Distributed event-triggered robust automatic generation control for networked power system with wind turbines

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1 INTRODUCTION

Among different kinds of renewable energy sources, wind energy is a mature power production technology. It is not only economically attractive to the increasing energy demand, but also a sustainable energy solution for global development with limited environmental impact [1, 2]. In the power system, especially with the participation of wind turbines, due to randomness and uncertainty of wind energy, disturbances occur in the power system. In recent years, automatic generation control (AGC) problem has been studied. Usually, the design of AGC has been proposed based on centralized control frameworks [3–5]. However, there are several points to be noted for centralized control: the controller is susceptible to the complete failure of the central processing unit; the cost of collecting data from a single sensor node by the central processing unit is very high; the computational burden of the central processing unit is increased, especially for large-scale power system with highly interconnected subsystems and complex dynamic performance [6, 7]. Therefore, some researchers proposed different distributed control methods to solve the AGC problem in large-scale power system [8–10]. Various sensors, controllers and actuators transmit a large amount of data information through a communication network. The usage of data information through the communication network has brought challenge in the design of multi-area AGC, such as system uncertainty, networked-induced delays and packet dropout, which will inevitably reduce the performance of the system and may even affect the stability of the large-scale power system. Compared with the conventional point-to-point interconnected control system, the primary advantages of networked control systems (NCSs) are modular and flexible system design, simple and fast implementation, ease of system maintenance and increased system agility. Therefore, some challenging problems are put forward in the study of distributed networked control systems (DNCSs). Many researchers have made progress in system design, high-speed computing and network technology. These works are unified and systematic. In order to solve some control problems of power system, practical challenges are put forward to the integration of communication, computation and control, and some basic work needs to be done [11–15]. In view of these points, with the increasing complexity of power system, the influence of network communication on power system performance cannot be underestimated. At present, there are few references about the design of distributed network controller for power system with by considering 3C (3C: Intersection of control, computation...
and communication) [16–20]. This is also the motivation to write this paper.

Distributed AGC problem of a multi-area networked power system with system parameters uncertainty and limited communication resources is studied in this paper. An event-triggered communication mechanism is developed to schedule interconnected subsystem’s communication, reduce unnecessary data exchange between subsystems and improve resource utilization. First, for the large-scale DNCSs with considering the system model with parameters uncertainty, effective transmission bandwidth and networked-induced delays, a new DNCSs model is proposed, event-triggered mechanisms (ETMs) are integrated for the DNCSs scheme. By constructing Lyapunov–Krasovskii functional method, based on linear matrix inequality (LMI), the sufficient conditions are proposed for DNCSs asymptotical stability. In order to verify the effectiveness of the proposed scheme, a multi-area power generation system (thermal power station, hydropower station, wind farm) is considered. The performance of the system under different load disturbances is simulated and analyzed. The simulation results show that the method can improve the power system performance in the case of effective transmission bandwidth, parameters uncertainty and time-varying communication delays.

The structure of this paper is as follows. In Section 2, an event-triggered distributed model for DNCSs scheme and the problem to be investigated are formulated. In Section 3, an interconnected controller design method is proposed, sufficient conditions are derived for asymptotical stability of the event-triggered DNCSs. Section 4 introduces the simulation analysis of typical interconnected system, a multi-area power system is considered and the dynamic performance of the system under different load disturbances is simulated and analyzed. Finally, Section 5 summarizes this paper.

2 | PROBLEM DESCRIPTION

NCSs have many coupled subsystems that exchange the data through the communication channel [21]. However, due to limited bandwidth and possible data loss in the communication network, the time-varying networked-induced delays are inevitable in these NCSs. In order to deal with the impacts of communication network uncertainty in designing of networked controller, an efficient DNCSs model is presented. The implementation of effective bandwidth results in network traffic reduction while maintaining acceptable system performance [22]. A node with effective bandwidth compares the value prepared to send to the network, \( x_{i,t} \), to either the last value sent, \( x_{i,\text{sent}} \), or a constant threshold \( \delta_{i,j} \). If the absolute value of the difference between \( x_{i,t} \) and \( x_{i,\text{sent}} \) is within the effective bandwidth, \( \delta_{i,j} \), then no update is sent to network

\[
\text{IF} |x_{i,t} - x_{i,\text{sent}}| \geq \delta_{i,j} \text{ (or} \delta_{j,i} \text{)}
\]

THEN

Broadcast \( x_{i,t} \)

\( x_{i,\text{sent}} = x_{i,t} \)

ELSE

No message broadcast

For the case when the term \( \delta_{i,j} \) is used the threshold changes as a function of the node state and be viewed as a relative threshold. When \( \delta_{i,j} \) is used, the threshold remains constant independent of the state.

