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Support vector regression model based predictive control of water level of U-tube steam generators

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HIGHLIGHTS

- Water level of U-tube steam generators was controlled in a model predictive fashion.
- Models for steam generator water level were built using support vector regression.
- Cost function minimization for future optimal controls was performed by using the steepest descent method.
- The results indicated the feasibility of the proposed method.

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ABSTRACT

A predictive control algorithm using support vector regression based models was proposed for controlling the water level of U-tube steam generators of pressurized water reactors. Steam generator data were obtained using a transfer function model of U-tube steam generators. Support vector regression based models were built using a time series type model structure for five different operating powers. Feedwater flow controls were calculated by minimizing a cost function that includes the level error, the feedwater change and the mismatch between feedwater and steam flow rates. Proposed algorithm was applied for a scenario consisting of a level setpoint change and a steam flow disturbance. The results showed that steam generator level can be controlled at all powers effectively by the proposed method.

1. Introduction

U-tube steam generators (UTSG) are some of the most important components of pressurized water reactors (PWR). Their main function is to transfer the heat generated in the reactor core by fission from the primary loop to the secondary loop. A typical 1200 MW_e PWR needs roughly 3600 MW_{th} heat transfer to the secondary side. Due to sheer magnitude of this power, a PWR of this size usually uses four steam generators running in parallel to accomplish the heat transfer duties. Although there is a variant called once through steam generator which is used in the old Babcock & Wilcox plants, most PWRs use UTSG type steam generators. Fig. 1 presents a typical UTSG diagram. Reactor coolant (water) from the primary loop with a 4.4 tons/s of mass flow rate enters the steam generator through hot leg at about 325 °C and leaves the steam generator through cold leg at about 290 °C (Westinghouse, 1984). Within the steam generator, primary coolant travels through a bundle of U-tubes and therefore this type of steam generator is known as U-tube steam generator. Primary coolant operating pressure is about 15.5 MPa which means that the primary coolant stays as liquid since the saturation temperature of water at that pressure is about 345 °C. On the shell side of UTSG, the operating pressure is about 6.9 MPa (with a saturation temperature of about 285 °C) and the feedwater of the secondary loop enters the steam generator, changes phase to vapor due to heat transfer, passes through separator and dryer regions and exits the UTSG as almost dry steam. It is usually a design requirement to limit the steam quality to a minimum of 99.75% at full rated power in order to send dry steam to the turbines on the secondary loop.

With respect to the working fluid, shell side of a UTSG has two distinct regions as the water section at the bottom and the vapor section on the top. Maintaining the water level within a UTSG is extremely important since there are severe consequences of not properly controlling it. If the water level in a UTSG is higher than

Abbreviations: GPC, generalized predictive control; GSS, golden section search; MISO, multiple input single output; MPC, model predictive control; PI, proportional and integral; PWR, pressurized water reactor; RBF, radial basis function; RMSE, root mean square error; SD, steepest descent; SVR, support vector regression; UTSG, U-tube steam generator.

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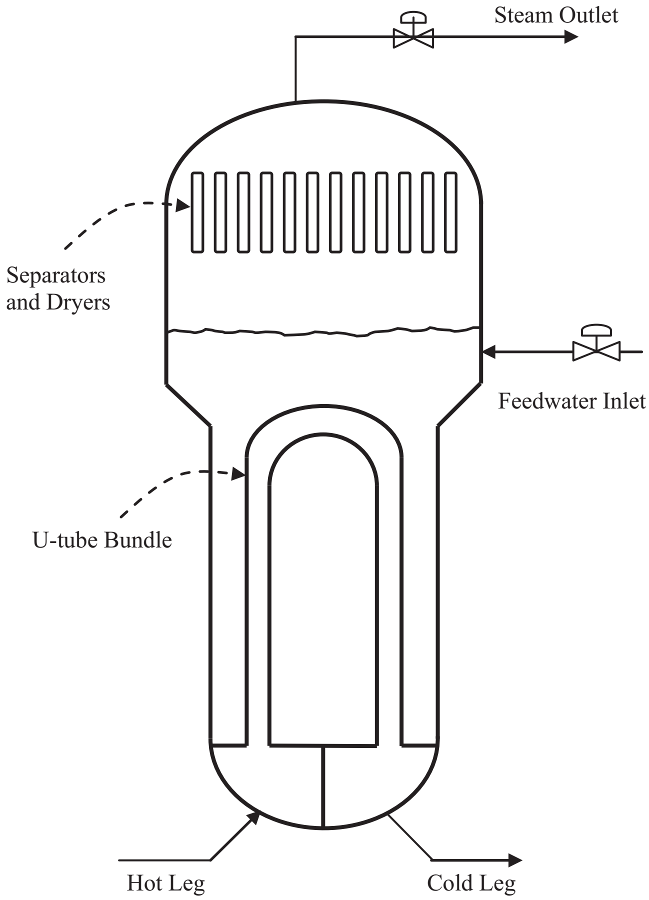

Fig. 1. Schematics of a typical UTSG.

what it should be, the amount of carryover of liquid water into the turbines increases. This is truly an undesired case for the turbine health as it will cause blade damage. If, on the other hand, the water level in a UTSG is lower than what it should be, the risk of exposing U-tube bundles to vapor rather than liquid increases. If that happens, the rate of heat transfer is reduced and as a result the steam generator tubes may overheat and cooling of the primary side core may become a serious problem. Due to those aforementioned problems, proper control of UTSG water level is an important control and operation problem for many PWR plants.

