Review on Application of Control Algorithms to Power Regulations of Reactor Cores

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Abstract. This research is to solve the stability analysis issue of nonlinear pressurized water reactor cores. On the basis of modeling a nonlinear pressurized water reactor core using the lumped parameter method, its linearized model is achieved via the small perturbation linearization way. Linearized models of the nonlinear core at six power levels are selected as local models of this core. The T-S fuzzy idea for the core is exploited to construct the T-S fuzzy model of the nonlinear core based on the local models and the triangle membership function, which approximates the nonlinear core model within the entire range of power level. This fuzzy model as a bridge is to cater to the stability analysis of the nonlinear core after defining its stability. One stability theorem is deduced to define the nonlinear core is globally asymptotically stable in the global range of power level. Finally, the simulation work and stability analyses are separately completed. Numerical simulations show that the fuzzy model can substitute the nonlinear core model; stability analyses verify the nonlinear core is globally asymptotically stable in the global range of power level.

1 Introduction

Nuclear power plants (NPPs) have underwent the sixty-year development process of generating electricity since 1950s. Though nuclear accidents such as Three Mile Island, Chernobyl and Fukushima invoked society fears of NPPs in different extent, nuclear energy as a clear energy makes the nuclear power industry be able to obtain sustainable development guaranteeing that NPPs operate safely and effectively. In terms of the nuclear power planning [1], the four-generation technologies of NPPs will be applied in 2030s. Hence, developing technologies of NPPs is an inevitable trend.

Of NPP technologies, the power regulation technology of reactor cores is a key one. Improving power regulation technology of cores by the introduction of control algorithms is an important measure for safety and availability of NPPs. Over the decades, many control algorithms have been exploited and applied by researchers to core power regulations, which are the state- or output-feedback control with a state observer [2-17], the optimal control [18,19], the neural network or fuzzy intelligent control [20-25], the model predictive control [26-28], the H_∞ robust control [29-31], the sliding model control [32-35], the fractional order control [36-41] and other control algorithms [42-50].

In the paper, a review on these control algorithms for core power regulations is proposed. This review can contribute to understand the past research work with separate merits, and exploit novel research directions about core control schemes in the light of this work. Eventually, conclusions are drawn.

The remainder of this paper is organized as follows. The review on the state- or output-feedback control with a state observer of cores is presented in Section 2. Section 3 shows the review on the optimal control of cores. The review on the neural network or fuzzy intelligent control of cores is provided in Section 4. Section 5 shows the review on the model predictive control of cores. The review on the H_∞ robust control of cores is provided in Section 6. Section 7 shows the review on the sliding model control of cores. The review on the fractional order control of cores is provided in Section 8. Section 9 shows other control algorithms of cores. This paper ends with Section 10 of making conclusions and references separately.

2 Feedback Control with State Observer

Edwards et al. [2,3] proposed the state-feedback assisted classical control (SFAC) for regulating the power of

reactor cores which retains a classical output-feedback control part and uses state-feedback to modify reference load signals so that desired reference inputs can be obtained. Simulations showed that SFAC is competent to perform power regulations. The flexibility idea, the multi-model modeling, and the state- or output-feedback control with full-state Kalman filters in which LQG, LQG/LTR, the robust or Ackermann pole placement method were applied were proposed by Li et al. [4-7] to design pressurized water reactor (PWR) core control systems for power regulations in the whole range of power level. Ben-Abdenmour et al. [8] used the LQG/LTR control to contrive a PWR core robust control system in order to improve dynamics of the fuel temperature and coolant temperature during core power regulations. The improved PWR core power LQG/LTR control system was achieved by Arab-Alibeik et al. [9] based on SFAC, where there are an inner loop to regulate reference load signals and a outer loop to control model outputs. Dong et al. [10-14] presented a physically-based feedback control approach with observers such as a dissipative high gain filter to devise reactor core power-level control systems. A multi-model feedback control with a state observer was proposed by Wu et al. [15] to carry out power regulations of a PWR core. Sharma et al. [16] developed the state-feedback based controller to control the power of a large PWR core through the introduction of an output sampling technique and a LMI formulation. A state-feedback controller is contrived by Xia et al. [17] to obtain desired power distributions of a CANDU reactor core based on the linear quadratic regulator control.

3 Optimal Controls

Park et al. [18] proposed the control method including coarse and fine regulation stages under the optimal control theory framework in order to design a core power control system. The partial-state-feedback was adopted by Zhao et al. [19] into the optimal transfer control method so that a core power optimal control system was achieved with optimal dynamic performance.

4 Neural Networks or Fuzzy Intelligent Control

Ku et al. [20] devised the core coolant temperature control system using the diagonal recurrent neural network control which contains a neuro-controller and a neuro-identifier so that core power regulations can be achieved well. The core power neural network control system was presented by Khajavi et al. [21] in which a robust optimal self-tuning regulator response is utilized as a reference trajectory to determine the feedback, feedforward and observer gains of this neural network controller. Khorramabadi et al. [22] designed the emotional learning based intelligent controller for regulating the core power which includes a neuro-fuzzy system with power error and its derivative as inputs. The novel fuzzy intelligent control system for core power regulations was provided by Rojas-Ramírez et al. [23]

tuning fuzzy system parameters through the use of a program based on a Lyapunov theory. Coban et al. [24] employed the multi-feedback layer neural network with a optimal process of using the particle swarm optimization to devise a core power control system. Simulations showed that the system has remarkable performance on the power level control for tracking step reference trajectories. The fuzzy intelligent control system to regulate the power of a reactor core was achieved by Coban et al. [25] exploiting genetic algorithms to optimize membership functions and weights.