As the size of the threshold parameters increases, \( \delta_{i,j} \), under the assumption that other conditions remain unchanged, the range of judgment conditions for the node to transmit information becomes wider, the node broadcast fewer messages. Implementing a threshold to reduce network traffic produces uncertainty in the state of the system. Since the controller relies on the broadcast state \( x_{i,j} \), to compute the control signal, it is important to determine whether this uncertainty could drive the system to instability. At any given time, the true state of the system \( x_{i} \) is: \( x_{i} = x_{i,t} + \delta_{i}, x_{i,\text{sent}} \) in case of the controller node, the control signal it sends to the plant is the following: \( u_{i} = K_{i}x_{i,j} \) the event-triggered control scheme consisting of ETMs and a discrete-time state feedback control law is described as: \( u_{i}(k) = K_{i}(I + \delta_{i})^{-1}x_{i}(k) \).

The influence of model uncertainties on system performance has always been the main direction in automatic control research. In practical application, the assumed dynamic model may not accurately predict the actual system dynamic performance. In addition, due to the aging of equipment and the change of magnetic saturation temperature, parameters such as transient reactance of generator may be time-varying, resulting in large uncertainties of model. These model uncertainties will inevitably affect the analysis and design in the dynamic and steady-state performance. In order to reduce the impact of model uncertainties, some robust control methods are applied to the dynamic state estimation of the power system.

Consider DNCSs \( S \) consisting of \( N \) subsystems, and subsystem \( S_{i}, i = (1, 2, \ldots, N) \), these subsystems are connected with each other through the network channel. Each subsystem transmits relevant data information through the communication network, including its own data information and the data information that is associated with other subsystems in the coupled system. If the subsystem \( S_{i} \) is associated with the subsystem \( S_{j}, \) the controller \( j \) sends the state data of the subsystem \( S_{i} \) to the \( j \)th controller through the network. \( S_{j} \) is related subsystem of \( S_{i}, \) the set of all neighbour subsystem of \( S_{i} \) is described by \( N_{i}, N_{i} = \{ S_{j} | i \neq j \text{ and } S_{j} \text{ is a neighbor of } S_{i} \} \). The \( i \)th subsystem of large scale interconnected distributed systems based on ETMs is as follow [23]:

\[
x_{i}(k + 1) = A_{i}x_{i}(k) + B_{i}u_{i}(k) + \sum_{j \in N_{i}} A_{ij}x_{j}(k).
\]

Therefore, the dynamic model of the \( i \)th subsystem \( S_{i} \) with modelling uncertainty, time-varying delay and interconnection can be described as the following model:

\[
x_{i}(k + 1) = (A_{i} + \Delta A_{i})x_{i}(k) + (A_{\delta} + \Delta A_{\delta})x_{i}(k - \tau_{i}(k)) + (B_{i} + \Delta B_{i})u_{i}(k) + \sum_{j \in N_{i}} (A_{ij} + \Delta A_{ij})x_{j}(k - \tau_{ij}(k))
\]

