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A Dynamic State Feedback Based Control Strategy and Simulation for Massively Interrelated Power System with Multi-overlapping Distributed limited-time Connectivity

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Abstract: This paper explores a practical perspective on the distributed $H\infty$ control strategy for limited-time control challenges in massively interrelated systems. For a specific type of massively interrelated systems characterized by a networked topological configuration, a robust, distributed control method for limited-time $H\infty$ connectivity stabilization, using dynamic feedback and addressing multiple overlaps, is proposed. It expands the state space of power systems and decomposes the system into a sequence of coupled subsystems in reverse order. Firstly, a distributed limited-time $H\infty$ dynamic feedback controller is designed for the subsystem, and then the designed repetitive controllers are compressed into the initial area. The synchronization of control strategies can be accomplished, and the system can be continuously stabilized in limited-time $H\infty$. Ultimately, the introduced approach is employed in a four-region interrelated system featuring a network architecture, and simulation outcomes validate both its practicality and efficacy. This study investigates the distributed limited-time $H\infty$ control of massively interrelated systems from an innovative viewpoint. This paper introduces a novel method for stabilizing massively interrelated, networked systems. It uses dynamic feedback, is robust and distributed, ensuring limited-time $H\infty$ stability. This involves expanding the system's scope and dividing it into coupled subsystems in a periodic reversal order. Firstly, a distributed limited-time $H\infty$ dynamic feedback controller is developed for the subsystem. Afterwards, the duplicated controllers are compressed back into the original area. Control algorithms can be synchronized. The law of contract can guarantee the continued stability of the system within a specific time frame, as quantified by $H\infty$. The proposed method is ultimately implemented on a networked four-region interrelated system, and the modeling outcomes clearly showcase the practicality and efficacy of the suggested approach.

Keywords: connective stability; interrelated systems; $H\infty$ control; limited-time; LMI; multi-overlapping distributed control

1 INTRODUCTION

With the increasing attention of the world towards the preservation of the environment and sustainable growth, the use of traditional fossil energy is limited, the advancement and use of renewable energy sources is greatly valued. As a clean and renewable energy source, wind energy development and utilization has become a crucial element in the worldwide shift towards sustainable energy. However, wind energy is also intermittent and uncertain, mainly reflected in the wind farm output power and will fluctuate with the change of wind speed. This volatility will adversely affect the stability and power quality of the power grid, and may even lead to grid failures or power outages. Therefore, studying the stability of wind energy systems and ensuring the secure and efficient functioning of electrical grids has become a major area of interest in the present energy sector. Because wind farms are usually distributed over a wide area, distributed control of each wind farm is required. At the same time, each wind farm is connected to each other through the power grid, forming an interrelated system. Therefore, when solving the stability of wind farm power system, we need to consider a class of massively interrelated systems. For linear interrelated systems, distributed control strategies [1-4] and LMI (Linear Matrix Inequality) [5-8] technique are often adopted.

However, solving LMIs with high dimensionality can be challenging, and the presence of too many subsystems may lead to situations where no solution exists. To address this limitation, a large amount of literature uses overlapping distributed control technique [9, 10]. However, only certain variable in subsystems is regarded as overlapping parts in this literature. In [11], the scenario in which the complete subsystem is treated as an overlapping component is taken into account. At present, literatures [12-14], distributed methods of control based on feedback from the state, feedback based on static outputs, and feedback derived from dynamic outputs are proposed for overlapping systems. Furthermore, it happens that dynamic state feedback controllers exhibit a greater capacity to fulfill an extensive array of specifications in comparison to their static counterparts. They possess the ability to more thoroughly integrate and harness both historical and contemporary information pertaining to the system, thereby manifesting notable superiority in terms of control performance, resilience to disturbances, and versatility across diverse applications. Conversely, controller designs that are contingent upon specific modes often lean towards a less conservative approach. So far, dynamic feedback has been applied in many fields. But most of the findings in this area relate to stability and performance criteria established within a limited-time frame. However, in numerous real-world scenarios, the main focus is on how the system performs within a limited-time frame. In wind farms, this usually means that under external disturbances such as wind speed changes and grid failures, the wind farm power system can recover and maintain stable operation within a brief time frame. The relevant concepts of limited-time stability were introduced for the first time in [15]. In what follows, a mass of results [16-19] have been reported about limited-time stability.

It is well known that $H\infty$ control is a good tool to tackling the external disturbances [20, 21]. Combining limited-time with $H\infty$ control, that is, limited-time $H\infty$ control has been intensively examined in [22-27]. The issue of limited-time $H\infty$ control has garnered considerable attention within the realm of diverse system types. This encompasses continuous linear systems, linear stochastic systems, discrete-time systems with unique uncertainties, time-varying delay systems, switched systems with time-dependent delays, linear time-invariant systems, and time-varying systems. Nonetheless, it is noteworthy that the aforementioned findings are primarily rooted in investigations conducted on individual, specific system paradigms, notably nonlinear time-delayed Hamiltonian systems. This underscores the need for a more comprehensive and generalized framework to address the limited-time $H\infty$ control problem across a broader spectrum of system configurations.

In [28], the method of distributed limited-time $H\infty$ control is used for interrelated linear systems. Furthermore, in [29], a distributed limited-time $H\infty$ connection control approach is suggested for a category of massively interrelated systems with an expanding structure. This approach serves as the theoretical foundation for the online expansion of massively interrelated systems.

Nevertheless, to date, there has been no research on the issue of multi-overlapping distributed limited-time $H\infty$ connective stabilization based on state feedback that is dynamic for a specific category of massively interrelated systems. It is of great significance to study this issue for promoting the sustainable development of wind power industry and improving the operating efficiency of wind farms.

