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A Concept of Instrumentation Failure Detection for Nuclear Power Plant

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1. Introduction

The monitoring system is one of the most important parts of the instrumentation and control (I&C) of nuclear power plants (NPPs). This system has a function to monitor NPP variables and provide data to other I&C systems and to operator for controlling the operation of the NPP. It has to provide the operators with accurate and appropriate information during both normal and abnormal operations. For providing the accurate and appropriate information, the monitoring system is supported by hundreds of measurements (instruments). Therefore it is important that instrument failures be detected before significant performance degradation. In this paper, an application of nonlinear filter to instrumentation failure detection mechanism is presented. The mechanism uses nonlinear filters to generate optimal estimates of the states. The nonlinear filter can work well for highly nonlinear problem that are difficult for the conventional Kalman filter.

Most of previous work on failure detection in a NPP used assumption that the dynamic plant that is monitored is linear or linearized so that conventional Kalman filter can be used as its estimator [1-6]. This paper reports on an attempt to apply a failure detection mechanism to the model of a pressurized water reactor (PWR) plant that is nonlinear. The proposed mechanism uses a bank of nonlinear filters to generate optimal estimates of the NPP states.

A PWR plant can be conveniently divided into components each of which can be modeled in the state space manner used in failure detection mechanism schemes based on the modern estimations theory. One of the important components is the pressurizer and this element was selected for the work reported here. The pressurizer of the loss-of-fluid test (LOFT) reactor was used because there is dynamic information available on this pressurizer [1-5]. This model has five instruments: a pressurizer sensor, a pressure sensor, a temperature sensor, and redundant level instruments

2. Discrete-Time Extended Kalman Filter

In estimating the states of a nonlinear system conventional Kalman filter is generally derived based on linearizing the nonlinear system around a nominal state trajectory. But it is difficult to know the nominal state trajectory. However, because the Kalman filter estimates the state of the system, the Kalman filter estimate can be used as the nominal state trajectory. The nonlinear system is linearized around the Kalman filter estimate by using this method. The Kalman filter estimate is based on the linearized system, which is the idea of the extended Kalman filter (EKF) [6-7].

It is assumed that the discrete-time system model is expressed as

$$\begin{aligned} x_k &= f_{k-1}\left(x_{k-1}, u_{k-1}, w_{k-1}\right) \\ y_k &= h_k\left(x_k, v_k\right) \\ w_k &\sim \left(0, Q_k\right) \\ v_k &\sim \left(0, R_k\right) \end{aligned} \tag{1}$$

The process noise w_k is discrete-time white noise with covariance Q_k, and the measurement noise v_k is discrete-time white noise with covariance R_k. By performing a Taylor series expansion of the state equation around $x_{k-1} = \hat{x}_{k-1}^{+}$ and $w_k = 0$, one obtains the following

$$x_k = F_{k-1} x_{k-1} + \tilde{u}_{k-1} + \tilde{w}_{k-1} \tag{2}$$

where the system dynamics matrix $F_{k-1} = \left.\frac{\partial f_{k-1}}{\partial x}\right|_{x_{k-1}=\hat{x}_{k-1}^{+}}$.

Linearization of the measurement equation around $x_k = \hat{x}_k^{-}$ and $v_k = 0$ leads to the following

$$y_k = H_k x_k + z_k + \tilde{v}_k \tag{3}$$

where the measurement matrix $H_k = \left.\frac{\partial h_k}{\partial x}\right|_{x_k=\hat{x}_k^{-}}$.

3. Pressurizer

The schematic diagram of the pressurizer model in this study is shown in Fig. 1. In the modeling it is assumed that steam and water within the pressure vessel is homogeneous saturated mixture. By applying mass and energy balances to this mixture and some manipulation, the following state equations may be obtained.

$$\frac{dP_p}{dt}=\frac{-v_p}{V_p\Gamma}\left\{v_p\frac{\partial h_p}{\partial X_p}\left(W_{su}+W_{sp}-W_{rv}\right)+\frac{\partial v_p}{\partial X_p}\left[Q_{htr}+W_{su}\left(h_{su}-h_p\right)+W_{sp}\left(h_{sp}-h_p\right)-W_{rv}\left(h_g-h_p\right)\right]\right\} \quad (4)$$

$$\frac{dX_p}{dt}=\frac{v_p}{V_p\Gamma}\left\{v_p\left[\frac{\partial h_p}{\partial P_p}-\frac{v_p}{J}\right]\left(W_{su}+W_{sp}-W_{rv}\right)+\frac{\partial v_p}{\partial P_p}\left[Q_{htr}+W_{su}\left(h_{su}-h_p\right)+W_{sp}\left(h_{sp}-h_p\right)-W_{rv}\left(h_g-h_p\right)\right]\right\} \quad (5)$$

$$\frac{dT}{dt}=\frac{m}{\tau}P_p-\frac{1}{\tau}T_x+\frac{c}{\tau} \quad (6)$$

Where $\Gamma=\frac{\partial v_p}{\partial P_p}\frac{\partial h_p}{\partial X_p}-\frac{\partial v_p}{\partial X_p}\left[\frac{\partial h_p}{\partial P_p}-\frac{v_p}{J}\right]$

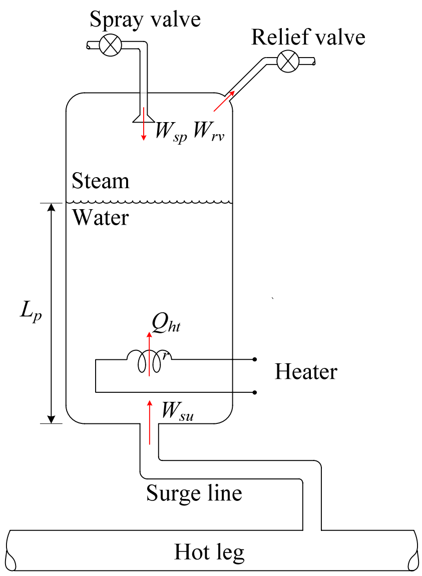

Fig. 1. Pressurizer model

4. Failure Detection

The scheme of the failure detection system is shown in Fig. 2. The filter produces a state estimate sensitive to particular instrument failure. The state estimates are then used to generate a failure decision function.

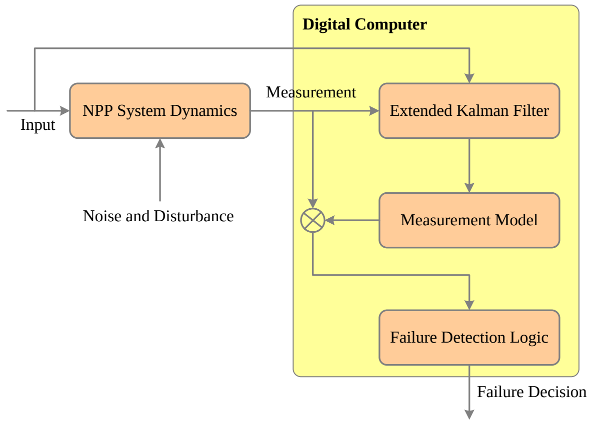

Fig. 2. Scheme of instrumentation failure detector

5. Conclusions

A concept of nonlinear filter application to instrumentation failure detection mechanism in NPP was presented. The mechanism uses nonlinear filters to generate optimal estimates of the NPP states. The nonlinear filter is one of alternative solutions to handle the NPP system highly nonlinear and very difficult for the conventional filter.

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