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Control of the nuclear steam generators using adaptive dynamic sliding mode method based on the nonlinear model

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ABSTRACT

The water level control problem of steam generators has been a main cause of unexpected shutdowns of nuclear power plants which must be considered for plant safety and availability. The control problem is challenging, especially at low power levels due to shrink and swell phenomena and flow measurement errors. Moreover, the dynamics of steam generator vary as the power level changes. Therefore, it is necessary to improve the water level control system of SG. In this paper, at the first a nonlinear model based on the fundamental conservation equations for mass, energy and momentum is presented for the nuclear steam generator which is validated with other computer programs and experimental results and then, an adaptive dynamic sliding mode control method is applied for the level control problem of U-tube steam generators based on the presented nonlinear model. The proposed method exhibits the desired dynamic properties during the entire output tracking process independent of perturbations. Simulation results are presented to demonstrate the effectiveness of the proposed controller in terms of performance, robustness and stability. Simulation results confirm the improvement in transient response obtained by using the proposed controller.

1. Introduction

One of the important components of a pressurized-water nuclear reactor is the U-tube steam generator (UTSG). Steam generators in PWR plants, transfer heat from a primary coolant system (pressurized water) to a secondary coolant system. The name UTSG is derived from the heat exchange region of the steam generator which consists of a number of equivalent inverted vertical U tubes.

The water level of the steam generator must not rise too high, because the steam will become moisture. Therefore, the wet steam may damage the turbine blades. Furthermore, if the water level is too low that the U-tubes are exposed, the heat will not transfer efficiently from the primary to secondary circuit. As a result, primary circuit accumulates heat within itself and leads to frequent reactor shutdowns. Therefore, the water level of a UTSG must be maintained at the preset limits in order to ensure a proper plant operation which has critical effects on the coolability, reactivity control, and pressure control of the reactor core, and the structural integrity of turbine blades.

The difficulties in designing an effective level controller for UTSG arise mainly from the following two factors: (1) the dynamics of a nuclear steam generator (SG) is very different according to the power levels and changes as time goes on. (2) Non-minimum phase characteristics of steam generator dynamics due to the so-called “swell and shrink” effect (Kothare et al., 2000).

It is well known that the conventional controller schemes do not offer a satisfactory automatic water level control for steam generators (Na and No, 1992). Therefore, many researchers have been engaged in designing effective water level controllers for SG, and many promising water level controllers have been established. Irving et al. (1979) presented a linear parameter varying model to describe the SG dynamics over the entire operating power range and proposed a model reference adaptive Proportional Integral Derivative (PID) level controller (Irving et al., 1979).The Irving model has probably been the most widely accepted SG models for the design of water-level controllers (Na and No, 1992; Choi et al., 1989). Designing suboptimal controller using linear output feedback control was reported by Feliachi and Belbelidia (1988). Various advanced control algorithms, which include robust control (Parlos et al., 2000), model predictive control (Kothare et al., 2000; Na, 2001) and intelligent control (Cho and No, 1997; Na, 1998), have been developed to control the water-level of SGs.

In spite of many advanced control methods proposed for controlling nuclear SG water level, operators are still experiencing

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difficulties especially at low powers. Therefore, it seems that a suitable controller with a higher control performance is still needed to replace the manual operations.

On the other hand, a successful strategy to control uncertain nonlinear systems is sliding mode control (John and james, 1993). The sliding mode controller is an attractive robust control algorithm because of its inherent insensitivity and robustness to plant uncertainties and external disturbances. However, the application of conventional sliding mode control to non-minimum phase systems is impeded due to the unstable inverse of such systems. To deal with the non-minimum phase characteristics of SGs, Ansarifar et al. presented a gain scheduled dynamic sliding mode controller based on Irving model for controlling the UTSG water level in the entire operating regime (Ansarifar et al., 2011). The dynamic sliding-mode controller exhibits acceptable tracking performance in the presence of parametric uncertainty only at the expense of high gains and control chattering. The performance of the dynamic sliding-mode controller depends on the size of the involved parametric uncertainties. This controller's performance degradation in gaining robustness is its undesirable characteristic which necessitates combining the control law with online parameter adaptation. In this paper, an *adaptive dynamic sliding mode controller* using the accurate and validated nonlinear model is presented for controlling the UTSG water level which improves the performance of the DSMC (dynamic sliding mode controller) proposed in Ansarifar et al. (2011), especially, in the face of parameter uncertainties.