\(\) (2)
where \( x_i(k), u_i(k) \) are the local state vector and control inputs, respectively. \( x_i(k - \tau_i(k)) \) and \( x_i(k - \tau_{ij}(k)) \) show the local delayed state variables and neighbour delays state variables, respectively. \( A_{ij}, A_{di}, B_{ij}, \) and \( B_i \) are known constant parameter matrices with appropriate dimensions. \( A_{ij} \) and \( B_{ij} \) are the system matrices, \( A_{di} \) shows the state delay matrix and \( A_{ij} \) denotes interconnection matrix, which reflects the relationship between the \( i \)th subsystem and the \( j \)th subsystem. If the state of the \( i \)th subsystem is not coupled with the \( j \)th subsystem, matrix \( A_{ij} \) will be zero. With consideration of bounded uncertainties, \( \Delta A_{ij}, \Delta A_{di}, \Delta B_{ij}, \) and \( \Delta A_{ij} \) are unknown norm bounded uncertainty matrices which represent the uncertainty of parameters in the model. For \( i, j = (1, 2, ..., N) \), the uncertainty matrix can be described as \( \Delta A_i, \Delta A_{di}, \Delta B_i, \) and \( \Delta A_{ij} \) are uncertain time-varying uncertainty matrices and satisfying \( F_j^T F_i \leq I_{\beta_i} \) and \( F_i^T F_i \leq I_{\beta_i} \), respectively. \( I_k \) denotes Unit matrix with proper dimension. \( D_i, E_{ai}, E_{adi}, L_{ai} \), and \( N_{ij} \) are known real matrix with proper dimension, describes the structure of uncertain parameters. \( \tau_i(k) \) and \( \tau_{ij}(k) \) for \( i = 1, ..., N, j \in N_i, \) are uncertain time-varying state delays and interconnection delays [24], respectively, meet the conditions: \( 0 \leq \tau_{inn} \leq \tau_i(k) \leq \tau_{iM} \) and \( 0 \leq \tau_{ijn} \leq \tau_{ij}(k) \leq \tau_{ijM} \).

### 3 DESIGN OF DISTRIBUTED NETWORKED ROBUST CONTROLLER BASED ON ETMS

The design of distributed control law for interconnected systems has received considerable attention in recent years. An interconnected system with distributed control architecture is known as distributed control law since the control law for each subsystem does not only depend on its own states but also the states of the other subsystems. Communication networks provide a larger flexibility for the control design of interconnected systems by allowing the information exchange between the local controllers of the subsystems which can be used to improve the overall system performance.

Based on the ETMs proposed in Section 2, a novel state feedback control law that consider the limited bandwidth and networked-induced delays is proposed for DNCSs, for the \( i \)th subsystem, the state feedback control law is designed as follows:

\[
\begin{align*}
\dot{x}_i(k) &= K_i (I + \delta_i)^{-1} x_i(k) + K_{di} (I + \delta_i)^{-1} x_i(k - \tau_i(k)) \\
&\quad + \sum_{j \in N_i} K_{ij} (I + \delta_j)^{-1} x_j(k - \tau_{ij}(k)) \quad (3)
\end{align*}
\]

where \( K_i, K_{di} \) and \( K_{ij} \) are the \( i \)th controller feedback gain, delayed state feedback gain and interconnected feedback gain, respectively. \( \delta_i \) is threshold parameter. The main purpose of this paper is to consider these feedback terms and feedback thresholds at the same time, so as to ensure the stability and improve the performance of DNCSs. In general, the stability analysis of NCSs with networked-induced delays can be divided into two categories: delay independent and delay dependent. In delay independent stability analysis, it is not necessary to know the values of delays or even their upper and lower bounds. Therefore, the stability criteria are independent of the time delay. In this paper, delay independent stability analysis is considered. A delay independent theorem based on LMI is proposed, and sufficient conditions for asymptotic stability of closed-loop DNCSs are obtained.

The control law proposed in (3) is applied to the subsystem \( \beta_i \), under the ETMs in Section 2, and the following closed-loop dynamic system is obtained:

\[
\begin{align*}
\dot{x}_i(k + 1) &= \left( (A_i + \Delta A_i) + (B_i + \Delta B_i) K_i (I + \delta_i)^{-1} \right) x_i(k) \\
&\quad + \left( (A_{di} + \Delta A_{di}) + (B_{di} + \Delta B_{di}) K_{di} (I + \delta_i)^{-1} \right) x_i(k - \tau_i(k)) \\
&\quad + \left( (B_i + \Delta B_i) K_i (I + \delta_i)^{-1} \right) (k - \tau_{ij}(k)). \quad (4)
\end{align*}
\]

For convenience, let

\[
\begin{align*}
A_{ij} &= (A_i + \Delta A_i) + (B_i + \Delta B_i) K_i (I + \delta_i)^{-1} \\
A_{di} &= (A_{di} + \Delta A_{di}) + (B_{di} + \Delta B_{di}) K_{di} (I + \delta_i)^{-1} \\
A_{ij} &= (A_{ij} + \Delta A_{ij}) + (B_{ij} + \Delta B_{ij}) K_{ij} (I + \delta_j)^{-1}
\end{align*}
\]

for \( i = 1, ..., N, j \in N_i \). Assuming \( A_i, A_{di}, A_{ij}, B_i, B_{ij}, \Delta A_i, \Delta A_{di}, \Delta A_{ij}, \Delta B_{ij} \) are known matrix with proper dimension, by the following Theorem 1, a sufficient condition LMI based for the asymptotic stability of the closed-loop DNCSs described in (4) can be derived.

