Physica A 395 (2014) 434–444

Contents lists available at ScienceDirect

Physica A

journal homepage: www.elsevier.com/locate/physa

Synchronization in complex networks with non-delay and delay couplings via intermittent control with two switched periods

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HIGHLIGHTS

- We first propose an intermittent control method with two switched periods.
- By using the above method, we study pinning synchronization in complex networks.
- Criteria ensuring global exponential synchronization are obtained.
- We give a method for calculating the minimum number of pinning nodes.

ARTICLE INFO

Article history:
Received 5 June 2013
Received in revised form 1 October 2013
Available online 11 October 2013

Keywords:
Complex network
Synchronization
Intermittent control with two switched periods
Non-delay and delay couplings

ABSTRACT

In this paper, we propose a pinning synchronization control scheme in complex networks with non-delay and delay couplings, which uses two switched periods to provide intermittent control. Criteria ensuring global exponential synchronization are obtained based on strict mathematical proofs. Meanwhile, it is shown that the delay does not depend on the control width and the non-control width. Moreover, we give a method for calculating the minimum number of pinning nodes required to achieve exponential synchronization. Finally, a numerical simulation shows the effectiveness of the pinning synchronization control scheme via an intermittent control method with two periods.

1. Introduction

In the past two decades, complex networks have been extensively investigated across many fields of science and engineering [1–5]. Synchronization is the process in which two or more dynamical systems adjust each other to lead to a common dynamical behavior. Synchronization includes complete synchronization and generalized synchronization. For complete synchronization, a wide variety of synchronization criteria have been derived. Moreover, generalized synchronization has drawn increasing attention, such as consensus or flocking of multi-agent systems. The synchronization of coupled oscillators not only can well explain many natural phenomena, but also has many potential applications in automatic control [6,7], secure communication [8], and biological systems [9], amongst others. Since the pioneering work of Pecora and Carroll [10], there has been a large amount of work on synchronization in complex networks. However, sometimes the complex networks may not be synchronized without any controllers on the nodes. Thus many control methods have been developed to drive complex networks to synchronize, such as adaptive control [11–14], pinning control [15–20], impulsive control [21–23], and intermittent control [24–27].

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http://dx.doi.org/10.1016/j.physa.2013.10.002

In some network circumstances, delay couplings can be ignored on some links in the complex network, and others caused by traffic congestions or long distance between two nodes are significant, and must be considered. For example, the coupling delay on some links can be considered to be zero, and the coupling delay on other links to be non-zero in a complex network. Therefore, this kind of synchronization problem can be converted into synchronization in complex networks with both non-delay and delay couplings. In Refs. [18,19,28–30], synchronization in complex networks with both non-delay and delay couplings has been investigated. Sun et al. [28] studied adaptive synchronization in complex networks with both non-delay and delay couplings by adding controllers to each node in the network. Li [29] discussed synchronization in complex networks without adding any controllers, and derived criteria for synchronization stability. Recently, Wang et al. [30] used output coupling to discuss a synchronization scheme with both non-delay and delay couplings. At the same time, by using pinning control, Guo et al. [18] studied global pinning synchronization in nonlinearly coupled complex networks, and gave some sufficient conditions for synchronization. Wu et al. [19] used diver and response systems to produce inner synchronization and outer synchronization. Further, Wu et al. [31–33] investigated models of networks with multiple delays and time-varying delay. For recurrent neural networks with multiple delays, less conservative results were obtained by using different methods. With respect to multiple delays and time-varying delay, Yu et al. [34] introduced a synchronization scheme of a linearly hybrid coupled network with time-varying delay. In particular, both delay-independent and delay-dependent sufficient conditions for the synchronization were deduced when the coupling matrix may be nonsymmetric or nondiagonal.

In 2000, intermittent control was first introduced to control dynamical systems by Zochowski [35]. Later, intermittent control was successfully applied to synchronization control in complex networks [24–27]. Yang et al. [24] considered a coupled neural network model with diffusive couplings and stochastic perturbations by utilizing intermittent control, and obtained several sufficient conditions ensuring exponential synchronization. By using pinning and periodically intermittent control, Xia and Cai et al. [25,26] investigated the synchronization scheme of complex delayed dynamical networks. Intermittent control has been used for a variety of applications such as communication and manufacturing. For instance, in an information transmission system, the signal may become weaker and weaker during transmission. In order to compensate for the lost signal and enable a signal to be received at the terminal, before signal distortion, an external control signal is added to reach an upper level of signal strength, and it persists for a certain time (control width). Subsequently, the external control is removed (non-control width). Using such a scheme repeatedly, intermittent control with periods can make systems synchronize, and save resources.

Master stability functions have been used to study synchronization in complex networks under circumstances without any controllers [10]. Later, Lü et al. [36,37] further explored synchronization in small networks and synchronization in complex networks with time-varying strength of coupling. However, whether complex networks without any controllers are synchronized depends mainly on their structures. Pinning control is an efficient control method: some controllers are added on some nodes to drive complex network synchronization. As for pinning synchronization in complex networks, comprehensive research has been carried out. Recently, Yu et al. [20] studied the problem of pinning synchronization based on the more detailed structural information of general complex dynamical networks, and obtained some new results.

In this paper, we use pinning control and intermittent control methods to discuss synchronization in complex networks with both non-delay and delay couplings. To our knowledge, research on synchronization in this type of complex network with delay couplings via pinning and intermittent controls has not been reported. Motivated by the above discussion, a new synchronization control scheme in complex networks is proposed in the paper, in which intermittent control with two switched periods and pinning control methods are used to handle the synchronization problem in complex networks with both non-delay and delay couplings. Compared to a control method with one period, the new control method is more flexible, and its application scope is wider. Less conservative exponential synchronization criteria are obtained for the synchronization control scheme, whose delay is not independent of the control width and the non-control width. Sufficient conditions are simple and easy to use. Moreover, the method is given for the calculating the minimum number of pinning nodes. A numerical simulation shows the effectiveness of the synchronization control scheme.

This paper is organized as follows. In Section 2, some necessary preliminaries, a hypothesis, and some lemmas are given, and the intermittent control scheme with two switched periods is introduced. In Section 3, some synchronization criteria for complex networks with both non-delay and delay couplings are established. The synchronization is analyzed to provide the minimum number of pinning nodes required. A numerical example is given in Section 4. Finally, we conclude the paper in Section 5.

2. Preliminaries

Consider a complex dynamical network consisting of N identical nodes with linearly diffusive couplings described by the following equation:

$$\begin{cases} \dot{x}_i(t) = f(x_i(t)) + c_0 \sum_{j=1}^{N} g_{ij} \Gamma x_j(t) + c_1 \sum_{j=1}^{N} \bar{g}_{ij} \Gamma x_j(t-\tau) + u_i(t), \quad (i = 1, 2, \ldots, l), \\ \dot{x}_i(t) = f(x_i(t)) + c_0 \sum_{j=1}^{N} g_{ij} \Gamma x_j(t) + c_1 \sum_{j=1}^{N} \bar{g}_{ij} \Gamma x_j(t-\tau), \quad (i = l+1, l+2, \ldots, N), \end{cases} \tag{1}$$