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Eliminating false alarms caused by fault propagation in signal validation by sub-grouping

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Abstract

Many signal validation methods detect sensor faults by comparing signal measurements with their estimates reconstructed from other correlated signals. For these methods, one faulty signal may cause all the other signals that use the faulty signal as an input in signal estimation to be un-correctly reconstructed and subsequently falsely identified as faulty too. This phenomenon is called fault propagation and can produce excessive false alarms in signal validation. This paper presents a general sub-grouping technique that uses specially designed intersections between sub-groups to eliminate the false alarms caused by fault propagation. Two methods are developed based upon this technique. Demonstration shows that both methods can dramatically reduce the occurrence of fault-propagation-caused false alarms in signal validation.

Keywords: Signal validation; Fault propagation; Sub-grouping technique

1. Introduction

Operation of a complex industrial system, like a nuclear power plant, highly relies on the information continuously collected by various detectors, sensors and instrument. Obviously, the reliability of instrument is crucial to the safe and economic operation of a nuclear power plant. Signal validation is an information processing technology that can provide online surveillance on instrument conditions and to detect signal changes caused by instrument faults. Various signal validation methods have been developed for nuclear and non-nuclear applications. Most of them validate signals by comparing signal measurements (sensor outputs) with their estimates reconstructed by outputs of other sensors that are correlated with the monitored signal. The difference between signal measurements and estimations, called residual signals, are then analyzed by either deterministic or stochastic rules to determine if the observed signal sequence has fault. This general methodology is shown in Fig. 1. Different methods (most of them are empirical) have been developed for system modeling and signal reconstruction. Typical examples include various artificial neural networks (ANN) based methods (Holbert and Upadhyaya, 1990; Upadhyaya and Eryurek, 1992; Fantoni and Mazzola, 1996; Hines et al., 1997; Erbay and Upadhyaya, 1997; Hines and Uhrig, 1998; Rasmussen et al., 2000), principle component analysis or its derivative independent component analysis (Penha and Hines, 2001; Ding et al., 2003), multivariate state estimation technique (MSET) (Singer et al., 1994; Singer et al., 1995), and support

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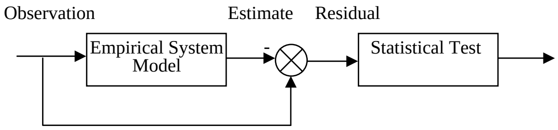

Fig. 1. A general methodology for signal validation.

vector machines (Zavaljevski and Gross, 2000). Most of these methods use a statistical tool, sequential probability ratio test (SPRT) (Wald, 1947), to analyze the residual signals (Gross and Kumenik, 1991).

However, there is a significant drawback in the signal validation process based upon the general methodology outlined in Fig. 1: if one signal (sensor output) is faulty, all signal estimates that use the faulty signal as an input in signal estimation generally are not correctly reconstructed and correspondingly do not agree with their signal measurements. This may cause healthy signals be falsely identified as faulty and thus lead to excessive false alarms in signal validation. This phenomenon is called fault propagation or spillover.

Fault propagation can be mathematically illustrated by a simple analysis. Assume we are interested in a group of correlated physical variables, denoted by X_1, X_2, …, X_p, of a plant state. The sensor outputs (signals) for these state variables are represented by x_1, x_2, …, x_p. The objective of signal validation is to make sure that the sensors faithfully measure the true physical quantities, i.e. $x_i \approx X_i$. The fundamental idea of the methodology given in Fig. 1 is to compare the sensor output x_i to its estimate $\hat{x}_i$, which is reconstructed by other observed signals x_1 to x_p (depending upon a specific system model, x_i itself may or may not be included) at the same physical state by either an explicit or an implicit function f; i.e.

$$\hat{x}_i = f(x_1, x_2, \ldots, x_p).$$

By applying Taylor expansion to this function around the true state variables, the residual signal r_i, the difference between the observed signal and its estimate, is then given by (Yu, 2002)

$$r_i \equiv x_i - \hat{x}_i = e_i - \sum_{k=1}^{p} \frac{\partial f}{\partial x_k} e_k$$

where $e_i \equiv x_i - X_i$ is the deviation of a sensor output from its true state variable. This expression clearly shows that in addition to fault in sensor i itself, fault in any other sensor in the group can also lead to a large residual signal r_i if that signal has a strong correlation with signal x_i (i.e. large $|\partial f / \partial x|$). Therefore, one faulty sensor may cause other sensors' outputs look suspicious and be wrongly detected as faculty too.

Fault propagation has been observed in various signal validation applications. This phenomenon cannot be avoided completely by improving system models alone. Fault propagation may not be a very serious problem for validating signals of a stationary state; but its effect is much more severe for validating signals of a transient process or multi-states, where it can cause a lot of false alarms. This paper presents a general strategy, a sub-grouping technique, to eliminate false alarms cause by fault propagation in signal validation.

2. Signal validation by sub-grouping

The basic idea of this sub-grouping technique is to decompose a group of correlated signals to be validated into several sub-groups with specially designed overlaps (intersections). The key is to make sure that each signal is assigned to more than one sub-group and no two signals are assigned to the same sub-groups so that each signal has a unique assignment code. Signals in each sub-group are validated by a system model built only upon these signals assigned to the sub-group. In this way, fault propagation is constricted only in these sub-groups that a faulty sensor, if any, is assigned to. Then based on the signal sub-group assignment scheme, the true faculty sensor can be identified easily.

Table 1 illustrates the basic idea of this sub-grouping assignment scheme by an example of decomposing 9 signals into 5 sub-groups, with each signal being assigned into 5 sub-groups. In the table, number '1' means a signal is assigned to a sub-group and '0' means it is not. These assignment 'numbers' form an assignment code for each signal; and obviously, each sensor (signal) has a unique binary assignment code so it can be easily identified if its outputs have fault.