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Designing an adaptive type-2 fuzzy logic system load frequency control for a nonlinear time-delay power system

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ABSTRACT

In this paper, a combination of type-2 fuzzy logic system (T2FLS) and a conventional feedback controller (CFC) has been designed for the load frequency control (LFC) of a nonlinear time-delay power system. In this approach, the T2FLS controller which is designed to overcome the uncertainties and nonlinearites of the controlled system is in the feedforward path and the CFC which plays an important role in the transient state is in the feedback path. A Lyapunov–Krasovskii functional has been used to ensure the stability of the system and the parameter adjustment laws for the T2FLS controller are derived using this functional. In this training method, the effect of delay has been considered in tuning the T2FLS controller parameters and thus the performance of the system has been improved. The T2FLS controller is used due to its ability to effectively model uncertainties, which may exist in the rules and data measured by the sensors. To illustrate the effectiveness of the proposed method, a two-area nonlinear time-delay power system has been used and compared with the controller that uses the gradient-descend (GD) algorithm to tune the T2FLS controller parameters.

1. Introduction

The objective of load frequency control (LFC) in an interconnected power system is to maintain the frequency of each area within limits and keep tie-line power flows within some pre-specified tolerances [1]. In LFC, the tie-lines are utilities for the contracted energy exchange between areas and they provide inter-area support in abnormal conditions. Changes in the area loads and abnormal conditions lead to mismatches in frequency and the scheduled power interchanges between areas. These mismatches have to be corrected by LFC, which is defined as the regulation of the power output of generators within a prescribed area [2–4]. Various controllers have been proposed for LFC, including classical controllers, such as adaptive [5–8] and robust controllers [9–13], and intelligent controllers, such as fuzzy logic system (FLS) [14–20] and artificial neural network (ANN) [21–24] based controllers. Although these controllers have led to the promising results, some of the undeniable power system characteristics such as delays and nonlinearities have not been taken into account. It is clear that ignoring these issues in designing of the LFC not only degrades its dynamic performance, but may also cause system instability. Any signal processing, filtering, and breakdown in the communication channel can introduce delays, and speed governor dead band can be a source of nonlinearity in the power system. Dedicated communication channels in conventional LFC schemes and open communication networks in the restructured power system will introduce constant and time-varying delays, respectively. Hence, time-delays have been considered in designing LFC in the traditional and restructured power systems [25–32]. Most of these works have employed a robust control design method in which delay was dealt with as a part of uncertainties. For example, in [27] a robust PI based controller, which uses the static output feedback control law in a linear matrix inequality (LMI) framework, has been designed for LFC. In [26], an H_∞ controller has been proposed for a two-area power system LFC with multiple state delays. In [30], a robust PID-type LFC scheme has been proposed for a power system with constant and time-varying delays. Also, authors of [31,32] have proposed a delay margin, which is a new performance index, as guidance for designing a robust controller for LFC. The main drawback of the robust control schemes is that they lead to high-order controllers and thus cause difficulty when implement in large scale systems such as LFC. Moreover, in many cases, all of the state variables of the system are needed for designing the controller. Therefore, it is necessary to have a controller which can overcome these problems. Based on artificial intelligence approaches, the FLS and ANN

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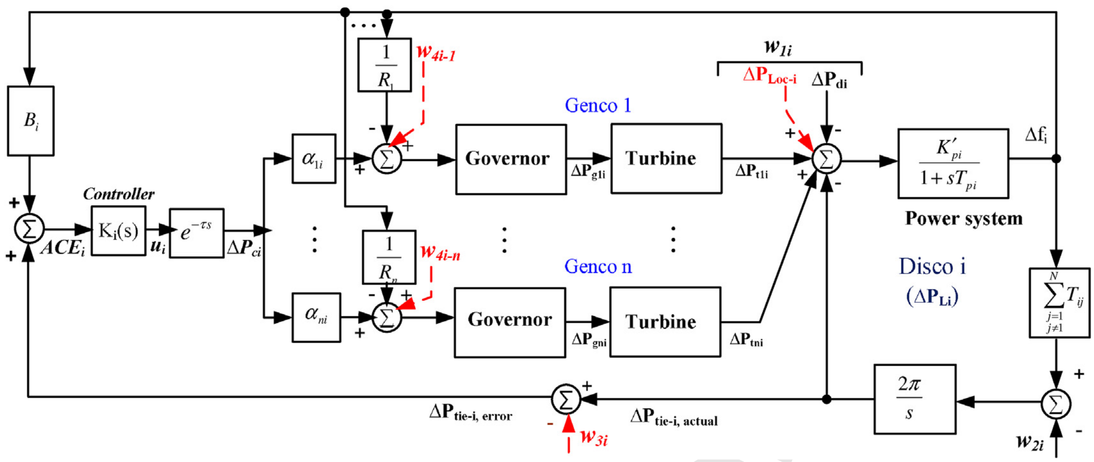

