}_i^{+}\tilde{B}_i)^{-1}\{\tilde{B}_i^{+}\tilde{B}_iF_i\hat{z}_i(t) + \tilde{B}_i^{+}\sum_{j=1,j\neq i}^{N}\widetilde{H}_{ij}\,\hat{z}_j(t) + \tilde{B}_i^{+}G_i[y_i(t) - \hat{y}_i(t)] + \mu_i\tilde{B}_i^{+}\hat{z}_i(0)e^{-\mu_i t}\} \tag{10}$$

By replacing (10) into the first equation of the original power system (2), is showed in (11):

$$\dot{z}_i(t) = [\tilde{A}_i - \tilde{B}_iF_i]z_i(t) + [\tilde{B}_iF_i - \tilde{B}_i(\tilde{B}_i^{+}\tilde{B}_i)^{-1}\tilde{B}_i^{+}G_i\tilde{C}_i]\,\omega_i(t) + \sum_{j=1,j\neq i}^{N}[\widetilde{H}_{ij} - \tilde{B}_i(\tilde{B}_i^{+}\tilde{B}_i)^{-1} \times \tilde{B}_i^{+}\widetilde{H}_{ij}]z_j(t) + \sum_{j=1,j\neq i}^{N}\tilde{B}_i(\tilde{B}_i^{+}\tilde{B}_i)^{-1}\tilde{B}_i^{+}\widetilde{H}_{ij}\,\omega_j(t) + \Pi_i\Psi_{d_i} - \mu_i\tilde{B}_i(\tilde{B}_i^{+}\tilde{B}_i)^{-1}\tilde{B}_i^{+}\hat{z}_i(0)e^{-\mu_i t} \tag{11}$$

The dynamics motion equation can be characterized as the combination in (12):

$$\begin{bmatrix}\dot{z}_i(t) \\ \dot{\omega}_i(t)\end{bmatrix} = \begin{bmatrix}\tilde{A}_i - \tilde{B}_iF_i & \Phi_i \\ 0 & \tilde{A}_i - G_i\tilde{C}_i\end{bmatrix}\begin{bmatrix}z_i \\ \omega_i\end{bmatrix} + \sum_{\substack{j=1 \\ j\neq i}}^{N}\begin{bmatrix}\widetilde{H}_{ij} - \Xi_i\widetilde{H}_{ij} & \Xi_i\widetilde{H}_{ij} \\ 0 & \widetilde{H}_{ij}\end{bmatrix}\begin{bmatrix}z_j \\ \omega_j\end{bmatrix} + \begin{bmatrix}I_i & \Omega_i \\ I_i & 0\end{bmatrix}\begin{bmatrix}\Pi_i\Psi_{d_i}(t) \\ e^{-\mu_i t}\end{bmatrix} \tag{12}$$

where $\Phi_i = \tilde{B}_i F_i - \tilde{B}_i.(\tilde{B}_i^+ \tilde{B}_i)^{-1} \tilde{B}_i^+ G_i \tilde{C}_i, \Xi_i = \tilde{B}_i.(\tilde{B}_i^+ \tilde{B}_i)^{-1} \tilde{B}_i^+,$ $\Omega_i = -\mu_i \tilde{B}_i (\tilde{B}_i^+ \tilde{B}_i)^{-1} \tilde{B}_i^+ \hat{z}_i(0)$. The eigenvalue of $(\tilde{A}_i - \tilde{B}_i F_i)$ is used to control the estimated plant variables into the sliding surface (5). Now, to validate the stability of the power plant dynamics, we consider the following Lyapunov positive definition function $V[z_i(t), \omega_i(t)] = \sum_{i=1}^{N} \begin{bmatrix} z_i(t) \\ \omega_i(t) \end{bmatrix}^T \begin{bmatrix} P_i & 0 \\ 0 & Q_i \end{bmatrix} \begin{bmatrix} z_i(t) \\ \omega_i(t) \end{bmatrix}$, where the positive matrices P_i and Q_i are defined by LMI (9). Then, by enchanting the time derivative of $V$and combining the statement (12), is showed as the following form:

$$\dot{V} < \left\{ \begin{bmatrix} z_i \\ \omega_i \end{bmatrix}^T \begin{bmatrix} \bar{\Xi}_i + \sum_{\substack{j=1 \\ j\neq i}}^{N} \left[\beta_j \left(\widetilde{H}_{ji} - \Xi_j \widetilde{H}_{ji} \right)^T \left(\widetilde{H}_{ji} - \Xi_j \widetilde{H}_{ji} \right) \right] + \eta_i P_i P_i + \bar{\mu}_i P_i \Pi_i \Pi_i^T P_i + \tilde{\mu}_i P_i \Omega_i \Omega_i^T P_i & P_i \Phi_i \\ \Phi_i^T P_i \bar{\Psi}_i + \sum_{\substack{j=1 \\ j\neq i}}^{N} \left[\bar{\beta}_j \widetilde{H}_{ji}^T \Xi_j^T \Xi_j \widetilde{H}_{ji} + \tilde{\beta}_j^{-1} \widetilde{H}_{ji}^T \widetilde{H}_{ji} \right] + \tilde{\beta}_i Q_i Q_i + \mu_i Q_i \Pi_i \Pi_i^T Q_i & \end{bmatrix} \times \begin{bmatrix} z_i(t) \\ \omega_i(t) \end{bmatrix} \right\} + \sum_{i=1}^{N} [\tilde{\eta}_i \nu^2 + \delta_i(t)] \quad (13)$$