Many operating PWR plants employ a control strategy called "Three-Element-Controller" to regulate the water level in their steam generators (Westinghouse, 1984). In essence, this control strategy is about using two error signals; first is the level error as the difference between level setpoint and level measurement and the second is the flow error as the difference between feedwater and steam flow rates. These two error signals are then sent to a proportional and integral (PI) controller block to adjust the feedwater flow regulating valve position to maintain the water level in the UTSG at the desired value. The difficulty in UTSG water level control is mainly due to an effect called "shrink and swell" (Dong et al., 2008). Primary reason for observing shrink and swell phenomena is the existence of vapor bubbles within the water section of UTSG. Starting at steady state, if the feedwater flow rate is increased, one would expect the water level to go up since more water is introduced to the system. Indeed, this is the long term behavior of the system. However, in the short term, since the introduction of more water does effectively cool the steam generator, it reduces the volume of the vapor bubbles and causes a temporary reduction in the water volume and thus level. This is what is called the shrink phenomenon and it causes problems for traditional feedback control systems as the system with reverse dynamics may cause controllers to react in the wrong direction. Swell phenomenon is the opposite of shrink as the reduced feedwater flow to the UTSG will lead to a temporary increase in the water level before it starts to decrease. These types of systems are known as non-minimum phase systems as similar behavior is observed in linear plants with transfer function zeros in the right half plane (or outside the unit circle for discrete case) causing system phase-frequency plot to be non-minimum. Indeed this reverse dynamics is one of the reasons for using flow error in addition to level error in three element controller to alleviate some of the control performance issues. However, at low powers and reactor start-up, the problem cannot be handled by automatic controllers as single element control or manual control is applied (Dong et al., 2008). It is evident that sophisticated control systems are needed to solve this problem at all power levels and operations.

There is a good number of quality papers published on steam generator level control. Zhang and Hu (2012) studied a class of level controllers based on two PI controllers with an emphasis on performance assessment. Parlos and Rais (2000) used H_∞ approach with gain scheduling to regulate water level. Dong et al. (2008) used water mass inventory to control water level whereas Liu et al. (2010) used proportional control with partial feedforward compensation and decoupling approach for the same task. Safarzadeh et al. (2011) applied quantitative feedback theory and showed the effectiveness of this method. Tan (2011) used a first order feedback and a second order feedforward controller and concluded that the proposed gain-scheduled controller achieved better control performance. Gain scheduling is also applied by Kim et al. (1999) and it is reported that gain-scheduled controller performed effectively and much better than the conventional controllers. Habibiyan et al. (2004) implemented a fuzzy-gain-scheduled neural controller with better results over the conventional control. For the level signal, their controller achieved a smaller undershoot and a shorter settling time for the level setpoint change and steam flow disturbances compared to PI control. For the feedwater signal, their controller provided better overshoot and eliminated the spike caused by the PI control. There is also a class of steam generator level control studies using methods based on the areas of artificial intelligence or machine learning such as neural networks, fuzzy models and genetic algorithms. Cho and No (1996) designed a neuro-fuzzy controller with gain evaluated through Lyapunov's stability criteria. Na (1998) successfully applied a genetic fuzzy controller. Park and Seong (1997) used a self-organizing fuzzy controller for level control. Shen and Doster (2009) proposed neural network controllers. Fakhrazari and Boroushaki (2008) used adaptive critic-based neuro-fuzzy controller successfully. Munasinghe et al. (2005) used an adaptive neuro-fuzzy controller with smaller root mean square errors compared to PI control.

Due to having reverse dynamics characteristics, UTSGs are excellent candidates for model predictive control (MPC). MPC is an umbrella term for a multitude of controllers that use a predictive system model to evaluate the control signal. While various forms of MPCs are dating back to the 1970s, Clarke et al. (1987a, 1987b) formulated the popular generalized predictive control (GPC) variant that is essentially a receding-horizon architecture. In this method, future response of the plant is calculated by a model and based on that future response; a sequence of optimal future control actions is evaluated. The first element of the control sequence is applied to the plant and the process is repeated for the next time step. There are numerous applications of model predictive controllers in various industries (Qin and Badgwell, 2003; Darby and Nikolaou, 2012). In the area of steam generator level control, Kothare et al. (2000) effectively implemented model predictive control by using a linear parameter varying model of the UTSG. Similar approach was also