5 Model predictive control

Etchepareborda et al. [26] applied a constrained output-feedback nonlinear receding horizon control to design a research core power controller with excellent performance for power regulation and known disturbances rejection. The robust model predictive control was utilized by Eliasi et al. [27] to devise a core power control system considering the limited input and output of this controlled core. Tai et al. [28] proposed the multi-model predictive control method to deal with the global power control issue for a PWR core within the whole range of power level.

6 H-infinity Robust Control

The H_∞ control was introduced by Suzuki et al. [29] to contrive a core power control system. Simulation results of the H_∞ control system were compared with that of the LQG control system, and comparisons showed the H_∞ control system has stronger robustness for stability and disturbances rejection. Chi et al. [30] adopted the H_∞ optimal control to control xenon oscillations in a core, and the designed H_∞ control system has desired stability robustness and performance robustness. Emara et al. [31] presented the combination of the H_∞ state-feedback control with LMI solution and the Schur model reduction approach to contrive a nonlinear reactor core power robust control system with satisfied dynamics.

7 Sliding model control

Shtessel [32] designed a sliding model control system for core power regulations so that robustness of the power control and tracking accuracy of the controlled power are enhanced. Simulation work showed that this system has good control performance. The combination of a sliding mode control method and a sliding mode observer was exploited by Ansarifard et al. [33] to devise a reactor core power control system, and stability analysis of this control system was also accomplished using the Lyapunov theory. Reddy et al. [34] contrived a PWR core spatial power control system by the use of the sliding mode control and a core state observer. The spatial power distribution control system of an advanced heavy water reactor core was achieved by Munje et al. [35] based on the sliding mode control.

8 Fractional Order Control

Linear reactor core models corresponding to five core power levels were solved and obtained by Das et al. [36] proposing innovative applications of the fractional order PID control with the genetic algorithm for optimizations of control parameters to these models, and simulations showed that this core power regulations can be carried out well. Saha et al. [37-39] devised a fractional order PID controller of the identification model and reduced order model for a CANDU type pressurized heavy water reactor with practical test data in order to regulate this reactor power. The combination of the fractional order PID control and the new neural network algorithm to optimize controller parameters was effectively exploited by Zhao et al. [40] to develop a PWR core power control system. Bhasse et al. [41] contrived a fractional order PI power control system for a pressurized heavy water reactor using the locus algorithm considering stability boundaries and step-back condition.

9 Other control

Torabi et al. [42] researched the PWR core power control issue for large operating ranges using the quantitative feedback control theory, and study conclusions show robust control performance of such control approach. The feedback dissipation and backstepping, or the physically-based control approach was applied by Dong et al. [43-45] to study core power nonlinear control systems for a modular high temperature gas-cooled nuclear reactor or PWR core. Dasgupta et al. [46] accomplished stability analysis of a networked discrete PID control system of a large pressurized heavy water reactor with incomplete data and varying delay developing a switching system solution. The fuzzy-like PD control system for spatial power regulations of an advanced heavy water reactor was achieved by Londhe et al. [47] introducing a robust rule base. Banerjee et al. [48] contrived a reactor power PID robust control system through the adoption of an interval approach for shift of reactor parameters based on a model of pressurized heavy water reactor. Sun et al. [49] tackled the power control issue for movable operation conditions modeling a multivariable model of a supercritical water-cooled reactor and developing a decoupling control system of this model according to the feedback control with gain scheduling. The feedback linearization robust control system of a research reactor core was proposed by Eom et al. [50], which possesses the ability of observing states and limiting the core power change rate.

10 Discussions

Obviously, the design of control systems for regulating the reactor core power can be achieved applying control algorithms aforementioned to linearized or nonlinear core models at the full power or the core multi-model at varying operation conditions. Generally speaking, linear core power control systems possess desired control ability in the $\pm 10\%$ FP range of power level, whereas

nonlinear or intelligent core power control systems have suitable control performance in larger ranges of power level; multi-model core power control systems show global control capability for nonlinear plants such as reactor cores.

11 Conclusions

Using nuclear energy to produce electricity will be an inevitable trend in the future. Continuous improvement for NPP technologies is required. Obviously, it is meaningful to research and develop high-performance control techniques for reactor cores. Great community efforts have been continuously made to propose advanced power control approaches of cores. The review on these core power control algorithms is necessary from the theoretical research or practical application level.

In this paper, this reviewing work is achieved, which involves the state- or output-feedback control with a state observer, the optimal control, the neural network or fuzzy intelligent control, the model predictive control, the H_∞ robust control, the sliding model control, the fractional order control and other control algorithms. The review provides a new viewpoint to understand the past work with respective advantages and exploit novel research fields on core power control.

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