**Theorem 1.** Consider system (4) under the ETMs in Section 2, for a given threshold \( \delta_i \), if there exist matrices \( R_{ij} > 0, Q_i > 0, P_i > 0 \) and \( H_i > 0 \) such that

\[
\begin{bmatrix}
\Xi_{11} & \Xi_{12} & \Xi_{13} & 0 & \Xi_{15} \\
* & \Xi_{22} & 0 & 0 & 0 \\
* & * & \Xi_{33} & 0 & 0 \\
* & * & * & \Xi_{44} & 0 \\
* & * & * & * & \Xi_{55}
\end{bmatrix} < 0. \quad (5)
\]

Then the closed-loop DNCSs \( \delta \) is asymptotically stable. Where

\[
\begin{align*}
\Xi_{11} &= -P_i^{-1} \\
\Xi_{12} &= A_{ii} \\
\Xi_{13} &= A_{di} \\
\Xi_{22} &= -P_i^{-1} + Q_i + (N - 1) H_i \\
\Xi_{33} &= -P_i^{-1} Q_i P_i^{-1}
\end{align*}
\]
\[ \Xi_{44} = - \text{diag} \{ R_{ij} \} - \text{diag} \{ H_j \} \quad j \in N_i \]

\[ \Xi_{55} = - \text{diag} \{ R_{ij} \} \quad j \in N_i \]

\[ \Xi_{15} = \text{row} \{ A_{ij} \} = \text{row} \{ A_{ij} \} + B_j \text{row} \{ K_j \} \quad j \in N_i. \]

**Proof:** Construct the following Lyapunov–Krasovskii function \( V(k) \) for the DNCSs as

\[ V(k) = \sum_{i=1}^{N_i} V_i(k) = \sum_{i=1}^{N_i} \left[ V_{1i}(k) + V_{2i}(k) + V_{3i}(k) \right] \quad (6) \]

where

\[ V_{1i}(k) = x_i^T(k) P_i x_i(k) \]

\[ V_{2i}(k) = \sum_{l=k-\tau_i(k)}^{k-1} x_i^T(l) Q_i x_i(l) \]

\[ V_{3i}(k) = \sum_{j \in N_i} \sum_{l=k-\tau_{ij}(k)}^{k-1} x_j^T(l) R_{ij} x_j(l). \]

With taking the forward difference along (6) and using (4), we have

\[ \Delta V(k) = \left[ A_{i1}^T x_i^T(k) + A_{i2}^T x_i^T(k - \tau_i(k)) \right. \]

\[ + \sum_{j \in N_i} A_{ij}^T x_j^T(k - \tau_{ij}(k)) \]

\[ \left. + A_{i1} x_i(k) + \sum_{j \in N_i} A_{ij} x_j(k - \tau_{ij}(k)) \right] P_i \left[ A_{i1}^T x_i(k) \right. \]

\[ - x_i^T(k) P_i x_i(k) + \sum_{j \in N_i} \left[ \sum_{h=k-\tau_i(k)}^{k-1} x_j^T(h) H_j x_j(h) \right] + x_i^T(k) Q_i x_i(k) \]

\[ - x_i^T(k - \tau_i(k)) Q_i x_i(k - \tau_i(k)) \]

\[ + \sum_{j \in N_i} \left[ x_j^T(k) R_{ij} x_j(k) \right. \]

\[ \left. - x_j^T(k - \tau_{ij}(k)) R_{ij} x_j(k - \tau_{ij}(k)) \right] \]

\[ = A_{i1}^T x_i^T(k) P_i A_{i1} x_i(k) \]

\[ + A_{i1}^T x_i^T(k) P_i A_{i2} x_i(k - \tau_i(k)) \]

\[ + A_{i1}^T x_i^T(k - \tau_i(k)) P_i A_{i1} x_i(k) \]

\[ + A_{i1}^T x_i^T(k - \tau_i(k)) P_i \sum_{j \in N_i} A_{ij} x_j(k - \tau_{ij}(k)) \]

