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Model-free adaptive control law for nuclear superheated-steam supply systems

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ABSTRACT

Nuclear steam supply system (NSSS), which provides saturated or superheated steam to the secondary loop system for electricity or cogeneration, is central in a nuclear plant. The control of NSSS is important for the safe, stable and efficient plant operation. Nuclear superheated-steam supply system (Su-NSSS), which is equipped with an under moderated fission reactor and a once-through steam generator (OTSG) for producing superheated steam flow, is an important type of NSSS that widely applied in the nuclear plants based on the common large pressurized water reactors (PWR) and small modular reactors (SMRs) such as integral PWR (iPWR) and modular high temperature gas-cooled reactor (MHTGR). There is still very limited results for the control of Su-NSSS. Motivated by the gap between the importance and the lack of results in the field of Su-NSSS control, a model-free adaptive power-level control law is developed for Su-NSSSs with forced primary circulation in this paper. This new control law is free from physical and thermal-hydraulic parameters, is in the simple proportional-integral (PI) or proportional-differential (PD) form. To verify the feasibility of the newly-built Su-NSSS controller, it is applied to the NSSS control of a two modular high temperature gas-cooled nuclear plant with comparison to a specific MHTGR-based NSSS control law. Numerical simulation results show that this new control law can improve the transient performance of neutron flux and steam temperature in normal operation case, and can realize system resilience in some abnormal cases.

1. Introduction

Nuclear fission energy is a very important clean energy that can substitute the fossil in a centralized way and in a great amount with both commercial availability and economic competitiveness. Because of its persistency in power supply, nuclear fission energy can also be incorporated with those renewable energy resources such as the wind and solar to build hybrid energy systems (HESs) [1,2] which have the virtues of persistent power supply and cogeneration of electricity, process heat, desalinated water, hydrogen and etc. The schematic diagram of a general nuclear plant is shown in Fig. 1, where a nuclear steam supply system (NSSS) is usually composed of a nuclear fission reactor, a steam generator (SG), the primary and secondary loop pumps and etc. Both the U-tube steam generator (UTSG) and once-through steam generator (OTSG) can be adopted to provide satisfactory steam flow for secondary loop system. The NSSS equipped with OTSG can produce superheated steam flow, which results in a high thermal efficiency. Actually, OTSG has already been commonly adopted in NSSSs based on small modular reactors (SMRs) such as integral pressurized water reactor (iPWR) and modular high temperature reactor (MHTGR) whose output electric power is no more than 300MW$_e$ [3–6]. Specifically, the MHTGR such as German HTR-module [7–9], US MHTGR [10], and Chinese HTR-PM [11–13] has already been seen as an inherently safe and strongly efficient nuclear fission energy source for the cogeneration of electricity and process heat. The inherent safety is determined by the low power density, strong negative temperature feedback effect and large surface-to-volume ratio, and the strong efficiency is given by the high outlet helium temperature. Fig. 2 gives a schematic diagram of the nuclear steam supplying system (NSSS) module of HTR-PM plant that is under constructed at Shandong Shidao bay of China [13]. As shown in Fig. 2, the cold helium pressurized by the blower to 7 MPa is guided through the boreholes in the side reflector upwards to the so-called cold gas plenum inside the top reflector where it is collected and deflected, and then flows downwards through the pebble-bed

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Nomenclature

c_r	normalized concentration of one-group precursor
n_r	normalized neutron flux
v_r	control rod speed (m/s)
G_r	differential worth of control rods
M_S	mass flowrate times its specific heat capacity of OTSG secondary flow (W/°C)
P_0	rated reactor thermal power (W)
T_R	temperature of the reactor core (°C)
$T_{R,m}$	initial equilibrium of T_R (°C)
T_P	temperature and reactivity feedback coefficient of the primary coolant (°C)
$T_{P,m}$	initial equilibrium of T_P (°C)
T_S	average temperature of OTSG secondary coolant (°C)
T_{Sin}	inlet temperature of the OTSG secondary coolant (°C)
α_C	reactivity coefficient of primary coolant temperature (1/°C)
α_R	reactivity coefficient of reactor core temperature (1/°C)
ρ_r	reactivity induced by the control rods
λ	precursor decay constant (1/s)
μ_R	total heat capacity of the reactor core (Ws/°C)
μ_P	total heat capacity of the primary helium flow (Ws/°C)
μ_S	total heat capacity of the secondary water/steam flow (Ws/°C)
Λ	effective prompt neutron life time (s)
Ω_P	heat transfer coefficient between the primary helium flow and reactor core (W/°C)
Ω_S	heat transfer coefficient between OTSG two sides (W/°C)