The rest of the paper is organized as follows: Section 2 focuses on the water level control problems and U-tube steam generator model. Sections 3 and 4 present the formulation of the sliding mode control algorithm and adaptive dynamic sliding mode control design for water level control, respectively. Section 5 illustrates the computer simulations and the comparative results with respect to the gain scheduled dynamic sliding mode controller presented in Ansarifar et al. (2011). Finally, Section 6 concludes the paper.

2. The water level control problems and U-tube steam generator model

In this section, a description of the water level control problems and a mathematical model for UTSG are given.

2.1. Level control problems in the UTSG of a nuclear power plant

UTSG is thermal–hydraulic component in PWR type nuclear power plants for exchange of heat between the primary and secondary circuits and provides the necessary steam for generating electricity.

As shown in Fig. 1, two types of water level measurements are provided: Narrow Range Level (NRL) and Wide Range Level (WRL) (Kothare et al., 2000).

For the SG in a nuclear power plant (NPP), the main goal of control system is to maintain the narrow range water level at a desired value by regulating the feed water flow rate.

Difficulties in designing a nuclear steam generator water level controller arise from some issues summarized below:

(1) The UTSG is an open loop unstable system.
(2) Reverse thermal dynamic effects of "shrink and swell", which are more prominent at start-up and low power range of operation. This phenomenon is due to the two phase mixture of steam and water present in the tube bundles; a detailed discussion can be found in Kothare et al. (2000).

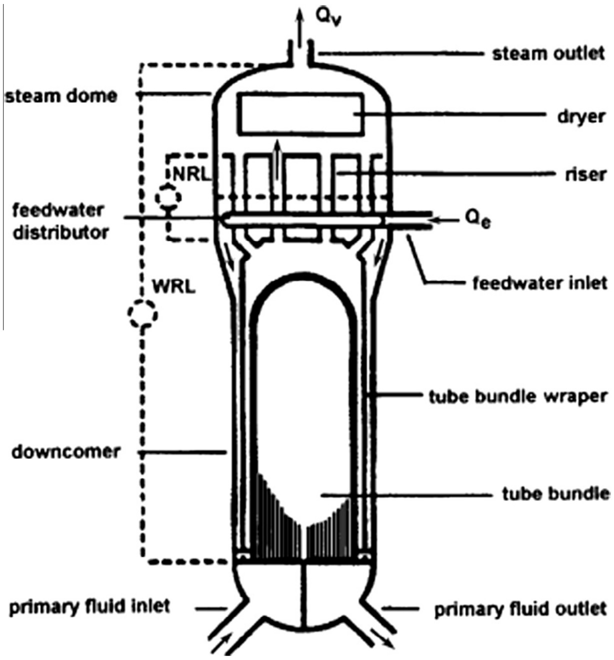

Fig. 1. A schematic of UTSG.

(3) Nonlinear plant characteristics, which is reflected by the fact that the plant model shows a significant variation with operating power.
(4) Process parameters uncertainties which need to be considered at the control design stage.
(5) An explicit limitation in the magnitude of the control signal. The problem in the water level control is the limited amount of feed water flow available for control.

2.2. Mathematical Model of UTSG

A widely used model for controlling UTSG is the linear parameter varying (LPV) model developed by Irving et al. (1979). But, considering nonlinear plant characteristics, to improve the efficiency and capability of controller and investigation of the thermal hydraulic parameters, a suitable nonlinear model based on the fundamental conservation equations for mass, energy and momentum, and basic thermodynamic principles is needed. Therefore, in this section a lumped nonlinear model based on the fundamental conservation equations for mass, energy and momentum is presented which is validated. Considering primary and secondary circuits, the mathematical model is given as follows:

Primary circuit

This section contains internal volume of the U-tubes, inlet and outlet of the coolant. Primary coolant temperature in the U-tubes is considered as:

$$T_{pr} = \frac{1}{2}(T_{SG} + T_{pro}) \tag{1}$$

where T_{SG} and T_{pro} are the primary inlet and outlet temperature, respectively. An energy conservation equation for the primary circuit can be written as follows:

$$\rho_{pr} V_{pr} C_{pr} \frac{dT_{pr}}{dt} = C_{pr} W_{pr}(T_{SG} - T_{pro}) - \alpha_{pr} A_{pr}(T_{pr} - T_m) \tag{2}$$

where, ρ_{pr}: primary coolant density, V_{pr}: total volume of the primary coolant inner tubes, C_{pr}: specific heat capacity of the coolant,

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