\[ + A_{i2}^T x_i^T(k - \tau_i(k)) P_i \sum_{j \in N_i} A_{ij} x_j(k - \tau_{ij}(k)) \]

\[ + A_{i2}^T x_i^T(k - \tau_i(k)) P_i A_{i1} x_i(k) \]

\[ + \sum_{j \in N_i} A_{ij}^T x_j^T(k - \tau_{ij}(k)) P_i A_{i1} x_i(k) \]
In order to reduce the conservatism of stability conditions, slack variable $H_i$ is introduced by (7), which aims to reduce conservatism and increase flexibility \[25, 26\]

\[
\sum_{i=1}^{N} \left[ \sum_{j \in N_i} x_i^T(k) H_{ij} x_j(k) - \sum_{j \in N_i} x_j^T(k) H_{ji} x_j(k) \right] = 0. \tag{7}
\]

Thus, we obtain

\[
\Delta V'(k) = \sum_{i=1}^{N} \Delta V_i'(k) = \sum_{i=1}^{N} \left[ \Delta V_{1i}'(k) + \Delta V_{2i}'(k) + \Delta V_{3i}'(k) \right]
\]

\[
+ \sum_{j \in N_i} x_j^T(k) Q_{ij} x_j(k) - \sum_{j \in N_i} x_j^T(k - \tau_i(k)) Q_{ij} x_j(k - \tau_i(k))
\]

\[
+ \sum_{j \in N_i} \left[ x_j^T(k) R_{ij} x_j(k) - x_j^T(k - \tau_i(k)) R_{ij} x_j(k - \tau_i(k)) \right]
\]

With mathematical manipulation, we have

\[
\Delta V'(k) = \sum_{i=1}^{N} \xi_i^T(k) \Theta_i \xi_i(k)
\]

\[
\xi_i(k) = \left[ x_i^T(k) x_i^T(k - \tau_i(k)) x_{\text{ne}}^T(k) x_{\text{ne}}^T(k - \tau_{\text{ne}}(k)) \right]
\]
where \( \Theta_i \) is shown in (9).

\[
\chi_{\text{nei}}(k) = \text{row} \left \{ x_j^T(k) \right \}, \quad j \in N_i
\]

\[
\chi_{\text{nei}}(k - \tau_{\text{nei}}(k)) = \text{row} \left \{ x_j^T(k - \tau_{ij}(k)) \right \}, \quad j \in N_i
\]

\[
\Theta_i = \begin{bmatrix}
\Theta_{11} & \Theta_{12} & 0 & \Theta_{14} \\
\Theta_{21} & \Theta_{22} & 0 & \Theta_{24} \\
0 & 0 & \Theta_{33} & 0 \\
\Theta_{41} & \Theta_{42} & 0 & \Theta_{44}
\end{bmatrix} < 0 \quad (9)
\]

\[
\begin{align*}
\Theta_{11} &= A_i^T P_i A_i - P_i + Q_i + (N - 1) H_i \\
\Theta_{12} &= A_i^T P_i A_{di} \\
\Theta_{14} &= A_i^T P_i A_{di} \\
\Theta_{21} &= A_i^T P_i A_i \\
\Theta_{22} &= A_i^T P_i A_{di} - Q_i \Theta_{24} = A_i^T P_i A_i
\end{align*}
\]

\[
\Theta_{33} = \text{diag} \left \{ R_{ij} - H_j \right \}, \quad j \in N_i
\]

\[
\begin{align*}
\Theta_{41} &= A_i^T P_i A_{di} \\
\Theta_{42} &= A_i^T P_i A_{di} \\
\Theta_{44} &= A_i^T P_i A_{di} - \text{diag} \left \{ R_{ij} \right \}, \quad j \in N_i
\end{align*}
\]

where index nei stands for the states of neighbouring subsystem \( S_j \). From the above analysis, implement Schur complement on (9), we have (5), which means if inequality (5) is satisfied, the closed-loop DNCSs is asymptotically stable. Moreover, inequality (5) is satisfied results in \( \Delta V(k) < 0 \), the system \( S \) is asymptotically stable. This completes the proof.