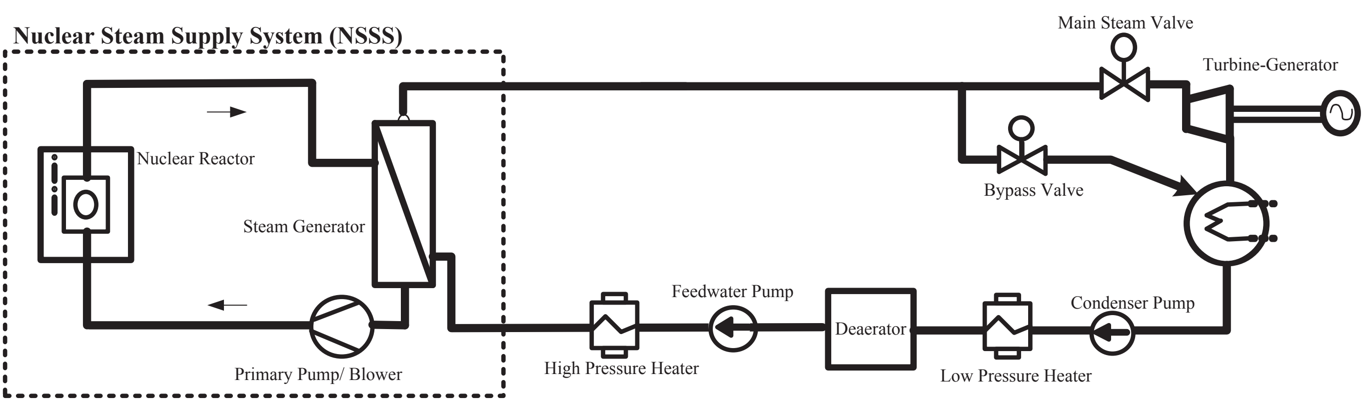

Fig. 1. Schematic diagram of a general nuclear power plant.

where it is heated up to 750 °C at the rated condition. The helium flow is collected in the hot gas plenum inside the bottom reflector, from where it is guided via the hot gas duct to the primary-side of helical-coil once-through steam generator (OTSG), and turns secondary feedwater to superheated steam of 571 °C and 13.9 MPa. The side-by-side arranged OTSG is lower than the MHTGR, which decouples the heat source away from the heat sink after a reactor shutdown, and enhances the safety performance. Moreover, based upon the multi-modular scheme, a system of multiple MHTGRs is suitable to build large-scale nuclear plants at any desired power ratings. The following Fig. 3 gives the schematic diagram of the two-modular HTR-PM plant. The combined steam flow from the two modules drives the turbine/generator for producing electricity, and becomes to the condensed flow which enters to the deaerator after being pressurized by the condenser pump and reheated by the low pressure heater (LPH). The saturated water inside the deaerator is injected to an MHTGR-based NSSS module for a new steam cycle after being pressurized by a feedwater pump and reheated by the high pressure heater (HPH). The main design parameters of HTR-PM plant are shown in Table 1.

Due to the ability of offering substantial benefits in safety, security, economics and operational flexibilities, SMRs have been well positioned to figure prominently in the second nuclear energy era [3]. Since the secondary-side heat capacity of OTSG is much smaller than that of UTSG, the secondary dynamics of the OTSG are tightly coupled with the primary side. Therefore, it is necessary to regard the OTSG-based nuclear superheated-steam supply system as an entire system, and develop proper control approach for this complex nonlinear system. However, the current research results focus on the individual control of fission reactors and SGs. In the field of nuclear reactor control, there have been many meaningful results such as the methods of state feedback assisted classical control (SFAC) [14–16], sliding mode control (SMC) [17,18], model predictive control (MPC) [19,20], fuzzy logic control (FLC) [21,22], fractional order control (FOC) [23] and physics-based control (PBC) [24–26]. The SFAC can strengthen the local stability by remaining the classical control loop and adding a state-feedback compensating loop. The SMC approach guarantees the globally asymptotic stability (GAS) based upon the interconnection of a sliding mode controller and a sliding mode observer. The MPC approach can not only well handle the constraints on system state and input but also give a high control performance by solving a constraint optimization problem for a finite future at current time. The FLC methods can well deal with the system nonlinearity by the advanced features of fuzzy sets and fuzzy logic. The FOC is a promising approach in optimizing closed-loop transient performance. The PBC method adopts the shifted-ectropies of neutron kinetics and thermal-hydraulics to construct Lyapunov functions, and provides simple control laws for closed-loop GAS. Moreover, in the field of SG control, the results mainly focuses on the regulation of UTSG water-level, and some effective level controller based upon the methods such as MPC [27,28], FLC [29,30] and neurofuzzy [31] were proposed, which can strengthen the water-level stability. Although there are still very limited results in the regulation of OTSG, some