Annals of Nuclear Energy 122 (2018) 229–240

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

A nonlinear model predictive tracking control strategy for modular high-temperature gas-cooled reactors

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ARTICLE INFO

Article history:
Received 8 May 2018
Received in revised form 13 July 2018
Accepted 22 August 2018

Keywords:
Model predictive control
Modular high-temperature gas-cooled nuclear reactor
Power level control
Quadratic programming
Takagi-Sugeno fuzzy system

ABSTRACT

Modular high-temperature gas-cooled nuclear reactor (MHTGR) has attracted comprehensive attention for its reliable inherent safety, and an effective control strategy is needed to control the output power of the MHTGRs at the desired level. Based on model predictive control (MPC) strategy, this paper aims to develop a nonlinear power-level tracking controller for the MHTGRs. By introducing Takagi-Sugeno (TS) fuzzy system for nonlinear modeling, the nonlinear MHTGR model is represented by TS models. Based on the TS models, a nonlinear MPC (NMPC) controller is developed. Moreover, system constraints are considered, and quadratic programming (QP) is introduced for system optimization under the constraints. In addition, the system stability is analyzed based on Pole-Zero map and Nyquist diagram. To evaluate the performance of the proposed NMPC strategy, a Proportional-Integral-Derivative (PID) control strategy and a fuzzy adaptive Proportional-Integral-Derivative (FPID) control strategy are presented for comparison. The effectiveness and the advantages of the proposed NMPC strategy are demonstrated by simulation results.

1. Introduction

Small modular reactors (SMRs) whose electrical output power is less than 300 MWe have captured comprehensive attention for the features of convenient utilization and favorable economic benefits. MHTGR has been viewed as one of the best candidates for SMR-based nuclear power plants, since MHTGR is characteristic of sound security due to its low power density and large heat capacity (Dong, 2012a, 2013a). An automatic control system is needed for the MHTGRs to track load changes as well as to operate at the desired power level efficiently and stably, and the MHTGR dynamics are known as nonlinear and are accompanied with uncertainties, which present great challenge in power-level control problem.

To overcome the challenging problems stated above, some control strategies were developed for power level control of the MHTGRs. In the former works, adaptive control schemes (Dong, 2014a, 2016; Dong et al., 2017; Dong, 2014b; Dong et al., 2016) have been applied to MHTGRs. For instance, an adaptive proportional-differential control strategy was developed in (Dong, 2014a), and a multi-layer artificial neural network algorithm was introduced to achieve the adaptive action and to suppress the negative influence caused by model uncertainties. Dong (2016) developed a nonlinear adaptive coordinated control strategy, and the stability of the proposed control system was theoretically guaranteed by the designed control law according to Lyapunov stability theory. An improved adaptive control strategy was developed in (Dong et al., 2017), and the control law was presented in proportional-integral/proportional-differential form. In addition, compared with the controller designed in (Dong, 2016), the advantages of the improved control strategy (Dong et al., 2017) were demonstrated by simulation results. An adaptive output-feedback control scheme was proposed in (Dong, 2014b), where the given parameters of the adaptive controller were tuned on-line. In other works, a dynamic output-feedback controller based on iterative damping assignment was developed by Dong (2012b). A nonlinear coordinated control strategy was presented in (Dong, 2014c), where the control law that was of simple structure was designed based on a PID control scheme. A proportional-differential controller was developed in (Dong, 2015), where input saturation was especially considered. The controllers (Dong, 2012a, 2013a, 2014a, 2016; Dong et al., 2017; Dong, 2014b, 2013b, 2012b, 2014c, 2015) were developed based on the

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https://doi.org/10.1016/j.anucene.2018.08.037
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Nomenclature

c_r	Relative concentration of the delayed neutron precursor
G_r	Differential worth of the control rods
n_r	Relative reactor power
P_0	Rated reactor power (MW)
T_H	Average temperature of the helium in the primary loop (°C)
T_R	Temperature of the reactor core (°C)
$T_{R,m}$	Initial equilibrium value of T_R (°C)
T_s	Average temperature of the coolant in the secondary loop (°C)
υ_r	Velocity of the control rods ($m\ s^{-1}$)
β	Fraction of the delayed neutrons
Λ	Neutron life time (s)
ρ_r	Reactivity due to the control rods
λ	Decay constant of the delayed neutron precursor (s^{-1})
α_R	Reactivity feedback coefficient of T_R (°C^{-1})
Ω_p	Heat transfer coefficient between the helium and the reactor core (W °C^{-1})
Ω_s	Heat transfer coefficient between the primary loop and the secondary loop in the once-through steam generator (W °C^{-1})
μ_R	Heat capacity of the reactor core ($W\ s$ °C^{-1})
μ_H	Heat capacity of the helium ($W\ s$ °C^{-1})
t	Time index (s)

nonlinear state-space model of the MHTGRs. The effectiveness of the control strategies designed in (Dong, 2012a, 2013a, 2014a, 2016; Dong et al., 2017; Dong, 2014b, 2013b, 2012b, 2014c, 2015) was demonstrated by simulation results.