In this section, a design method of distributed networked controller suggested in (3) based on ETMs is proposed. Because the inequality (5) is not a LMI, it is difficult to solve this kind of inequality. Though variable substitution, inequality (5) can be transmitted into a line matrix inequality, the designer can use the existing LMI solver and calculate the stable feedback gain \( K_i, K_{di} \) and \( K_{ij} \). For convenience, the following lemmas are introduced.
Lemma 1. [27]: For the symmetric matrix $S = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}$, the following are equivalent.

(i) $S < 0$;
(ii) $S_{11} < 0$ and $S_{22} - S_{12}S_{11}^{-1}S_{12} < 0$;
(iii) $S_{22} < 0$ and $S_{11} - S_{12}S_{22}^{-1}S_{12} < 0$.

Lemma 2. [28]: Let $Y$, $D$, $E$ be constant matrices of appropriate dimensions, and $Y = Y^T$, then $Y + DFE + E^TF^TD^T < 0$, $\forall F : F^TF \leq I$ holds if and only if for some $\varepsilon > 0$, $Y + \varepsilon DD^T + \varepsilon^{-1}EE^T < 0$.

Lemma 3. [29]: For given real matrices $H$ and $E$ with appropriate dimensions, and the matrix $F = \text{diag}\{F_1, F_2, \ldots, F_l\}$, which satisfies the condition $F^TF \leq I$, the following matrix inequality holds:

$$HFE + E^TF^TH^T \leq \Gamma_s H^T + E^TG^{-1}E$$

where $F_l \in \mathbb{R}^{n \times n}$, $\Gamma_s = \text{diag}\{\gamma_1I_{l_1}, \gamma_2I_{l_2}, \ldots, \gamma_lI_{l_l}\}$, $\Gamma_s = \text{diag}\{\gamma_1I_1, \gamma_2I_2, \ldots, \gamma_lI_l\}$, $\gamma_1, \ldots, \gamma_l$ is a set of positive scalars.

Theorem 2. Given DNNs $S_i$ described in (2) under ETMs in Section 2, there is the state feedback controller (3) in such a way that the closed-
loop system (4) is asymptotically stable, if there exist matrices $R_{ij} > 0$, $\bar{Q}_i > 0$, $X_i > 0$, $\bar{H}_i$, $K_{di}$ and $K_{ij}$ for $j \in N_i$ of appropriate dimensions, such that satisfy

$$
\begin{bmatrix}
\Pi_{11} & \Pi_{12} & \Pi_{13} & \Pi_{15} & 0 & \Pi_{17} \\
\Pi_{22} & 0 & 0 & 0 & \Pi_{26} & 0 \\
\star & \Pi_{33} & 0 & 0 & \Pi_{56} & 0 \\
\star & \star & \Pi_{44} & 0 & 0 & 0 \\
\star & \star & \star & \Pi_{55} & 0 & 0 \\
\star & \star & \star & \star & \Pi_{66} & 0 \\
\star & \star & \star & \star & \star & \Pi_{77}
\end{bmatrix} < 0 \quad (10)
$$

where

$$
\begin{align*}
\Pi_{11} &= -X_i \\
\Pi_{12} &= A_d X_i + B_d K_d \\
\Pi_{13} &= A_d X_i + B_d K_d \\
\Pi_{15} &= \bar{A}_{ij} = \text{row}\{A_{ij}\} + B_i \text{row}\{K_{ij}\} \quad j \in N_i \\
\Pi_{17} &= L_{ij} \\
\Pi_{22} &= -X_i + \bar{Q}_i + (N - 1) \bar{H}_i \\
\Pi_{26} &= (E_{ai} X_i + E_{bi} K_i)^T \\
\Pi_{33} &= -X_i Q_i X_i \\
\Pi_{56} &= (E_{ai} X_i + E_{bi} K_{di})^T \\
\Pi_{44} &= \text{diag}\{R_{ij}\} - \text{diag}\{\bar{H}_i\} + N_j^T \Gamma_{ai} N_j \quad j \in N_i \\
\Pi_{55} &= -\text{diag}\{R_{ij}\} \quad j \in N_i \\
\Pi_{66} &= -\varepsilon_i I \\
\Pi_{77} &= -\Gamma_{ai}
\end{align*}
$$

