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A nonlinear voltage controller based on interval type 2 fuzzy logic control system for multimachine power systems

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ABSTRACT

In this paper, we propose an interval type-2 fuzzy controller that has the ability to enhance the transient stability and achieve voltage regulation simultaneously for multimachine power systems. The design of this controller involves the direct feedback linearization (DFL) technique. The DFL compensated system model is transformed into an equivalent type 1 T–S fuzzy model using linearly independent functions. This paper highlights the mathematical foundations for analyzing the stability and facilitating the design of stabilizing controllers of the interval type 2 Takagi–Sugeno fuzzy control systems (IT2 T–S FLCSs). Sufficient conditions for designing the interval type-2 fuzzy controller with meeting quadratic *D* stability constraints are obtained by using Linear Matrix Inequalities (LMIs). Based on only local measurements, the designed controller guarantees transient stability, voltage regulation and satisfies desired transient responses. The proposed controller is applied to two-generator infinite bus power system. Simulation results illustrate the performance of the developed approach regardless of the system operating conditions.

1. Introduction

Power system stability has been recognized as an important problem since the electricity has been used in everyday life. Although power system stability may be broadly defined according to different conditions, two major issues are frequently considered; the first is the problem of transient stability and the second is the voltage regulation. In order to obtain high quality transient stability and voltage regulation, many researches has been established and numerous papers are published [1–10].

Generator excitation systems play a fundamental role in power system control. Indeed, the basic function of the excitation system is to supply and automatically adjust the field current of the synchronous generator to regulate the terminal voltage. The power system stabilizer (PSS) provides the supplementary signal through the excitation automatic voltage regulator (AVR) loop which dampens the power oscillations. The common feature of AVR/PSS controllers is that they are typically based on models established by approximate linearization of the nonlinear equations of a power system at certain operating point [2,3]. But, in case of large disturbances, these linearized control techniques are not effective since the modern power systems are highly complex and nonlinear and their operating conditions can vary over a wide range. Hence, attention has been focused on the application of nonlinear controllers, which are independent of the equilibrium point and take into account the important nonlinearities of the power system model.

The application of nonlinear control techniques to solve the transient stabilization problem has been given much attention [5–8]. Most of these nonlinear excitation controllers are based on feedback linearization technique [5–7]. The drawback of the existing nonlinear excitation controller designs is that the post-fault voltage varies considerably from the pre-fault one; this is mainly due the heavy inherent nonlinear characteristics of the terminal voltage which prevents us from using it as feedback variable.

In the last decades, nonlinear control approaches based on the Takagi–Sugeno fuzzy model solved this voltage regulation problem by including terminal voltage as feedback variable [9,10]. Takagi–Sugeno fuzzy logic control systems (T–S FLCSs) have been mostly considered as one of the best suitable tools for modeling and control of nonlinear systems. Based on the Lyapunov method, some significant stability analysis results have provided sufficient stability conditions in Linear Matrix Inequalities (LMIs) terms to ensure the overall system stability. The controller is synthesized via the parallel distributed compensation (PDC) technique [11–13]. However, based on precise type-1 (T1) fuzzy sets, the type-1 T–S FLCSs have the common problem that they cannot fully handle the linguistic and numerical uncertainties with an unknown, uncertain and perturbed nonlinear dynamical system.

Recently, the applications of type-2 fuzzy logic controllers to uncertain control processes have received considerable attention

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[14]. The type-2 fuzzy logic controller based on the T2-fuzzy sets can deal with both the linguistic and the numerical uncertainty effectively; these fuzzy sets include a third dimension and footprint of uncertainty. Thus, the type-2 fuzzy logic controller can obviously outperform its T1 counterpart under the situation of high uncertainty.

One of the first studies on type-2 fuzzy logic controller that have been employed for solving the rotor angle stability problems is reported in [15]. There, for both small and large disturbance, oscillations are damped by using a power system stabilizer (PSS). With this controller, considerable efforts have been devoted to damp frequency oscillations in the power systems, and less attention has been paid to the voltage quality and to the excursions of generator rotor angles. In this paper, motivated by exploiting the advantages of the interval type-2 fuzzy controller, we have investigated the transient stability enhancement and the voltage regulation of multimachine power systems in the framework of the interval type-2 Takagi–Sugeno fuzzy logic control system (IT2 T–S FLCS). The aim of this work is to present and discuss the stability of the IT2 T–S FLCS through the Lyapunov stability theory; where a set of LMI-based stability conditions are derived to guarantee the system stability and facilitate the control synthesis. Moreover the desired transient specification behaviors of the closed loop system, which is commonly expressed in terms of transient responses [16], can be guaranteed by constraining the closed-loop poles to lie in a suitable sub-region of the left-half of the complex plane [17].

IT2 T–S FLCS theory is advantageous in that it is able to handle nonlinearity smoothly, which is an attractive method to overcome the heavy nonlinear characteristics of the terminal voltage in power system. In this paper, The DFL technique has been used to linearize and decouple a nonlinear n machine power system to n independent DFL compensated models. These compensated models are described by type 1 T–S models. The proposed IT2 fuzzy controller is simulated on a two-generator infinite bus power system. The simulation results exhibit the effectiveness of the designed controller, in the sense that both voltage regulation and system stability enhancement can be achieved in the presence of variation of operation points, fault location, network parameters and step change of the mechanical input power.

The layout of the paper is as follows. In Section 2, the background materials concerning type 1 T–S fuzzy model, IT2 fuzzy controller and IT2 T–S FLCS are introduced. Sufficient conditions for stability and pole location requirements formulated in terms of LMIs are represented in Section 3. In Section 4, the T–S fuzzy model of the power system is described. The nonlinear voltage controller derived from the proposed methodology and based on constructed type 1 T–S Fuzzy model is designed in Section 5. This control scheme is implemented in a two-machine infinite bus power system and simulation results are provided to demonstrate the performance of the proposed controller in Section 6. Finally, conclusions are drawn in Section 7.