Fig. 1. Configuration of the *i*th control area.

controllers are more suitable in this respect. The most salient feature of these techniques is that they provide a model-free description of control systems and do not require model identification or an exact model of the system. Also, type-2 FLSs (T2FLSs), which are an extension of the type-1 FLSs (T1FLSs), have been considered as a suitable solution to deal with measurement noise and parametric uncertainties of a system [33–40]. In type-2 fuzzy sets, membership functions (MFs) themselves are fuzzy and, therefore, they are a favourite solution for handling uncertainties [41,42]. Following the aforementioned properties of T2FLSs, in [43,50], type-2 fuzzy controllers have been designed for LFC in a typical nonlinear power system with system parametric uncertainty. These controllers have a fixed structure and the effect of delay has not been considered in the synthesis of the controllers. Besides, an adaptive T2FLS controller for a delay-free power system has been proposed in [44]. This control strategy is based on feedback error learning (FEL) approach. In this approach, the T2FLS controller is in the feedforward path and a conventional feedback controller (CFC) (i.e. proportional-derivative (PD)) is in the feedback path. The classic controller is used for stabilization and the intelligent part (the T2FLS controller) is designed to overcome the variations and nonlinearities in the controlled system. In that work, a simple gradient descent (GD) algorithm has been used to tune the T2FLS parameters and the effect of delay has been ignored in the synthesis of the controller. Motivated by the above-mentioned observations, in this paper an adaptive T2FLS controller based on FEL approach has been designed for LFC in a nonlinear time-delay power system. The most important contributions of this paper, and improvements to the work [44], can be considered as follows:

(i) The delayed power system with speed governor dead band nonlinearity has been considered in this study. Whereas, in [44] the delay-free power system was considered and in the dynamic model of the power system the linear model was used for the governor unit.
(ii) The Lyapunov–Krasovskii functional has been utilized to evaluate the stability of the system; and the adaptation laws for the parameters of the T2FLS controller have been derived using this functional. The adaptation laws involve relationships between the controller parameters and the maximum values of the time-varying delays. So, the proposed strategy can deal with the time-varying delays and increase the performance of the power system. It is worth pointing out that the in the previous work, there was not any stability analysis for the proposed controller and the effect of delay has been ignored in the designing of the controllers.

Since only the training error signal and its derivative have been used in the construction of the Lyapunov–Krasovskii functional, the achieved adaptation laws for the T2FLS parameters are very simple. Unlike the other Lyapunov based control approaches such as robust controller, in the synthesis of the proposed scheme, there is no need for any prior knowledge about the mathematical model or its parameters.

A two-area nonlinear time-delay power system is assumed to show the effectiveness of proposed controller. The proposed Lyapunov–Krasovskii based controller has been compared with the controller proposed in [44]. The remaining part of the paper is organized as follows: in Section 2, the dynamic model of a two-area nonlinear time-delay power system is presented. The proposed adaptive controller is derived for LFC in Section 3. Section 4 includes the simulation results for a two-area power system. Finally, the conclusions are given in Section 5.

2. Model description

In a traditional power system structure, a single entity called a Vertically Integrated Utility (VIU) generates, transmits and distributes power to customers at the regulated rates and tie-lines connect all control areas. The load disturbance in a given area results in a transient change in the areas. Through a feedback mechanism, the turbine tries to modify the generation corresponding to the load. In the steady state, there is a match between the generation and load and then the tie-line power and frequency deviations are driven to zero. In the restructured power systems, there are some generation companies (Gencos) and distribution companies (Discos) in each area. A block diagram of the *i*th control area in the restructured power system for LFC is shown in Fig. 1 [3,30,32]. In this system, in an open energy market, Gencos may or may not participate in the LFC task and they can sell power to various Discos at competitive price [3]. Also, Discos have the liberty to choose the Gencos for contracts. In this power system, the concept of "generation participation matrix" (GPM) is used to facilitate visualization of the contracts. GPM shows the participation factors of each Genco in the considered control area and each control area is determined by a Disco. The rows of a GPM correspond to Genco and the columns correspond to the control areas that contract power. For example, for a large scale power system with *m* control areas (Discos) and *n*

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