In this paper, distributed limited-time $H\infty$ control issue of massively interrelated systems [30] is considered from a different perspective. Due to the complexity of massive systems, it is difficult to directly design a limited-time $H\infty$ controller to stabilize interrelated systems. The core principle of the inclusion principle involves the effective management and control of large-scale and structurally complex systems by employing methodologies such as system decomposition and aggregation, hierarchical and decentralized control strategies. These approaches aim to optimize overall system performance and stability by enabling a more manageable and coherent system structure. By breaking down complex systems into more tractable components and then aggregating them in a manner that retains essential system properties, this principle facilitates enhanced decision-making and control capabilities, ultimately contributing to the achievement of optimal system behavior. On the basis of inclusion principle, breaking down the massive system into a series of coupled subsystems. Therefore, controller design of massive systems is changed as that of each pair of subsystems. The contributions of this work are including:

(i) According to inclusion principle, multi-overlapping distributed control technique is utilized to simplify the complexity of controller design.

(ii) In this work, connective stability of multi-overlapping limited-time is considered for the massive systems.

(iii) The issue of multi-overlapping controllers is addressed through the implementation of a novel proposed scheme. Therefore, multi-overlapping distributed control can be accomplished based on dynamic state feedback.

(iv) Multi-overlapping limited-time $H\infty$ distributed controller is obtained for a class of interrelated systems featuring a networked topological arrangement.

(v) The suggested method is used for a four-area interrelated system with a networked framework. Simulation outcomes demonstrate the practicality and efficacy of the suggested methodology.

The subsequent parts of this paper are arranged in the manner outlined below. In Section 2, system model is given and multi-overlapping structural decomposition method is carried out. Section 3 presents the framework for paired subsystems and some preliminary results. Section 4 outlines the necessary conditions that must be met for existence of distributed control laws based on dynamic state feedback for limited-time $H\infty$ connective boundedness of massively interrelated systems featuring a networked topological arrangement. In Section 5, an illustration is conducted to showcase the efficacy of the suggested methodology. The discussion of the conclusions can be found in Section 6.

2 SYSTEM MODEL AND DECOMPOSITION OF MULTI-OVERLAPPING STRUCTURES

2.1 Mathematical Framework of Massive Systems Featuring a Networked Topological Arrangement

Considering a massively interrelated system consisting of N subsystems, where each subsystem is interrelated with the rest to form a networked topology, we can construct a mathematical model to describe its dynamic behavior. The model not only includes the internal dynamic characteristics of each subsystem, but also reflects the interaction and interconnection between subsystems. Here, the mathematical framework S can be characterized by:

$$\begin{aligned} \dot{\chi}(t) &= A\chi(t) + Bu(t) + \Gamma\omega(t) \\ z(t) &= Cx(t) \end{aligned} \tag{1}$$

where $x \in R^n$, $u \in R^m$, $z \in R^l$ and $\omega \in R^r$ are the system's state, input for control, output, and vectors of external interference, individually. The coefficient matrices of (30) are as follows:

$$A = \begin{bmatrix} A_{11} & A_{12} & \cdots & A_{1N} \\ A_{21} & A_{22} & \cdots & A_{2N} \\ \vdots & \vdots & \cdots & \vdots \\ A_{N1} & A_{N2} & \cdots & A_{NN} \end{bmatrix}$$

$$B = \text{blockdiag}\left(B_{11}, B_{22}, ..., B_{NN}\right)$$

$$C = \text{blockdiag}\left(C_{11}, C_{22}, ..., C_{NN}\right)$$

$$\Gamma = \text{blockdiag}\left(\Gamma_{11}, \Gamma_{22}, ..., \Gamma_{NN}\right)$$

The matrix A reflects the interrelated configuration of the system.

2.2 Multi-Overlapping Structural Decomposition of Interrelated Systems Featuring a Networked Topological Arrangement

For the system (30), we use the large system inclusion principle to achieve decomposition of multiple overlapping structures. In this process, each subsystem is considered an overlapping component of the other subsystems. According to [31], we extend the system with the following specific equations.

$$\begin{aligned} \tilde{A} &= VAU + M_A, \tilde{B} = VBQ + M_B \\ \tilde{C} &= TCU + M_C, \tilde{\Gamma} = VTQ + M_\Gamma \end{aligned} \tag{2}$$

where V, U, Q and T constitute the matrices for expansion, and M_A, M_B, M_C and M_Γ are the compensation matrices. The selection of these matrices is as follows:

$$V = bkd\left[\frac{\overbrace{I_{n_1}, ..., I_{n_1}}^{N-1}, ..., \overbrace{I_{n_N}, ..., I_{n_N}}^{N-1}}{N}\right]$$

$$U = \frac{1}{N-1} bkd\left[\frac{\overbrace{I_{n_1}, ..., I_{n_1}}^{N-1}, ..., \overbrace{I_{n_N}, ..., I_{n_N}}^{N-1}}{N}\right]$$

$$Q = \frac{1}{N-1} bkd\left[\frac{\overbrace{I_{m_1}, ..., I_{m_1}}^{N-1}, ..., \overbrace{I_{m_N}, ..., I_{m_N}}^{N-1}}{N}\right]$$

$$T = bkd\left[\frac{\overbrace{I_{l_1}, ..., I_{l_1}}^{N-1}, ..., \overbrace{I_{l_N}, ..., I_{l_N}}^{N-1}}{N}\right]$$

$$M_A = \frac{1}{N-1}\begin{bmatrix} (N-2)A_{ij} & \cdots & -A_{ij} \\ -A_{ij} & \cdots & -A_{ij} \\ \vdots & \ddots & \vdots \\ -A_{ij} & \cdots & (N-2)A_{ij} \end{bmatrix}, i = j$$

$$M_A = \frac{1}{N-1}\begin{bmatrix} -A_{ij} & \cdots & (N-2)A_{ij} & \cdots & -A_{ij} \\ -A_{ij} & \cdots & (N-2)A_{ij} & \cdots & -A_{ij} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ -A_{ij} & \cdots & (N-2)A_{ij} & \cdots & -A_{ij} \end{bmatrix}, i \neq j$$