Moreover, $\bar{Q}_i = -X_i Q_i X_i$, $\bar{H}_i = -X_i H_i X_i$, $K_i = \bar{K}_i X_i^{-1}$, $K_{di} = \bar{K}_d X_d^{-1}$ and $K_{ij}$, $j \in N_i$ are obtained directly.
Proof: By applying Lemma 1 to inequality (5), it can be seen that \( \Delta V(k) < 0 \) if the following inequality is satisfied:

\[
\begin{bmatrix}
-\frac{P_i^{-1}+\varepsilon_i D_i^T}{\varepsilon_i} A_{ii} - A_{adi} 0 A_{id} 0 \quad 0 0 0 0 0 \\
\gamma_i 0 0 0 0 0 0 0 0 \\
0 -\gamma_i 0 0 0 0 0 0 0 \\
0 0 0 \eta_i 0 0 0 0 0 \\
0 0 0 0 \eta_2 0 0 0 0
\end{bmatrix}
< 0.
\]

If inequality (11) holds, we can get (12) by Lemma 2.

\[
\begin{bmatrix}
-\frac{P_i^{-1}}{\varepsilon_i} A_{ii} - A_{adi} 0 A_{id} 0 \\
(A_{adi})^T \gamma_i 0 0 0 + \begin{bmatrix} D_i \\ 0 0 0 0 0 0 \\ 0 0 0 0 0 0 \end{bmatrix} F_i \begin{bmatrix} D_i \\ 0 0 0 0 0 0 \end{bmatrix} \\
0 0 0 0 0 0 0 0 0 \\
0 0 0 0 0 0 0 0 0 \\
0 0 0 0 0 0 0 0 0
\end{bmatrix}
\]

\[
= \begin{bmatrix} L_{ij} \\ 0 0 0 0 N_{ij} \end{bmatrix}^T F_i \begin{bmatrix} L_{ij} \\ 0 0 0 0 N_{ij} \end{bmatrix} < 0
\]

by Lemma 3, a sufficient condition for matrix inequality (11) to hold for all allowed uncertainties is that there exists a set of positive scalars \( \varepsilon_i, \gamma_i, i = 1, 2, \ldots, N \), such that

\[
\begin{bmatrix}
-\frac{P_i^{-1}}{\varepsilon_i} A_{ii} - A_{adi} 0 A_{id} 0 \\
A_{adi}^T \gamma_i 0 0 0 + \varepsilon_i \begin{bmatrix} D_i \\ 0 0 0 0 0 0 \\ 0 0 0 0 0 0 \end{bmatrix} F_i \begin{bmatrix} D_i \\ 0 0 0 0 0 0 \end{bmatrix} \\
0 0 0 0 0 0 0 0 0 \\
0 0 0 0 0 0 0 0 0 \\
0 0 0 0 0 0 0 0 0
\end{bmatrix}
\]

\[
= \begin{bmatrix} L_{ij} \\ 0 0 0 0 N_{ij} \end{bmatrix}^T F_i \begin{bmatrix} L_{ij} \\ 0 0 0 0 N_{ij} \end{bmatrix} < 0
\]

(12)

Then inequality (11) holds where

\[
\begin{align*}
\Gamma_{ai} &= \text{diag}\{\gamma_{a1}, \gamma_{a2}, \ldots, \gamma_{aN}\} \\
\Gamma_{bi} &= \text{diag}\{\gamma_{b1}, \gamma_{b2}, \ldots, \gamma_{bN}\}
\end{align*}
\]

By defining \( P_i = P_i^{-1} \), and multiplying \( \Gamma_{ai} P_i^{-1} \) to both sides of (11), the LMI (10) is obtained. This completes the proof. \( \square \)

Therefore, by solving LMI (10) using one of the existing convex programming tools such as LMI toolbox MATLAB, the asymptotically stable feedback controller will be straightforwardly designed for each subsystem.

**4 AGC SYSTEM DESIGN**

In this section, as is shown in Figure 1, a four-area interconnected power system with wind turbines is adopted to demonstrate the design effectiveness of the proposed event-triggered AGC scheme for load frequency control system. The system parameters of the four-area interconnected power system used in simulations are as follows [20] (see also Table 1).

The system is composed of a thermal power plant, variable speed wind turbines (VSWTs) and hydropower plant, which is used to design a distributed networked AGC system. As shown in Figures 1 and 2 wind turbines with three blades, a horizontal axis and variable speed. In addition, area 4 is a thermal power plant, area 2 and area 3 are hydropower plants. The details of the regional composition and mathematical representation of wind turbines, thermal power plants and hydroelectric power plants can be seen in [20]. In addition, area 1 includes an aggregated wind model consisting of 30 VSWTs units of 2 MW.

