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Coordinated control system design and verification of HTR-PM plant

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ABSTRACT

The modular high temperature reactor (MHTGR), which uses helium as coolant and graphite as both moderator and structural material, has inherent safety features. It is multi-modular, i.e. the superheated steam produced by multiple MHTGR-based nuclear supplying system (NSSS) modules are combined to drive a common thermal load. The inherent safety feature of MHTGR can applied to a large-scale nuclear plant of any desired power ratings by adding modules. Since the plant power control technique of classical single-modular plants cannot be directly applied to multi-modular plants, it is necessary to design a new power control system for multi-modular plants. In this paper, the coordinated control system is presented for the two-module HTR-PM plant, the first multi-modular high temperature gas-cooled nuclear plant to be constructed in the world. The control system design is tested on the full-scale simulator of HTR-PM plant for the cases of power and high ramp down pressure heater bypass. The results demonstrate the feasibility of control system design and the acceptable transient performance of the multi-module plant.

1. Introduction

The modular high temperature gas-cooled reactor (MHTGR) uses helium as coolant and graphite as moderator and structural material, and its inherent safety is determined by the low power density, strong negative temperature feedback effect and slim reactor shape (Lohnert 1990). China began to study the MHTGR technique at the end of 1970s, and a 10 MWth pebble-bed high temperature gas-cooled reactor HTR-10 achieved its first criticality in 2000 and full power in 2003 (Wu et al., 2002). Six safety demonstration tests were done on the HTR-10, which manifested its inherent safety and self-stabilizing features (Hu et al., 2006). Based on the HTR-10, a high temperature gas-cooled reactor pebble-bed module (HTR-PM) plant was proposed, which consists of two pebble-bed one-zone MHTGRs with a combined $2 \times 250\,\mathrm{MW_{th}}$ power, and adopts the scheme of two nuclear steam supplying system (NSSS) modules driving one turbine (Zhang and Sun, 2007; Zhang et al., 2009; Zhang et al., 2016). Each NSSS module of the HTR-PM plant is mainly composed of an MHTGR, a helical-coil once-through steam generator (OTSG), and a primary helium blower. As shown in Fig. 1, in the rated condition, 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 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 flow to superheated steam flow of 571 °C and 13.9 MPa. The side-by-side arranged OTSG is lower than the MHTGR, which decouples the heat source from the heat sink after a reactor shutdown, and enhances the safety performance. Moreover, based upon the multi-modular scheme, multiple MHTGRs can be used to build large-scale nuclear plants at any desired power ratings. The combined steam flow from the two NSSS modules drives the turbine/generator for producing electricity. The flow from the turbine is condensed, pressurized, deaerated, and reheated by the low pressure heater (LPH) before returning to the OTSG. 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). Now, the HTR-PM is in the stage of construction and commissioning. By incorporating more MHTGR-based modules, larger scale multi-modular high temperature gas-cooled nuclear plant can be realized. Plant power control is a key technique to provide safe, stable and efficient operation for every nuclear plant and to balance the power supply and demand. With comparison to the abundant results in reactor power-level regulation such as the classical modern control method, nonlinear control method and intelligent method (Edwards et al., 1990; Na et al., 2006; Ansarifar and Akhavan, 2015), there are still less results in the field of plant control. Shtessel gave a sliding mode plant control and state-observer for space plant TOPAZ II (Shtessel, 1998). Huang, Edwards, and