$$M_\Delta = \frac{1}{N-1}\begin{bmatrix} (N-2)\Delta_{ij} & \cdots & -\Delta_{ij} \\ -\Delta_{ij} & \cdots & -\Delta_{ij} \\ \vdots & \ddots & \vdots \\ -\Delta_{ij} & \cdots & (N-2)\Delta_{ij} \end{bmatrix}, i = j$$

$$M_\Delta = 0, i \neq j$$

Where *bkd* means block diag and it is noted that for M_A with $i \neq j$, if $i < j$, then $(N-2)A_{ij}$ locates in the $(j-i)^{\text{th}}$ column; otherwise, it locates in the $N+(j-i)^{\text{th}}$ column. It follows from Eq. (2) that the system S is expanded to the system $\tilde{S}$ which is as follows:

$$\begin{aligned} &\tilde{\chi}(t) = \tilde{A}\tilde{x}(t) + \tilde{B}\tilde{u}(t) + \tilde{\Gamma}\tilde{\omega}(t) \\ &\tilde{z}(t) = \tilde{C}\tilde{x}(t) \end{aligned} \tag{3}$$

where $\tilde{x} \in R^{\tilde{n}}, \tilde{u} \in R^{\tilde{m}}, \tilde{z} \in R^{\tilde{l}}$ and $\tilde{\omega} \in R^{\tilde{r}}$ are the system's state, input for control, output, and vectors of external interference of the expanded system, individually. It can be deduced from the process of expanding that $n \leq \tilde{n}, m \leq \tilde{m}, l \leq \tilde{l}, r \leq \tilde{r}$. The expanded coefficient matrices $\tilde{A}, \tilde{B}, \tilde{C}, \tilde{\Gamma}$ are described in the following form:

$$\tilde{A} = bkd\left(A_{ij}, A_{ij}, ..., A_{ij}\right), i = j$$

$$\tilde{A} = \begin{bmatrix} 0 & \cdots & A_{ij} & \cdots & 0 \\ 0 & \cdots & A_{ij} & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & \cdots & A_{ij} & \cdots & 0 \end{bmatrix}$$

$$\tilde{\Delta} = \text{bkd}\left(\Delta_{ii}, \Delta_{ii}, ..., \Delta_{ii}\right)$$

where $i, j = 1, 2, ..., N(N-1)$. It should be pointed out that for A, if $i < j$, then A_{ij} locates in the $(j-i)^{\text{th}}$ column; otherwise, it locates in the $\left[N+(j-i)^{\text{th}}\right]$ column.

Next the system $\tilde{S}$ need to be permutated as pair-wise subsystems. It follows from Definition 1, Lemma 1 and (4) in [14] that $\frac{N(N-1)}{2}$ pair-wise subsystems S_{ij} is obtained which is defined by $S_{12}, S_{23}, S_{13}, ..., S_{(N-1)N}, S_{(N-2)N}, ..., S_{2N}, S_{1N}$ where $i = j-k, j = 2, 3, ..., N, k = 1, 2, ..., j-1$.

3 THE MODEL OF PAIR-WISE SUBSYSTEMS BASED ON DYNAMIC STATE FEEDBACK AND PRELIMINARY RESULTS

3.1 The Model of Pair-Wise Subsystems Based on Dynamic State Feedback

After completing the decomposition process of multiple overlapping, the system (30) appears as a series of coupled subsystems in the extended space. Consider the interconnections among these subsystems, each pair-wise subsystem S_{ij} can be described as follows:

$$\begin{aligned} &\dot{x}_i(t) = A_{ii}x_i(t) + B_{ii}u_i(t) + \Gamma_{ii}\omega_i(t) + e_{ij}A_{ij}x_j(t) \\ &z_i(t) = C_{ii}x_i(t) \\ &\dot{x}_j(t) = A_{jj}x_j(t) + B_{jj}u_j(t) + \Gamma_{jj}\omega_j(t) + e_{jj}A_{ji}x_i(t) \\ &z_j(t) = C_{jj}x_j(t) \end{aligned} \tag{4}$$

Where $i = j-k, j = 2, 3, ..., N, k = 1, 2, ..., j-1. e_{ij}$ constitutes a part of the connective matrix $E = (e_{ij}). e_{ij} = 1$ represents that S_j has an effect on S_i, $e_{ij} = 0$ indicates that S_j does not influence on S_i. Here, assume that each subsystem lacks self-interconnection, that is, $e_{ii} = 0$. Define $h_i(x_j(t), E) = e_{ij}A_{ij}x_j(t)$ and $h_j(x_i(t), E) = e_{ji}A_{ji}x_i(t)$.

In this work, we construct the following pair of dynamic state feedback controllers to stabilize system (4)

$$\begin{aligned}\dot{\chi}_{ki}(t)&=A_{ki}\chi_{ki}(t)+B_{ki}\chi_i(t)\\ \dot{\chi}_{ki}(t)&=A_{ki}\chi_{ki}(t)+B_{ki}\chi_i(t)\end{aligned}\tag{5}$$

$$\begin{aligned}\dot{\chi}_{kj}(t)&=A_{kj}\chi_{kj}(t)+B_{kj}\chi_j(t)\\ u_j(t)&=C_{kj}\chi_{kj}(t)+D_{kj}\chi_j(t)\end{aligned}\tag{6}$$

where: $x_{ki}\in R^{ki}$ and $x_{kj}\in R^{kj}$ are the state vectors of the dynamic state feedback controllers, $A_{ki}, B_{ki}, C_{ki}, D_{ki}, A_{kj}, B_{kj}, C_{kj}$ and D_{kj} are constant matrices with appropriate dimensionality. Substituting Eq. (5) and Eq. (6) into Eq. (4), it yields.