The state vectors for area \( i \) are defined as follows:

\[
\begin{align*}
\Delta x_i &= \begin{bmatrix} \Delta P_{a1,i} & \Delta P_{a2,i} & \Delta X_{g1,i} & \Delta X_{g2,i} & \Delta \omega_{s1} & \Delta \omega_{s2} & \Delta \theta \end{bmatrix}^T, \quad \text{for } i = 1 \\
\Delta x_i &= \begin{bmatrix} \Delta P_{a1,i} & \Delta X_{g1,i} & \Delta X_{g2,i} \end{bmatrix}^T, \quad \text{for } i = 2, 3 \\
\Delta x_i &= \begin{bmatrix} \Delta P_{a1,i} & \Delta \omega_{s1} & \Delta \omega_{s2} \end{bmatrix}^T, \quad \text{for } i = 4
\end{align*}
\]

To obtain the control law (3), according to Wang et al. [30], the sampling time \( T_s = 20 \text{ ms} \) of four-area interconnected system is chosen in this paper. The changes in parameter uncertainties are within 20%. The corresponding controller gain \( K_i \), \( K_{di} \) and \( K_{ij} \) could be obtained based on MATLAB LMI solver.
In order to verify the effectiveness of the proposed method, the following two cases are considered:

**Case 1:** ETMs, sensors node and actuators node with constant threshold \( \delta_{si}, \delta_{ai} \), load disturbance change 0.01 p.u. under the system parameter uncertainties.

**Case 2:** ETMs, sensors node and actuators node with constant threshold \( \delta_{si}, \delta_{ai} \), load disturbance change 0.1 p.u. under the system parameter uncertainties.

A simultaneous step load change of 0.01 and 0.1 p.u. in four areas. Figures 3 and 4 show the frequency deviation and tie-line active power deviation according to 0.1 p.u. step load disturbance (Case 2: \( \delta_{si} = 0.02, \delta_{ai} = 0.02 \) (solid line); \( \delta_{si} = 0.06, \delta_{ai} = 0.06 \) (dotted line)).
power deviation of the four areas power system, respectively. It can be seen that the frequency deviation and tie-line power deviation reach zero with the designed event-triggered robust controller. Moreover, simulation results in Figures 5 and 6 show that with the increase of disturbance amplitude and threshold value, the corresponding overshoot of the system will increase and the regulation time will be longer.

The proposed event-triggered AGC scheme can reduce the number of signal transmission by increasing the event-triggered parameters, so as to improve the effective utilization of network bandwidth, which is the guarantee of system performance. Pitch control, which a series of mechanical components execute the power regulation command, the actuator’s response speed is slower than the speed control, and the frequency action of pitch angle will also aggravate the wear of the wind turbines and increase the maintenance cost of the wind turbines. Therefore, the relationship between speed and pitch angle should be properly coordinated when the wind turbines participate in frequency modulation. It can effectively avoid the number of mechanical actions and avoid the frequent start and stop of the corresponding actuators in thermal power plant and hydropower plant, so as to avoid the abrasion caused by the frequent adjustment of the wind turbines blade control system. However, too large event-triggered parameter may lead the proposed condition (10) in Theorem 2 infeasible, that is, it is inappropriate to ensure the prescribed system performance criteria of the controlled system with too large event-triggered parameter.

### 5 CONCLUSION

With the development and increasing complexity of modern power system, the control of geographically distributed power grids with the usual traditional point-to-point connection will become difficult or even impracticable. In this paper, considering the large-scale networked multi-area power system with wind turbines, a control scheme of networked distributed AGC system based on ETMs is proposed. Dynamic model of DNCs model considering limited communication resources, networked-induced delays and system parameter uncertainty is established based on the problems encountered in the network data information transmission of each subsystem (state delay, system parameter uncertainty, interconnection link information transmission delay and packet loss). Then, by constructing Lyapunov–Krasovskii function, the asymptotic stability criterion of the DNCSs is given based on the feasible solution of LMI. An event-triggered distributed networked controller is designed to ensure the stability and robustness of the DNCSs. The proposed AGC structure is applied to the multi-area networked power system AGC considering wind turbines, which demonstrates the effectiveness of the proposed scheme.

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