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Global power-rate synchronization of chaotic neural networks with proportional delay via impulsive control☆

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A R T I C L E I N F O

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A B S T R A C T

This paper considers the problem of global power-rate synchronization of chaotic neural networks with proportional delay via impulsive control. By establishing a novel impulsive delayed differential inequality, some delay-dependent impulsive controlled laws are derived to guarantee the global power-rate synchronization of chaotic neural networks with proportional delay. Two examples with numerical simulations are given to illustrate the feasibility and advantage of the proposed control schemes.

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1. Introduction

It is well known that time delay is ubiquitous in implementation of neural network models, and frequently results in performance degradation, instability, and even chaotic behaviors of systems [8,12,15]. Therefore, it is necessary to consider delay effect on the dynamics of neural networks. During the past two decades, the problems of stability and chaos synchronization of delayed neural networks have been widely studied, see [4–8,17,25,31,50] for example.

Recall that proportional delay, which is a special class of delays, exists objectively in the real life world, and the corresponding delay systems have been used to model many practical problems in various scientific and engineering fields including population biology, electrodynamics, astrophysics, control theory, and Web quality of service routing decision (see [1,9,11,16,28] and the references cited therein). For example, Ockendon and Tayler [28] employed a system with proportional delay to model the current collection for an electric locomotive. A similar equation was established by Fox et al. [11] for the wave motion of a stretched string under an applied force which moves along the string. Dovrolis et al. [9] applied a proportional model in the differentiation of queueing delays to study appropriate packet scheduling mechanisms. To be noted that, in practical implementation, neural network models usually have a spatial nature owing to the presence of an amount of parallel pathways with a variety of axon lengths and sizes, and thus time delays encountered in neural networks are often time-varying, even unbounded [14,30]; so in some cases, one desires to choose suitable proportional delay factors in view of different network topology and materials and adopt proportional delays to characterize these unbounded delays [32,47,48]. In a practical neural network model described by a proportional delay, the state vector $x(t)$ of the system at time t is determined by its historical state vector $x(qt)$, where the constant q is usually called proportional delay factor and satisfies $0 < q < 1$. Meanwhile, the proportional delay function $\tau(t) = (1 - q)t$ is a monotonically increasing function in the time interval $(0, \infty)$ so that one can control conveniently the operation time of the system according to the proportional delay factor q. Therefore, proportional delays have predictable and controllable characteristics [14], and furthermore, it is reasonable and desired to introduce proportional delays in neural networks according to the network topology and the material [47,48]. As

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a result, proportional delays have recently been introduced and discussed for many practical models of neural networks such as bidirectional associative memory neural networks [32,47], shutting inhibitory neural networks [39], Hopfiled-type neural networks [42], recurrent neural networks [46,48]. The dynamical behaviors, especially stability and chaos synchronization of neural networks with proportional delays have gained increasing attention in recent years [14,23,24,32,39,42–48]. For instance, Zhou and Zhang [44] studied the problem of exponential stability of a class of cellular neural networks (CNNs) with multi-pantograph delays by nonlinear measure. Liu [23] analyzed the global exponential convergence for a class of non-autonomous shunting inhibitory CNNs involving multi-proportional delays based on some differential inequality techniques. In [39], Yu investigated the problem of global exponential convergence for a class of of high-order CNNs with neutral time-proportional delays based on some new analysis techniques. Zhou [45] addressed the dissipativity of a class of CNNs with proportional delays in terms of the inner product properties. By utilizing the nonlinear transformation $y(t) = x(\exp(t))$ to transform the considered CNNs with multiple proportional delays into the equivalent CNNs with multiple constant delays and time-varying coefficients, and employing the Lyapunov functional method, Zhou [42,46] established some delay-dependent conditions to guarantee the exponential stability and chaos synchronization of such CNNs with multiple proportional delays, respectively.