$$\begin{aligned}&\begin{bmatrix}\dot{x}_i(t)\\ \dot{x}_{ki}(t)\end{bmatrix}=\left(\begin{bmatrix}A_{ii}&0\\0&0\end{bmatrix}+\begin{bmatrix}B_{ii}&0\\0&I\end{bmatrix}\begin{bmatrix}D_{ki}&C_{ki}\\B_{ki}&A_{ki}\end{bmatrix}\right)\\ &\times\begin{bmatrix}x_i(t)\\x_{ki}(t)\end{bmatrix}+\begin{bmatrix}\Gamma_{ii}\\0\end{bmatrix}\omega_i(t)+\begin{bmatrix}h_i(x_j,E)\\0\end{bmatrix}\\ &z_i(t)=\begin{bmatrix}C_{ii}&0\end{bmatrix}\begin{bmatrix}x_i(t)\\x_{ki}(t)\end{bmatrix}\\ &\begin{bmatrix}\dot{x}_j(t)\\ \dot{x}_{kj}(t)\end{bmatrix}=\left(\begin{bmatrix}A_{jj}&0\\0&0\end{bmatrix}+\begin{bmatrix}B_{jj}&0\\0&I\end{bmatrix}\begin{bmatrix}D_{kj}&C_{kj}\\B_{kj}&A_{kj}\end{bmatrix}\right)\\ &\times\begin{bmatrix}x_j(t)\\ \dot{x}_{ki}(t)\end{bmatrix}+\begin{bmatrix}\Gamma_{jj}\\0\end{bmatrix}\omega_j(t)+\begin{bmatrix}h_j(x_i,E)\\0\end{bmatrix}\\ &z_j(t)=\begin{bmatrix}C_{jj}&0\end{bmatrix}\begin{bmatrix}x_j(t)\\x_{kj}(t)\end{bmatrix}\end{aligned}\tag{7}$$

In order to express simply, Eq. (7) is rewritten as the subsequent concise representation:

$$\begin{aligned}\dot{\hat{x}}_i(t)&=\left(\hat{A}_i+\hat{B}_i\hat{K}_i\right)\hat{x}_i(t)+\hat{\Gamma}_i\omega_i(t)+\hat{h}_i\left(x_j(t),E\right)\\ z_i(t)&=\hat{C}_i\hat{x}_i(t)\\ \dot{\hat{x}}_j(t)&=\left(\hat{A}_j+\hat{B}_j\hat{K}_j\right)\hat{x}_j(t)+\hat{\Gamma}_j\omega_j(t)+\hat{h}_j\left(x_i(t),E\right)\\ z_j(t)&=\hat{C}_j\hat{x}_j(t)\end{aligned}$$

where:

$$\begin{aligned}&\hat{A}_i=\begin{bmatrix}A_{ii}&0\\0&0\end{bmatrix},\hat{A}_j=\begin{bmatrix}A_{jj}&0\\0&0\end{bmatrix}\\ &\hat{B}_i=\begin{bmatrix}B_{ii}&0\\0&I\end{bmatrix},\hat{B}_j=\begin{bmatrix}B_{jj}&0\\0&I\end{bmatrix}\\ &\hat{C}_j=\begin{bmatrix}C_{ii}&0\end{bmatrix},\hat{C}_j=\begin{bmatrix}C_{jj}&0\end{bmatrix}\\ &\hat{\Gamma}_j=\begin{bmatrix}\Gamma_{ii}\\0\end{bmatrix},\hat{\Gamma}_j=\begin{bmatrix}\Gamma_{jj}\\0\end{bmatrix}\\ &\hat{K}_i=\begin{bmatrix}D_{ki}C_{ki}\\B_{ki}A_{ki}\end{bmatrix},\hat{K}_j=\begin{bmatrix}D_{kj}C_{kj}\\B_{kj}A_{kj}\end{bmatrix}\\ &\hat{x}_i(t)=\left[x_i^Tx_{ki}^T\right]^T,\hat{x}_j(t)=\left[x_j^Tx_{kj}^T\right]^T\end{aligned}$$

$$\int_0^\infty\hat{\omega}^T(t)\hat{\omega}(t)\mathrm{d}t<d^2,d>0$$

$$\hat{h}_i\left(x_j,E\right)=\left[h_i^T\left(x_j,E\right)0\right]^T,\hat{h}_j\left(x_i,E\right)=\left[h_j^T\left(x_i,E\right)0\right]^T$$

By combining two subsystems using feedback-oriented dynamic regulator, we are able to realize the subsequent closed-loop setup:

$$\begin{aligned}\hat{x}(t)&=\left(\hat{A}_D+\hat{B}_D\hat{K}_D\right)\hat{x}(t)+\hat{\Gamma}_D\hat{\omega}(t)+\hat{h}\left(\hat{x}(t),E\right)\\ &=\hat{\hat{A}}_D\hat{x}(t)+\hat{\Gamma}_D\hat{\omega}(t)+\hat{h}\left(\hat{x}(t),E\right)\\ \hat{z}(t)&=\hat{C}_D\hat{x}(t)\end{aligned}\tag{8}$$

where:

$$\begin{aligned}&\hat{x}(t)=\left[\hat{x}_i^T(t),\hat{x}_j^T(t)\right]\\ &\hat{z}(t)=\left[z_i^T(t),z_j^T(t)\right]^T\\ &\hat{\omega}(t)=\left[\omega_i^T(t),\omega_j^T(t)\right]^T\\ &\hat{A}_D=bkd\left(\hat{A}_i,\hat{A}_j\right),\hat{B}_D=bkd\left(\hat{B}_i,\hat{B}_j\right)\\ &\hat{C}_D=bkd\left(\hat{C}_i,\hat{C}_j\right),\hat{\Gamma}_D=bkd\left(\hat{\Gamma}_i,\hat{\Gamma}_j\right)\\ &\hat{K}_D=bkd\left(\hat{K}_i,\hat{K}_j\right)\\ &\hat{h}\left(\hat{x}(t),E\right)=\left[\hat{h}_i^T\left(x_j(t),E\right),\hat{h}_j^T\left(x_i(t),E\right)\right]^T\\ &\hat{\hat{A}}=\begin{bmatrix}\hat{A}_i+\hat{B}_i\hat{K}_i&0\\0&\hat{A}_j+\hat{B}_j\hat{K}_j\end{bmatrix}\end{aligned}$$

3.2 Preliminary Results

The following preliminaries are given firstly before the main result of this paper is obtained.

