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Supervision of an industrial steam generator. Part II: Online implementation

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Abstract

A bond graph model based Fault Detection and Isolation approach applied to design of a supervision system for a complex steam generator is presented. The non-linearities and energetic couplings involved in the dynamics require a suitable and adaptive supervision environment. The analytical redundancy relations are derived from bond graph model of the process by utilising of the structural and causal properties of the model. The decision procedure to detect and isolate the faults uses the residuals, evaluated online. Due to measurement noises and uncertainties in the process, many complementary decision procedures based on different methods of signal treatment are used to form an integrated supervision environment. The integrated platform allows to monitor the plant in normal operation as well as in the presence of faults. Finally, redundancy information is used for both automatic and manual reconfigurations to safely increase process availability by using adaptive real-time modifications to process control laws as well as equations of the process and the residuals to reflect the dynamics of the new configuration.

Keywords: Steam generator; Bond graph; Residual; Decision procedure; Supervision; Toolbox integration

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1. Introduction

According to statistical data, 70% of industrial accidents are due to human errors (Venkatasubramanian, 2001). In spite of the advances achieved in the control domain and in the computational capabilities in the field of process engineering, severe accidents have occurred in the last years: AZF of Toulouse, Union Carbide's Bhopal plant in India, the explosion at the Kuwait Petrochemical's Mina Al-Ahmedi refinery which resulted in hundreds of millions of dollars in damages, but especially the injury and death of many people.

That is where, a supervision platform as an integrated analysis and management environment plays a vital role. The term 'Supervision' means a set of tools and methods used to operate an industrial process in normal situation as well as in the presence of failures or undesired disturbances. The activities concerned with the supervision are the Fault Detection and Isolation (the FDI level), the diagnosis and the decision making to accommodate the fault by performing necessary reconfiguration, whenever possible (the fault tolerant control, FTC, level). The presence of a fault is detected at the monitoring level which determines whether the process is in normal operation or not. The tools associated with diagnosis and other high level tasks are executed only after detection of abnormal process state.

Each process has its own complexities which needs to be described by following a specific methodology, accordingly. The various fault detection and diagnosis methods can be broadly classified into quantitative model based methods, qualitative model and search based methods and process history based methods

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(Venkatasubramanian, Rengaswamy, Yin, & Kavuri, 2003c). Further subclassifications and detailed reviews on each approach are given in Venkatasubramanian et al. (2003c), Venkatasubramanian, Rengaswamy, and Kavuri (2003a), Venkatasubramanian, Rengaswamy, Yin, and Kavuri (2003b). In the first part of this two part series of papers, a quantitative model based method based on analytical redundancy relations (ARR) derived from bond graph (Thoma, 1975; Karnopp, Margolis, & Rosenberg, 1990; Mukherjee & Karmakar, 2000) model of processes is presented. The quantitative evaluation of ARR leads to a set of residuals, which can then be used for FDI. The residuals obtained numerically or from evaluation of ARR using real process measurements are extremely noisy signals due to the effect of noise in the measurements as well as the process drifts and uncertainties. Thus, well developed decision procedures are required to extract meaningful information in real-time from the residual signals. A comprehensive coverage of algorithms to detect abrupt faults is given in Basseville and Nikiforov (1993). Robust detection schemes aim at minimising the false alarms and non-detections.

When a fault is detected and isolated, a decision has to be taken to ensure the continuity of the process operation in the presence of the fault. This is done by applying the fault accommodation and reconfiguration techniques (Maciejowski, 1999; Kobi, Nowakowski, & Ragot, 1994). The reconfiguration strategy manages the transition from one operating mode to another according to the availability of the services (Ould Bouamama, Medjaher, Bayart, Samantaray, & Conrard, 2005, Oh & Quek, 2001).

In this paper, the ARR for the process are obtained using the bond graph model of the process in preferred differential causality and the algorithms presented in the first part of this series of papers. The obtained theoretical fault signature matrix is analyzed to derive the practical fault signature matrix in online implementation. The ARR obtained for the steam generator process are evaluated to generate the residuals and then they were treated using two different decision procedures. The online residual responses obtained during various forms of faults in the process and the isolation of the corresponding faults are presented. Finally, the information obtained from isolation of faulty components and redundancy information obtained from bond graph model are used for adaptive reconfigurations and online fault tolerant control of the process.

2. ARR for supervision of the steam generator process

The process and instrumentation diagram (P&ID) of steam generator process and its description are, respectively, given in Fig. 3 and Section 4 of the first part of this series of papers. The global bond graph model was also developed therein. The methodology for ARR generation from coupled bond graph models is explained with a pedagogic example. Following that methodology, the global bond graph model in preferred differential causality is given in Fig. 1. Furthermore, the static constraints between variables are added to the graph. In the behavioral model, static constraints are either unnecessary or are hidden within the relationships of the elements (e.g. linear dependence of rows of a matrix for a field element).

The pressure and temperature of steam in saturated condition are related by thermodynamic equilibrium conditions given in the steam tables. Thus, when one of them is considered as an independent variable (pressure is considered as independent variable here), the other becomes a dependent variable. In the model, the steam temperature is represented as a function of the steam pressure using the block Ps2Ts. Similarly, the condenser has a constant volume and measurement of the liquid volume by sensors L_{18} and L_{19} implicitly leads to measurement of the steam volume. Such static constraints are represented as virtual sensors in the model. The thermal resistance, R_{fm} between the boiler and its body is neglected. Note that the non-linear coupling capacitor, C_s, used to avoid algebraic loops in the steam expansion sub-system is not necessary in the preferred differential causality model.

When the causality of some sensors are inverted to assign differential causality to storage elements, the causalities of a set of sensors cannot be inverted. The sensors whose causalities cannot be inverted represent direct hardware redundancies (Staroswiecki, 2000) in sensor placement. The direct hardware redundancies detected in the steam generator installation are given in Table 1.

The 9 direct redundancies lead to 9 static ARR. These redundancies not only improve the fault isolation algorithm, but also provide the means for system reconfiguration and fault tolerant control of the process in the presence of faults.

In this section, we discuss only some complex parts of the process. The relations for the C_b field in differential causality describing the mass and energy storage in the boiler is given by $[m\ H] = \Phi_{C_b}(P, T,\ L)$, where m, H, P, T and L represent the total mass and enthalpy of the mixture, steam pressure, temperature and volume of the liquid phase, respectively. Note that since the steam temperature is a dependent variable, mass and enthalpy flow cannot be calculated using the effort information in the two passive ports. The inverted causality in the active port imparting measured liquid level information is used to calculate those variables as follows:

$$m_l = \frac{L_8}{v_l(P_7)}, \quad m_v = \frac{V_b - L_8}{v_v(P_7)}, \quad X = \frac{m_v}{m_l + m_v},$$
$$m = m_l + m_v, \quad H = m_l\, h_l(P_7) + m_v\, h_v(P_7), \tag{1}$$