On the other hand, impulsive phenomena also occur unavoidably in neural networks. Thus, it is of great importance to consider impulsive effect and delay effect on the dynamics of neural networks. Consequently, the dynamical behaviors of neural networks with impulses and delays have attracted much research attention, and a large number of interesting results have been reported over the past decades [2,3,18–22,26,30,33,35–37,40,41,49]. In particular, the impulsive control method has been widely and successfully employed to synchronize chaotic neural networks because of its effectiveness and robustness, see [18,19,26,33,35–37,40] and references therein. For example, Li and Rakkiyappan [19] studied the problem of global asymptotic synchronization of a class of chaotic neural networks with bounded time-varying and unbounded distributed delays by utilizing the stability theory of impulsive functional differential equations and LMI approach. Yang and Yang [35] investigated the global exponential synchronization of TS fuzzy CDNs with multiple bounded time-varying impulsive delays and stochastic effects, by establishing two novel impulsive inequalities involving bounded time-varying delays, constructing some Lyapunov functions, and using the stochastic analysis techniques. In [37], Yang et al. obtained several conditions ensuring the global exponential synchronization of a class of neural networks with time-varying discrete and distributed delays via state feedback and impulsive control, by using the Lyapunov method and new analysis techniques. Zhang and Sun [40] dealt with the problem of robust synchronization of coupled delayed neural networks under general impulsive control by applying the Lyapunov method and LMI approach. However, almost of all the above-mentioned studies on chaos synchronization via impulsive control are limited to systems without time delay or delayed systems with constant, bounded time-varying and unbounded distributed delays. As we all know, proportional delay is an important type of unbounded time-varying delay, and much different from unbounded distributed delay. For unbounded distributed delay [3,4,19,30,41,49], it is often required that the delay kernel functions $k_{ij} : \mathbb{R}_+ \to \mathbb{R}_+$ satisfy $\int_0^\infty k_{ij}(s)ds = 1,\ \int_0^\infty sk_{ij}(s)ds < \infty,$ or there exist a positive number μ such that $\int_0^\infty e^{\mu s}k_{ij}(s)ds < \infty,$ furthermore, the use of these inequalities makes unbounded distributed delay easier to handle. While compared with unbounded distributed delay, due to the proportional delay function $\tau(t) = (1-q)t \to \infty$ as $t \to \infty$ and there being no any other conditions, it is relatively difficult to deal with proportional delay in the derivation of dynamical behaviors of impulses-free neural networks. Furthermore, the presence of impulsive effects makes proportional delay much harder to handle, and meanwhile, the special structure and unboundedness nature of proportional delay imply that the existing results for impulsive systems with bounded delays and unbounded distributed delays cannot be directly applied to impulsive equations with proportional delays. Because of the difficulties of dealing with both impulses and proportional delays, the results obtained for neural networks with impulses and proportional delays are rare [29]. Song et al. [29] recently established some conditions to guarantee the global asymptotic stability of CNNs with impulses and proportional delays by utilizing the same nonlinear transformation $y(t) = x(\exp(t))$ as Refs. [42,45] and the nonlinear measure theory, where the impulses act as perturbations rather than stabilizers. It can be seen that, by means of this kind of transformation, systems with proportional delays do become the equivalent systems with constant delays and one may use the transformation on occasions, but it does not always simplify the analysis to do so since the equivalent systems' coefficients containing $\exp(t)$ are unbounded and time-varying. Thus, some new techniques and methods need further development for neural networks with impulses and proportional delays. It has been found that proportional delays, which often occur in neural processing and signal transmission, can cause instability and chaotic behaviors [14,45–47]. Therefore, it is necessary to study the problems of stabilization and chaos synchronization of neural networks with proportional delays. Recently, Zhou [46] obtained some decentralized feedback control laws to guarantee the exponential synchronization of recurrent neural networks with multiple proportional delays by applying the same nonlinear transformation technique as Refs. [42,45] and constructing some Lyapunov functionals. More recently, Kinh et al. [14] studied the global power-rate synchronization of fractional-order neural network models with proportional delays by using the Leibniz rule for fractional differentiation and a novel comparison technique. As far as we know, however, the problem of impulsive synchronization of chaotic neural networks with proportional delays has not been investigated yet. It can be known that the global power-rate synchronization implies the global asymptotic synchronization but not vice versa. Therefore, it is interesting and challenging to study the problem of global power-rate chaos synchronization of neural networks with proportional delays via impulsive control, and consequently derive some impulsive control laws to ensure the global asymptotic chaos synchronization of such neural networks, which motivates the present work.

In this paper, a novel impulsive differential inequality involving proportional delay is established from the impulsive control point of view. Based on this inequality, some delay-dependent conditions are derived to guarantee the global power-rate stability of the error dynamical system, and thus the impulsive controlled response system globally power-rate synchronizes with the drive system. Different from the prior work on impulsive synchronization of chaotic systems with the conventional delays such as constant, bounded time-varying and unbounded distributed delays [19,33,35–37,40], delay here is proportional delay which is unbounded and time-varying, and so the obtained results are completely new. The main contributions of this work are the following three aspects: (i) the problem of global power-rate synchronization via impulsive control is first addressed for chaotic neural networks with proportional delay, and its characteristic lies in unveiling a power convergent rate; (ii) a new method based on establishing the novel impulsive delay inequality is proposed to investigate the global power-rate synchronization, which is different from the nonlinear transformation method employed in [29,46], and the obtained inequality will play a key role in studying impulsive stabilization of systems with proportional delay; and (iii) the established delay-dependent

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