Assumption 1. For a specific constant T, the external disruption $\hat{\omega}(t)$ varies over time and meets the specified constraint

$$\int_0^\infty\hat{\omega}^T(t)\hat{\omega}(t)\mathrm{d}t<d^2,d>0\tag{9}$$

Assumption 2. The item of interconnection $\hat{h}\left(\hat{x}(t),E\right)$ is unknown and fulfills the subsequent inequality.

$$\hat{h}^T\left(\hat{x}(t),E\right)\hat{h}\left(\hat{x}(t),E\right)\leq\hat{\beta}^2\hat{x}^T(t)\hat{Q}_D^T\hat{Q}_D\hat{x}(t)\tag{10}$$

where $\hat{\beta}>0$ is a limiting factor and $\hat{Q}_D$ is a interrelated matrix of constraints.

Next, several useful definitions and lemmas are presented.

Definition 1 [29]. (limited-time connective stability). Given a positive delimited matrix R, three constant positive numbers c_1, c_2, T with $0<c_1<c_2$, and the system Eq. (8) is reported that limited-time

connectively bounded in relation to $\left(c_1, c_2, T, d, R\right)$, if $\hat{x}_0^{\mathrm{T}} R\hat{x}_0 \le c_1$, then: $\hat{x}^{\mathrm{T}}\left(t\right)R\hat{x}\left(t\right) < c_2, \forall t \in \left[0, T\right]$.

For any $E_{ij}, i = 1, ..., N, j = 1, ..., N$ and any non zero $\widehat{\omega}\left(t\right)$ satisfying Eq. (9).

Definition 3 [29]. (limited-time $H\infty$ connective boundedness). The system outlined in Eq. (8) is reported to be limited-time $H\infty$ connectively bounded if:
(i) The system with feedback control Eq. (8) is limited-time connectively bounded.
(ii) Starting with no initial conditions:

$$\int_0^t \| \hat{z}\left(s\right) \|^2 \, ds \langle y^2 \int_0^t \| \hat{\omega}\left(s\right) \|^2 \, ds \tag{11}$$

for any $E_{ij}, i = 1, ..., N, j = 1, ..., N$ and any non zero $\hat{\omega}\left(t\right)$ satisfying Eq. (9) where γ is a constant positive number and $t \in \left[0,T\right]$.

To achieve the primary findings of this paper, the next two lemmas are introduced.

Lemma 1 [29]. System Eq. (8) is limited-time connectively bounded in relation to $\left(c_1, c_2, T, d, R\right)$ if there exist three scalars $\alpha \ge 0, \hat{\beta} > 0, \gamma > 0$ as well as the interrelated matrix of constraints $\hat{Q}_D$ and a symmetric positive delimited matrix P_D such that:

$$\begin{bmatrix} 0 & \hat{P}_D \hat{\Gamma}_D & \hat{P}_D \\ \hat{\Gamma}_D^T \hat{P}_D & -y^2 I & 0 \\ \hat{P}_D & 0 & -1 \end{bmatrix} \langle 0 \tag{12}$$

and:

$$\frac{c_1}{\lambda_{\min}\left(P_D\right)} + d^2\gamma^2 \langle \frac{c_2 e^{-aT}}{\lambda_{\max}\left(P_D\right)} \tag{13}$$

With $\Theta = \hat{\hat{A}}_D^{\mathrm{T}} \hat{P}_D + \hat{P}_D \hat{\hat{A}}_D - \alpha \hat{P}_D + \hat{\beta}^2 \hat{Q}_D^{\mathrm{T}} \hat{Q}_D, \hat{P}_D = R^{1/2} P_D^{-1} R^{1/2}$ and $\lambda_{\min}\left(P_D\right), \lambda_{\max}\left(P_D\right)$ representing the smallest and largest eigenvalues of P_D, individually.

Lemma 2 [29]. System Eq. (8) is limited-time $H\infty$ connectively bounded in relation to $\left(c_1, c_2, T, d, R\right)$ if there are three scalars $\alpha \ge 0, \hat{\beta} > 0, \gamma > 0$, as well as the interrelated matrix of constraints $\hat{Q}_D$ and a symmetric positive delimited matrix P_D such that:

$$\begin{bmatrix} 0 & \hat{P}_D \hat{\Gamma}_D & \hat{P}_D \\ \hat{\Gamma}_D^T \hat{P}_D & -y^2 e^{-aT} I & 0 \\ \hat{P}_D & 0 & -1 \end{bmatrix} \langle 0 \tag{14}$$

and:

$$\frac{c_1}{\lambda_{\min}\left(P_D\right)} + d^2\gamma^2 \langle \frac{c_2 e^{-aT}}{\lambda_{\max}\left(P_D\right)} \tag{15}$$

With:

$$\overline{\Theta} = \hat{A}_D^{\mathrm{T}} \hat{P}_D + \hat{P}_D \hat{\hat{A}}_D - \alpha \hat{P}_D + \hat{C}_D^{\mathrm{T}} \hat{C}_D + \hat{\beta}^2 \hat{Q}_D^{\mathrm{T}} \hat{Q}_D,$$
$$\hat{P}_D = R^{1/2} P_D^{-1} R^{1/2}$$

4 MAIN RESULTS

4.1 Limited-time $H\infty$ Controller Design for Pair-Wise Subsystems Based on Dynamic State Feedback

The primary conclusion is presented in Theorem 1, which is founded on Lemma 1 and Lemma 2 in Section 3.