where $\bar{\Xi}_i = P_i(\tilde{A}_i - \tilde{B}_i F_i) + (\tilde{A}_i - \tilde{B}_i F_i)^T P_i, \bar{\Psi}_i = Q_i(\tilde{A}_i - G_i \tilde{C}_i) + (\tilde{A}_i - G_i \tilde{C}_i)^T Q_i,$ $\eta_i = \beta_i^{-1} + \bar{\beta}_i^{-1}$, $\tilde{\eta}_i = \mu_i^{-1} + \bar{\mu}_i^{-1}, \nu_i = \left\| \Psi_{d_i}(t) \right\|$, and $\delta_i(t) = \mu_i^{-1} (e^{-\mu_i t})^T e^{-\mu_i t}$.
Then, applying well-known LMI technique [25] to inequality (9), we attain:

$$\widetilde{\Upsilon}_i = - \begin{bmatrix} \bar{\Xi}_i + \sum_{j=1, j\neq i}^{N} \left[\beta_j \left(\widetilde{H}_{ji} - \Xi_j \widetilde{H}_{ji} \right)^T \left(\widetilde{H}_{ji} - \Xi_j \widetilde{H}_{ji} \right) \right] + \eta_i P_i P_i + \bar{\mu}_i P_i \Pi_i \Pi_i^T P_i + \tilde{\mu}_i P_i \Omega_i \Omega_i^T P_i & P_i \Phi_i \\ \Phi_i^T P_i & \bar{\Psi}_i + \sum_{j=1, j\neq i}^{N} \left[\bar{\beta}_j \widetilde{H}_{ji}^T \Xi_j^T \Xi_j \widetilde{H}_{ji} + \tilde{\beta}_j^{-1} \widetilde{H}_{ji}^T \widetilde{H}_{ji} \right] + \tilde{\beta}_i Q_i Q_i + \mu_i Q_i \Pi_i \Pi_i^T Q_i \end{bmatrix} > 0 \quad (14)$$

According to (13) and (14), and the term $\delta_i(t)$ in statement (13) will converges to zero after the time approaches infinity, it can be realized that $\dot{V}[z_i(t), \omega_i(t)] \leq \sum_{i=1}^{N\Sigma} \left[-\lambda(\widetilde{\Upsilon}_i) \|\widehat{z_i(t)}\|^2{}_{i_{i\,min}}^{2} [] \right]$ where the positive value $\tilde{\eta}_i \nu_i^2 = (\mu_i^{-1} + \bar{\mu}_i^{-1}) \left\| \Psi_{d_i}(t) \right\|^2$ and the eigenvalue of a matrix Consequently, $\dot{V}[z_i(t), \omega_i(t)] < 0$ is attained with $\|\hat{z}_i(t)\| > \sqrt{\frac{\tilde{\eta}_i \nu_i^2}{\lambda(\Upsilon_i)_{min}}}$ Later, the switching dynamics motion (12) is asymptotically stable. Resulting that, Figure 1 describes the flowchart of the suggested estimator single-phase variable structure control technique.

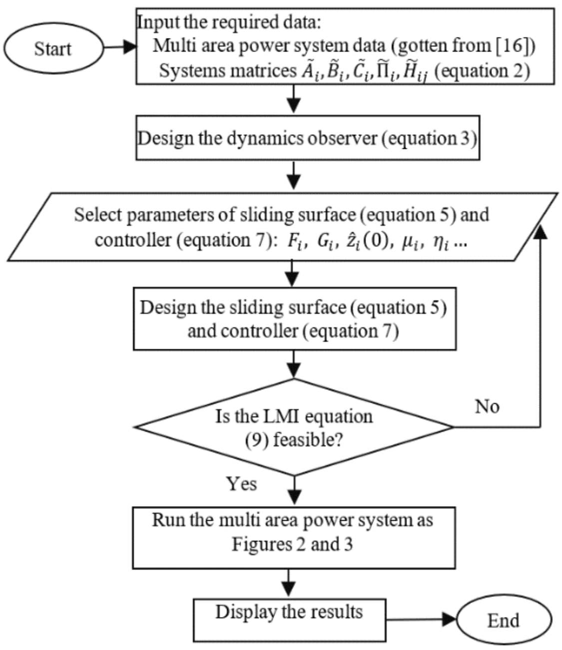

Figure 1. The flowchart of the suggested estimator-based SPRLFSMC

4. SIMULATION TEST

In order to analyze and evaluate the usefulness of the suggested LFC based on estimated variables and output information, in this section, the suggested method has been implemented to the three-area power systems gotten from [16]. The attainments of simulations are display in Figures 2(a) to (c).