Undoubtedly, favorable achievements were obtained in (Dong, 2012a, 2013a, 2014a, 2016; Dong et al., 2017; Dong, 2014b, 2013b, 2012b, 2014c, 2015). However, none of the controllers can effectively handle the system constraints in the controller design stage. Moreover, the MHTGRs are known as strongly nonlinear, which also presents great challenge. The aim of this paper is to develop a nonlinear tracking controller based on an MPC scheme that can handle the system constraints for the MHTGRs.

Modeling of the controlled plant is extremely significant for the design of model-based control strategies. The accuracy of the plant model might greatly influence the performance of these model-based controllers. Therefore, this paper also focuses on the nonlinear modeling of the MHTGRs based on TS fuzzy system. TS fuzzy control that was initially presented by Takagi and Sugeno in 1985 (Takagi and Sugeno, 1985) is widely proposed for the modeling of nonlinear systems (Zhang et al., 2017; Wu et al., 2015; 2014a; Kong et al., 2015; Wang et al., 2016); and then the global behaviors of these nonlinear dynamic systems can be accordingly described by the corresponding TS models. For instance, TS fuzzy control was introduced for the nonlinear modeling of an ultra-supercritical boiler-turbine unit (Zhang et al., 2017) and the nonlinear modeling of a hydro-turbine governing system (Wang et al., 2016). MPC is an optimal control algorithm subject to the defined cost function, and by minimizing the defined cost function, a sequence of optimal control inputs can be obtained based on an explicit prediction of plant outputs within the prediction horizon (Moon and Lee, 2009). The controller outputs are computed at every sampling time, and only the control input for the current time is implemented to the controlled plant. The major advantage of MPC is to handle system constraints in the controller design stage. Since system constraints are usually existed in actual industrial systems, MPC has been widely applied to industrial processes (Moon and Lee, 2009; Wang et al., 2017a,b; Man et al., 2006, 2005; Wu et al., 2013, 2016; Liu and Kong, 2013; Zhang et al., 2011, 2014). For instance, MPC was proposed for load tracking control of pressurized water reactors (Wang et al., 2017a,b; Man et al., 2006, 2005). Wu et al. (2013) developed an MPC controller for a boiler–turbine unit. The velocity constraints on the control rod and the constraints on the control inputs deserve careful consideration for the reliability and the security of the MHTGRs. Thus, MPC is reasonable and appropriate to be utilized for power level control of the MHTGRs.

Motivated by the aforementioned analysis, this paper aims to develop an NMPC controller for the MHTGRs. TS fuzzy system is introduced for the nonlinear modeling of the MHTGRs, and then the nonlinear model is represented by TS models. Based on the TS models, the NMPC strategy is developed according to the defined cost function. Moreover, system constraints are considered, and QP is introduced for system optimization under the constraints. To evaluate the performance of the proposed NMPC strategy, a PID strategy and an FPID strategy are presented as comparisons. The effectiveness and the performance of the proposed NMPC strategy are demonstrated by simulation results.

The main contribution of this paper is as follows: Firstly, TS fuzzy system is introduced for the nonlinear modeling of the MHTGRs, which has never been done in previous literature. Resultantly, the nonlinear reactor model is represented by the proposed TS fuzzy models. Then, based on the TS models, QP-based MPC algorithm is applied to the tracking control of the MHTGRs. In addition, the stability of the proposed nonlinear fuzzy system is analyzed based on Pole-Zero map and Nyquist diagram. It should be mentioned that the proposed TS models can be utilized to develop other kinds of control algorithms.

The rest of this paper is constructed as follows. The reactor model of the MHTGRs is presented in Section 2. TS fuzzy system is introduced, and the proposed NMPC strategy based on QP is detailed in Section 3. Simulation results are given and discussed in Section 4. Finally, conclusions are drawn in Section 5.

2. MHTGR model

In MHTGRs, the reactor power is regulated by the movement of the control rod. Shown as Fig. 1, the reactor is connected with the once-through steam generator (OTSG) via a horizontal coaxial hot gas duct. Helium that is served as the coolant circulates between the reactor and the OTSG, and the heat produced in the reactor is taken away simultaneously. Based on reactor kinetics with one equivalent delayed neutron group considered, temperature feedback and reactivity feedback determined by the pebble-bed/reflector community, the dynamic model of the MHTGRs can be described as (Dong, 2014a,b; Zhe, 2015; Dong, 2014c, 2015):

$$\begin{cases} \dot{n}_r = \frac{\rho_r-\beta}{\Lambda} n_r + \frac{\beta}{\Lambda} c_r + \frac{\alpha_R}{\Lambda}(T_R - T_{R,m}) n_r \\ \dot{c}_r = \lambda(n_r - c_r) \\ \dot{T}_R = -\frac{\Omega_P}{\mu_R}(T_R - T_H) + \frac{P_0}{\mu_R} n_r \\ \dot{T}_H = \frac{\Omega_P}{\mu_H}(T_R - T_H) - \frac{\Omega_S}{\mu_H}(T_H - T_S) \\ \dot{\rho}_r = G_r \upsilon_r \end{cases} \quad (1)$$