Theorem 1. The distributed limited-time $H\infty$ connective control issue for Eq. (8) can be resolved using dynamic state feedback controller Eq. (5) and Eq. (6) if there exist three scalars $\alpha \ge 0, \hat{\varepsilon} > 0$, $\gamma > 0$ as well as matrix $\hat{M}_D$, the interrelated matrix of constraints $\hat{Q}_D$, symmetric positive delimited matrice $\hat{Y}_D$ and P_D such that:

$$\min\left(\gamma^2 + \hat{\varepsilon} + c_2\right) \tag{16}$$

$$\begin{bmatrix} \hat{\psi}_D & \hat{\Gamma}_D & I & \hat{Y}_D \hat{Q}_D^T & \hat{Y}_D \hat{C}_D^T \\ \hat{\Gamma}_D^T & -\gamma^2 e^{-aT} I & 0 & 0 & 0 \\ I & 0 & -I & 0 & 0 \\ \hat{Q}_D \hat{Y}_D & 0 & 0 & -\hat{\varepsilon} I & 0 \\ \hat{C}_D \hat{Y}_D & 0 & 0 & 0 & -I \end{bmatrix} \langle 0 \tag{17}$$

and:

$$\frac{c_1}{\lambda_{\min}\left(P_D\right)} + d^2\gamma^2 \langle \frac{c_2 e^{-aT}}{\lambda_{\max}\left(P_D\right)} \tag{18}$$

where:

$$\hat{\psi}_D = \hat{Y}_D \hat{A}_D^T + \hat{A}_D \hat{Y}_D + \hat{M}_D^T \hat{B}_D^T + \hat{B}_D \hat{M}_D - a\hat{Y}_D$$
$$\hat{\varepsilon} = \frac{1}{\hat{\beta}^2}$$
$$\hat{Y}_D = \hat{P}_D^{-1}$$
$$P_D = R^{1/2} P_D^{-1} R^{1/2}$$

With $\lambda_{\min}\left(P_D\right)$ and $\lambda_{\max}\left(P_D\right)$ indicating the minimum and maximum characteristic values of P_D, individually. The determination of the control principle may be established by $\hat{K}_D = \hat{M}_D \hat{Y}_D^{-1}$.

Proof. In accordance with Lemma 1 and Lemma 2, let $\hat{M}_D = \hat{K}_D \hat{Y}_D$. Then, (17) can be expressed as being equivalent to the inequality stated below.

$$\begin{bmatrix} \hat{\psi}_D & \hat{\Gamma}_D & I & \hat{Y}_D\hat{Q}_D^T & \hat{Y}_D\hat{C}_D^T \\ \hat{\Gamma}_D^T & -\gamma^2 e^{-\alpha T} I & 0 & 0 & 0 \\ I & 0 & -I & 0 & 0 \\ \hat{Q}_D\hat{Y}_D & 0 & 0 & -\hat{\varepsilon}I & 0 \\ \hat{C}_D\hat{Y}_D & 0 & 0 & 0 & -I \end{bmatrix} \langle 0 \tag{19}$$

With:

$$\hat{\psi}_D = \hat{Y}_D\hat{A}_D^T + \hat{A}_D\hat{Y}_D + \hat{Y}_D^T\hat{K}_D^T\hat{B}_D^T + \hat{B}_D\hat{K}_D\hat{Y}_D - a\hat{Y}_D$$

Using Schur complement lemma, then Eq. (19) can be reformulated as:

$$\hat{\psi}_D = \hat{Y}_D\hat{A}_D^T + \hat{A}_D\hat{Y}_D + \hat{Y}_D^T\hat{K}_D^T\hat{B}_D^T + \hat{B}_D\hat{K}_D\hat{Y}_D - a\hat{Y}_D$$

$$\begin{bmatrix} \tilde{\Psi}_D & \hat{\Gamma}_D & I & \hat{Y}_D\hat{Q}_D^{\mathrm{T}} \\ \hat{\Gamma}_D^{\mathrm{T}} & -\gamma^2 e^{-\alpha T} I & 0 & 0 \\ I & 0 & -I & 0 \\ \hat{Q}_D\hat{Y}_D & 0 & 0 & -\hat{\varepsilon}I \end{bmatrix} < 0 \tag{20}$$

With:

$$\tilde{\Psi}_D = \hat{Y}_D\hat{A}_D^{\mathrm{T}} + \hat{A}_D\hat{Y}_D + \hat{Y}_D\hat{K}_D^{\mathrm{T}}\hat{B}_D^{\mathrm{T}} + \hat{B}_D\hat{K}_D\hat{Y}_D - \alpha\hat{Y}_D + \\ +\hat{Y}_D\hat{C}_D^{\mathrm{T}}\hat{C}_D\hat{Y}_D$$

Set $\Xi = \mathrm{diag}\left(\hat{Y}_D^{-1}, I, I, I\right)$ and $\hat{Y}_D^{-1} = \hat{P}_D$. Then, pre- and post-multiplying Eq. (20) by Ξ yields

$$\begin{bmatrix} \bar{\Psi}_D & \hat{P}_D\hat{\Gamma}_D & \hat{P}_D & \hat{Q}_D^{\mathrm{T}} \\ \hat{\Gamma}_D^{\mathrm{T}}\hat{P}_D & -\gamma^2 e^{-\alpha T} I & 0 & 0 \\ \hat{P}_D & 0 & -I & 0 \\ \hat{Q}_D & 0 & 0 & -\hat{\varepsilon}I \end{bmatrix} < 0 \tag{21}$$

With:

$$\bar{\Psi}_D = \hat{A}_D^{\mathrm{T}}\hat{P}_D + \hat{P}_D\hat{A}_D + \hat{K}_D^{\mathrm{T}}\hat{B}_D^{\mathrm{T}}\hat{P}_D + \hat{P}_D\hat{B}_D\hat{K}_D - \alpha\hat{P}_D + \hat{C}_D^{\mathrm{T}}\hat{C}_D = \\ = \hat{A}_D^{\mathrm{T}}\hat{P}_D + \hat{P}_D\hat{A}_D - \alpha\hat{P}_D + \hat{C}_D^{\mathrm{T}}\hat{C}_D$$

due to $\hat{\hat{A}}_D = \hat{A}_D + \hat{B}_D\hat{K}_D$

Applying Schur complement lemma again, we can verify that Eq. (21) can be considered as equal to Eq. (14), thus completing the evidence. When the value of E_{ij} varies between 1 and 0, the state change of the system is limited and controllable. Therefore, the control law $\hat{K}_D$ can guarantee both the system's stability and the stability of its connections.