2. T1 T–S fuzzy model, IT2 fuzzy controller and IT2 T–S FLCS

An IT2 T–S FLCS is referred to a closed-loop system consisting of a type1 T–S fuzzy model and an IT2 fuzzy controller connected in a closed loop [18].

2.1. Type 1 T–S fuzzy model

It should be pointed out, that almost all nonlinear dynamical systems can be represented by type 1 Takagi–Sugeno fuzzy models to high degree of precision. In fact, it is proved that type 1 Takagi–Sugeno fuzzy models are universal approximations of any smooth nonlinear system [11], [18] and [19].

Bae et al. in [19] presented a method for constructing T–S fuzzy model using the sum of products of linearly independent functions from nonlinear systems. To this end the following nonlinear system is considered

$$\dot{\boldsymbol{x}} = \boldsymbol{F}(z(t))\boldsymbol{\eta}(t) \tag{1}$$

where $\boldsymbol{\eta}^T(t) = [\boldsymbol{x}^T(t)\boldsymbol{u}^T(t)]^T$, the matrix function $\boldsymbol{F}(z(t))$ is represented as

$$\boldsymbol{F}(z(t)) = \begin{bmatrix} f_{11}(z(t)) & f_{12}(z(t)) & \cdots & f_{1(n+m)}(z(t)) \\ f_{21}(z(t)) & f_{22}(z(t)) & \cdots & f_{2(n+m)}(z(t)) \\ \vdots & \vdots & \ddots & \vdots \\ f_{n1}(z(t)) & f_{n2}(z(t)) & \cdots & f_{n(n+m)}(z(t)) \end{bmatrix} \tag{2}$$

where $f_{ij}(z(t))$ is the (i,j) element of the $\boldsymbol{F}(z(t))$ matrix.

The nonlinear system (1) can be rewritten as follows

$$\dot{\boldsymbol{x}}(t) = \left[\boldsymbol{F}_0 + \sum_{i=1}^{w} f_i(z(t))\boldsymbol{F}_i\right]\boldsymbol{\eta}(t) \tag{3}$$

where

$$f_i(z(t)) = \prod_{j=1}^{v} g_i^{l_{ij}}(z(t)), \quad \forall i = 1,2,\ldots w \tag{4}$$

where 'v' is the least number of linearly independent functions g_j $(z(t))$. When we express f_i $(z(t))$ to the form of Eq. (4), l_{ij} is '1' if f_i $(z(t))$ has the term of $g_j(z(t))$, otherwise l_{ij} is '0'. It is also possible to rewrite the nonlinear system (1) to the form of Eq. (3).

Substituting Eq. (4) into Eq. (3) gives

$$\dot{\boldsymbol{x}}(t) = \left[\boldsymbol{F}_0 + \sum_{i=1}^{w}\prod_{j=1}^{v} g_j^{l_{ij}}(z(t))\boldsymbol{F}_i\right]\boldsymbol{\eta}(t) \tag{5}$$

and Eq. (5) is equivalent to

$$\dot{\boldsymbol{x}}(t) = \left[\boldsymbol{F}_0 + \sum_{i=1}^{w}\prod_{j=1}^{v}\sum_{k=0}^{1} h_{jk}(z(t))g_{jk}^{l_{ij}}\boldsymbol{F}_i\right]\boldsymbol{\eta}(t) \tag{6}$$

where

$$\begin{aligned} &h_{j0}(z(t)) = \frac{g_{j1} - g_j(z(t))}{g_{j1} - g_{j0}}; \quad h_{j1}(z(t)) = \frac{g_j(z(t)) - g_{j0}}{g_{j1} - g_{j0}} \\ &g_{j0} = \min_z\{g_j(z)\}; \quad g_{j1} = \max_z\{g_j(z)\} \end{aligned} \tag{7}$$

for all $j = 1, 2, \ldots, v$. To verify that Eqs. (5) and (6) are equivalent, we need to show that the following expressions are true

$$g_j^{l_{ij}}(z(t)) = \sum_{k=0}^{1} h_{jk}(z(t))g_{jk}^{l_{ij}} \tag{8}$$

$$\sum_{k=0}^{1} h_{jk}(z(t)) = 1 \tag{9}$$

for all $j = 1, 2, \ldots, v$. Eq. (9) is shown from Eq. (6). And Eq. (7) is derived from

$$\begin{aligned} g_j^{l_{ij}} &= [h_{j0}(z(t))g_{j0} + h_{j1}(z(t))g_{j1}]^{l_{ij}} \\ g_j^{l_{ij}} &= \begin{cases} h_{j0}(z(t))g_{j0} + h_{j1}(z(t))g_{j1}, & l_{ij} = 1 \\ 1(= h_{j0}(z(t))g_{j0} + h_{j1}(z(t))g_{j1}), & l_{ij} = 0 \end{cases} \\ g_j^{l_{ij}} &= h_{j0}(z(t))g_{j0}^{l_{ij}} + h_{j1}(z(t))g_{j1}^{l_{ij}} \end{aligned} \tag{10}$$

using the T–S fuzzy model representation, Eq. (6) is rewritten as

$$\dot{\boldsymbol{x}}(t) = \sum_{i=1}^{r} h_i(z(t))[\boldsymbol{A}_i\boldsymbol{x}(t) + \boldsymbol{B}_i\boldsymbol{u}(t)] \tag{11}$$