Remark 1: all the plant's variables are utilized in suggested controller in (7) is get from the state estimator in (3). At this fact, the external perturbations of three areas are respectively assumed as ΔP_{d1}=0.01, ΔP_{d2}=0.015, and ΔP_{d3}=0.02. The performance of the controller in this power systems are illustrated in Figure 2. Where Figure 2(a) is frequency aberration of zones 1 to 3, respectively. Figure 2(b) is tie-line power difference between three zones. Figure 2(c) is the LFC of three-area power plants with external instabilities. From these records which display the time difference of the output signal, we can effortlessly see that frequency aberration in both zones converge to zero in 2 s with under shoot are -2.2×10^{-4} (pu MW) and -2.7×10^{-4} (pu MW) in the zones 1 to 3. From these outcomes, it is understandable that anticipated controller has good performance with small over/under shoots and soft settling times. In order words, the states of the plant tend to the specified sliding surface $\vartheta_i(t)$=0 in finite time which the published works [6], [21], [22] could not be performed the achievement. In addition, the suggested method in our research does not need the accessibility of the MAIPS's state variables.

Remark 2: the time replies for each zone that administrated by the sliding function in (5) are shown in Figure 2(c). It is understandable that the switching variables of each zone hit to zero from the commencement time ($t \geq 0$) which is indicated the removal of the reaching phase in TSMC approach. That is, the paths states of the plants always start from the sliding surface and the wanted reply of the system is guaranteed from the beginning of its motion. It can be specified that the improved robustness and the desired dynamic response of the MAIPS are attained by canning reaching phase that has reduced the limitations required in other studies [3]–[5]. Consequently, the performance and robustness of the total plant have been improved.

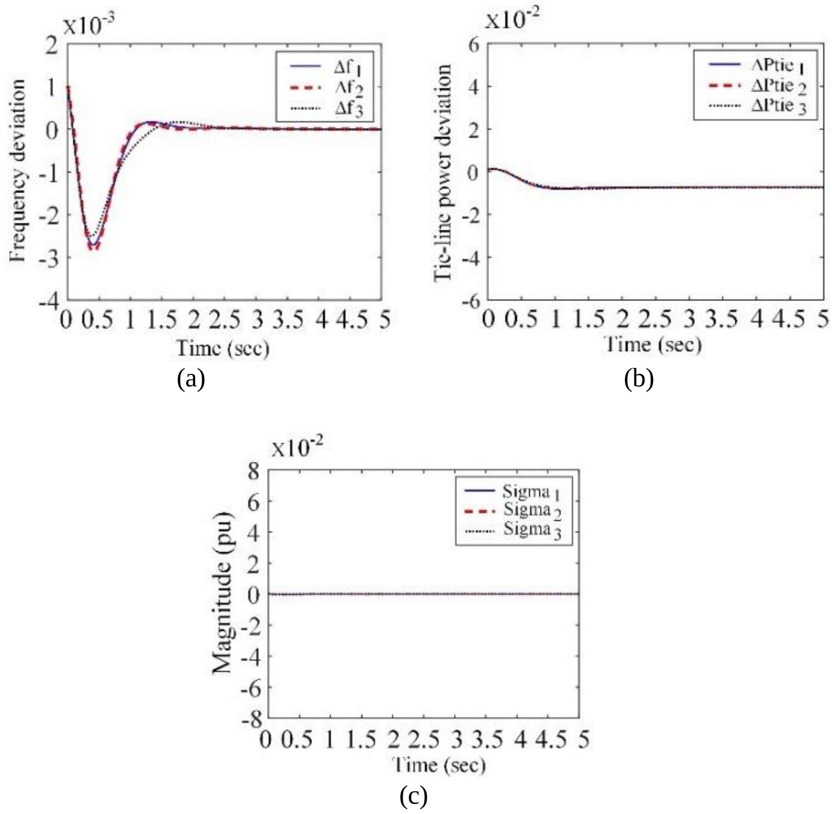

Figure 2. Time response of; (a) the frequency aberrations, (b) the tie-line power aberrations, and (c) the single-phase switching surfaces of three-area power plants with external disturbances

From the examination of the obtained results, the proposed method does not need the accessibility of the plant states. We can accomplish that the suggested technique is competent for answering the stabilization problem for the MAIPS with the extended disturbances. Consequently, this technique is very valuable and more realistic, since it can be effortlessly executed in many practical MAIPSs.

5. CONCLUSION

To solve the problem of a global stability and the unmeasurable states variables of the system in the MAIPS, a novel estimator-based SPRLFSMC is proposed in this paper. The new single phase switching function has been established to drive the plant's trajectories to the switching surface from the initial time moment. We have designed the new observer to guess the immeasurable states helping the LFC strategy. The new SPRLFSMC for the MAIPS has been proposed by using the observer 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 property of asymptotical stability. Finally, the simulated marks of the three-area interconnected power system prove viability, usefulness and robustness of the suggested control arrangement even in the attendance of the external instabilities. The development of the offered technique to the MAIPS involving renewable energy sources could be the future trend.

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