Clearly, Eq. (18) does not represent a LMI. Nevertheless, by applying certain conditions, it can be ensured that the desired outcome is achieved.

$$\lambda_1 I < P_D < I \tag{22}$$

$$\frac{c_1}{\lambda_1} + d^2\gamma^2 < c_2 e^{-\alpha T} \tag{23}$$

For a positive number λ_1. Using Schur complements, inequality Eq. (23) can be converted to the following LMI.

$$\begin{bmatrix} c_2 e^{-\alpha T} & \sqrt{c_1} & d\gamma \\ \sqrt{c_1} & \lambda_1 & 0 \\ d\gamma & 0 & 1 \end{bmatrix} > 0 \tag{24}$$

Therefore, if the LMIs Eq. (22) and Eq. (24) are true, it follows that Eq. (18) is also true. Considering the issue from a computational perspective, the key point is that for a particular α value, the issue of assessing the viability of certain conditions mentioned in Theorem 1 can be expressed as a feasibility issue of solving LMIS.

LMI Feasibility issue (from Theorem 1). For system Eq. (8), given c_1, T, R and $\alpha > 0$, let $\hat{P}_D = R^{1/2}P_D^{-1}R^{1/2}$, locate a symmetric matrix which is also positive definite denoted as $\hat{Y}_D$ and a positive scalar λ_1 satisfying the LMIs Eq. (16), Eq. (17), Eq. (22) and Eq. (24). If the issue is achievable, the distributed limited-time $H\infty$ connective control issue can be addressed through $\hat{K}_D = \hat{M}_D\hat{Y}_D^{-1}$.

4.2 Collaboration of the Multi-Overlapping Distributed Control Principles

By repeating the processes involved in design mentioned earlier, an independent dynamic feedback controller can be configured for every combination of subsystems in the system. The matrix of gains $\tilde{\tilde{K}}$ in the extended space can be constructed in the following manner.

$$\tilde{\tilde{K}} = bkd\begin{bmatrix} \hat{K}_1^1, \hat{K}_2^1, \hat{K}_2^2, \hat{K}_3^1, \hat{K}_1^2, \hat{K}_3^2, ..., \\ \hat{K}_2^N, \hat{K}_N^{N-1}, \hat{K}_1^N, \hat{K}_N^N \end{bmatrix} \tag{25}$$

To deploy distributed control in the original setup, $\tilde{\tilde{K}}$ ought to contract back to its initial space. As stated in reference [31], to begin with, $\tilde{\tilde{K}}$ needs to be rearranged, and the rearranged version is as follows.

$$\bar{\tilde{K}} = Z\tilde{\tilde{K}}W \tag{26}$$

where, matrix Z is comparable to P_B, but the difference between them is that the dimensionality of the identity matrix in Z represents the total of the dimensionality of the identity matrix in P_B and the dimensionality of controller. Matrix W is comparable to P_C^{T}, where the dimensionality of space W is equal to the total of the dimensionality of the space represented by P_C^{T} and the dimensionality of controller. After permuted, $\bar{\tilde{\tilde{K}}}$ turns into:

$$\overline{\tilde{K}} = bkd\left[\hat{K}_1^1, \hat{K}_1^2, ..., \hat{K}_1^{N-1}, ..., \hat{K}_N^1, \hat{K}_N^2, ..., \hat{K}_N^{N-1}\right] \tag{27}$$

And then $\overline{\tilde{K}}$ should be shrunk back into the initial area. However, direct contraction using the method described in reference [31] is not feasible, because K is $\begin{bmatrix} D_k & C_k \\ B_k & A_k \end{bmatrix}$. Therefore, the contraction transform matrix should be remade through the application of the formula provided below:

$$K = L\overline{\tilde{K}}F \tag{28}$$

The matrix of contractions following the reformulation is:

$$L = \frac{1}{N-1} bkd\left(\left[\overbrace{I_{m_1+k_1}, ..., I_{m_1+k_1}}^{N-1}\right], ..., \left[\overbrace{I_{m_N+k_N}, ..., I_{m_N+k_N}}^{N-1}\right]\right)$$

$$F = bkd\left(\left[\overbrace{I_{l_1+k_1}, ..., I_{l_1+k_1}}^{N-1}\right]^{\mathrm{T}}, ..., \left[\overbrace{I_{l_N+k_N}, ..., I_{l_N+k_N}}^{N-1}\right]^{\mathrm{T}}\right)$$

here, k_i and l_i represent the dimensionality of the controller and the dimensionality of output z_i individually.

As a result, multi-overlapping distributed limited-time $H\infty$ control law based on state feedback that is dynamic for a specific category of interrelated systems with a networked framework can be acquired in the following manner.

$$K = \mathrm{blockdiag}\left(K_1, K_2, ..., K_N\right) \tag{29}$$

5 SIMULATION EXAMPLE

Consider a four-area interrelated power system which is represented in state-space form as:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + \Gamma\omega(t) \\ y(t) &= Cx(t) \end{aligned} \tag{30}$$

The parameters of each coefficient matrix among them are:

$$A = \begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{bmatrix} \tag{31}$$

$$B = \mathrm{blkdiag}\left(B_{11}, B_{22}, B_{33}, B_{44}\right) \tag{32}$$

$$C = \mathrm{blkdiag}\left(C_{11}, C_{22}, C_{33}, C_{44}\right) \tag{33}$$

$$A_{ii} = \begin{bmatrix} -\dfrac{D_i}{M_i} & \dfrac{1}{M_i} \\ 0 & -\dfrac{1}{T} \end{bmatrix} B_{ii} = \begin{bmatrix} \dfrac{1}{M_i} \\ 0 \end{bmatrix} C_{ii} = \left[01\right] \Gamma_i = [0.10.1]^T$$

The meanings and values of each variable are as follows D_i : coincidence damping coefficient, $D_1 = D_3 = 8$, $D_2 = D_4 = 12$. M_i: moment of inertia of the motor, $M_1 = M_2 = M_3 = M_4 = 1$. T : time constant, T = 0.1. External disturbance vector: $\omega_1 = \omega_2 = \omega_3 = \omega_4 = 0.1$.