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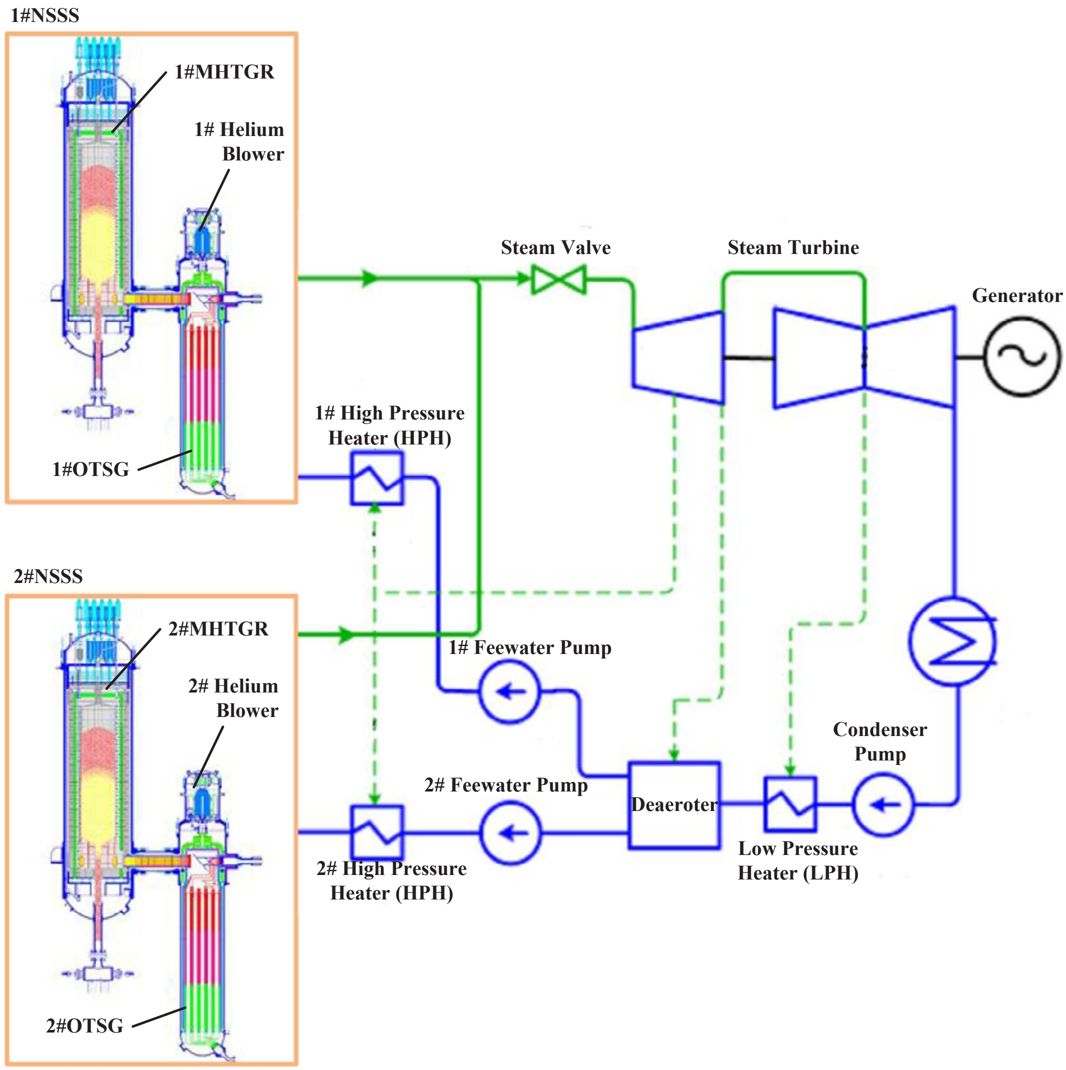

Fig. 1. Simplified diagram of HTR-PM plant.

Lee (2004) gave a fuzzy-adapted recursive sliding-mode plant controller for the advanced boiling water reactor (ABWR) plant. However, these results are suitable for the single modular plant. Due to the two-modular scheme, the key difference between the control of HTR-PM plant and that of those single modular plant is the coordination between two NSSS modules, which leads to the necessity of design and verification of the HTR-PM plant coordinated control system. The coordinated control system should be able to realize the control of every NSSS module and the coordination between the two modules. Based on the recently built physics-based control method for MHTGRs, OTSGs and NSSSs constituted by MHTGR and OTSG (Dong et al., 2011; Dong, 2015b; Dong, 2016) as well as multimodular coordinated control method (Dong, 2015a; Dong et al., 2016), it is now feasible to give the design of coordinated control system for HTR-PM plant.

In this paper, the coordinated control system design of HTR-PM plant including both the feedback loops and control laws is first proposed. Then, the verification of this engineering design is performed based upon the full scale simulator of HTR-PM plant, and the simulation results in the cases of power ramp down and bypass of high pressure heater are given, which shows that the stability and transient performance of HTR-PM plant is acceptable.

2. Coordinated control system design

Since the two NSSS modules of the HTR-PM plant are coupled together by the common secondary loop including the turbine/generator set, and since the side-by-side arranged MHTGR and OTSG of a NSSS module are tightly coupled with each other through the connecting pipes, it is more difficult to design a power control strategy for the two-modular HTR-PM plant than for those traditional single-modular traditional nuclear plants. Actually, the HTR-PM plant is essentially a large-scale and multi-inputmultioutput (MIMO) nonlinear system whose complexity of dynamics leads to the complexity of plant control. The coordinated control system of HTR-PM plant can be divided into two layers, i.e. the layer of NSSS module control and that of two-modular coordinated control. In this section, the control system design including design of control loops and that of control laws in these two layers are proposed.

2.1. NSSS module control

2.1.1. NSSS control problem

From Fig. 1, each NSSS module is constituted by an MHTGR, a side-by-side arranged OTSG, a primary helium blower mounted on top of the OTSG and the coaxial pipeline connecting the vessels of MHTGR and OTSG. Both the nodalization of a NSSS module and the relationship between the nodes are shown in Fig. 2, where the headers provided by the helium blower and feedwater pump can deeply affect the heat transfer between the reactor core and primary helium flow and that between the flows inside the two-sides of OTSG. The main NSSS