Initial state vector: $X^{\mathrm{T}} = \left[X_1^{\mathrm{T}}, X_2^{\mathrm{T}}, X_3^{\mathrm{T}}, X_4^{\mathrm{T}}\right]$, $X_i^{\mathrm{T}} = \left[0.1, 0.1\right]$, $\alpha = 0.1, T = 1, c_1 = 1, d = 1, R = I$. After calculation the average value of $\min\left(c_2\right)$ is 1.1061. $q = \sum_{i=1}^{4} \hat{x}_i^{\mathrm{T}}\left(t\right) R_i \hat{x}_i\left(t\right)$ illustrated in the manner illustrated in Fig. 1. It is readily apparent from Fig. 1 that $q < 1.1061$, $t \in \left[0,1\right]$, which means that the multi-overlapping distributed limited-time $H\infty$ control issue can be resolved.

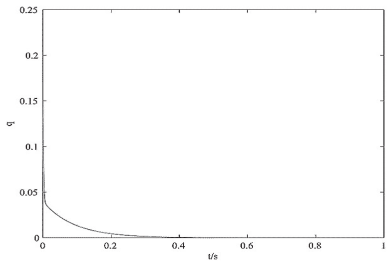

Figure 1 The simulation result of a four-area interrelated system featuring a networked topological arrangement

To verify the system's connective stability, the interconnection E_{12} is cut off. The result is shown in Fig. 2. It follows from Fig. 2 that the system with a closed loop is distributed limited-time $H\infty$ connectively bounded.

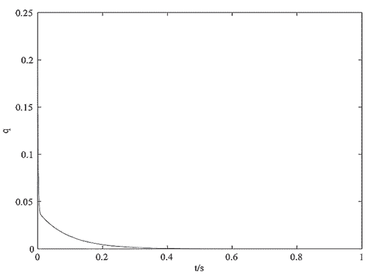

Figure 2 The simulation result of the system when E_{12} varies from 1 to 0

To compare with the outcomes of the direct approach to design utilizing LMI. Here, directly method is that solving the LMI directly without the process of expanding and contracting. The Response curve of the four subsystems of the two methods are drawn for comparison. It can be seen that in Fig. 3 to Fig. 6 all subsystems are stable, and the proposed approach demonstrates superior dynamic performance compared to the direct method.

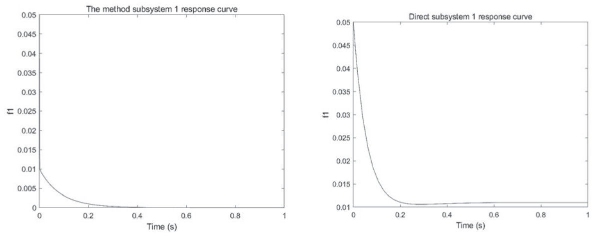

Figure 3 Comparison of subsystem 1 response curves

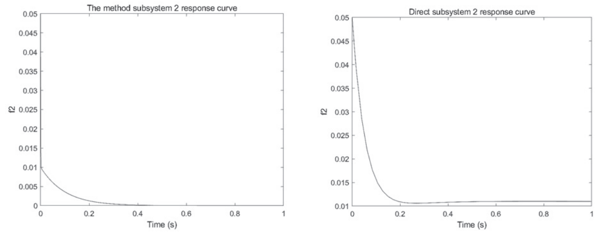

Figure 4 Comparison of subsystem 2 response curves

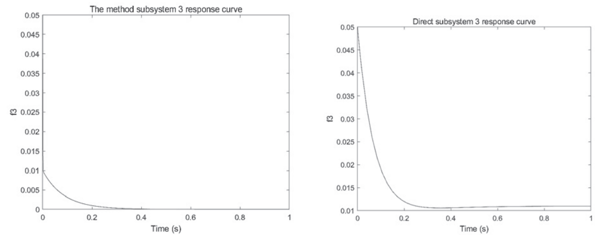

Figure 5 Comparison of subsystem 3 response curves

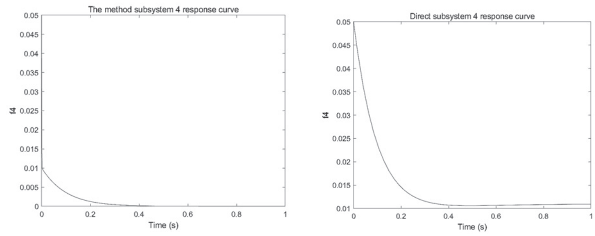

Figure 6 Comparison of subsystem 4 response curves

6 CONCLUSIONS

This paper proposes a dynamic state feedback-based control strategy that resolves distributed limited-time $H\infty$ connective stabilization for networked large-scale power systems through multi-overlapping structural decomposition and contraction transformation. By extending system state spaces and decomposing complex interactions into pairwise subsystems, the method enables robust controller design via LMI optimization while addressing dimensionality challenges. The key innovation lies in unifying finite-time boundedness, $H\infty$ disturbance attenuation, and structural connectivity constraints into a cohesive framework, supported by a novel contraction mechanism ensuring stability preservation during dimensionality reduction. The approach demonstrates significant practical value for renewable-integrated power grids, particularly in coordinating distributed wind farms under intermittent disturbances, as validated by a four-area networked system simulation. This work advances control theory for interrelated systems and provides a scalable paradigm for smart grid resilience enhancement, with potential applications extending to microgrid coordination and critical infrastructure networks.

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