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Detecting and Isolating Actuators Faults of Steam Boiler

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Abstract. *This paper deals with the Fault Detection and Isolation (FDI) on industrial systems such as steam generator process whose model is nonlinear and covers also the reconfiguration of the system in case of fault isolated. The FDI method is based on Analytical Redundancy Relations which are generated from a bipartite graph. These relations are used to detect and isolate faults using structural analysis, based on the elimination of the unmeasured variables of the system. An offline analysis of the system consists, after the reachability study, the FDI analysis and of postponing for each detectable and isolable fault. Online, an occurrence of fault is simulated. Then, FDI is in charged of detecting and isolating the actuator faults*

Keywords. *Reachability analysis, fault detection and isolation, structural analysis, steam boiler, fault tolerance, actuator faults*

1. Introduction

The steam generator process has a very large scale of applications in the industrial world. The abundance of the water on our planet and its interesting, thermodynamic characteristics are the best qualities needed to generate and to carry energy. And this energy is used in numerous ways like electricity or others. The steam generator vapor is an essential link of the water cycle.

This paper deals with the Fault Detection and Isolation in sensors around the steam generator vapor. The first step consists of modeling the steam generator vapor. Then, a nonlinear reachability analysis [1] of the system for the nominal set of actuators and

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all its subsets help us to apprehend the problem of FDI which constitutes the next step.

Nonlinear plants for FDI are a subject of fundamental importance in many areas of control engineering. In recent years, several methods are proposed to solve FDI problems such as approach based on analytical redundancy known as parity space in linear case and elimination theory in nonlinear case. Generation of residuals could be based on the technique of structural analysis [2], [3],[4]. This approach consists in finding analytical redundancy relations which contain only known variables. Those relations are satisfied if the residuals are null during the normal system functioning and non-null when the system fails. The bipartite graph is built representing the steam generator vapor's model. This graph is constituted by a set of nodes related each over by a set of arcs. Each node represents a variable of the system or a function related those variables. From this bipartite graph we obtain the incidence matrix and then the residuals.

The set of residuals generates a binary sequence where "0" represents a null residual and "1" a non-null residual. Those binary sequences are called signatures. By comparing those signatures with theoretical, known signatures representing the faults, faulty actuators could be deduced.

The FDI analysis done, the last step to set up a fault tolerant sensor system consists of postponing a reconfiguration of the control law after the localization of fault using only the remaining healthy actuators in order to continue to reach the objectives. In this paper, the reconfiguration could be not considered. But a reconfiguration could be used if the remaining set of actuators allows to reach the states of the system. So, offline analysis of the system consists of the modeling, the reachability analysis and the FDI analysis and of postponing for each detectable and isolable actuator faults (see [5]).

The second part is focused on an on line experimentation. An occurrence of actuator fault is simulated. Then, FDI is in charge to detect and to isolate the faults.

2. Offline analysis

2.1 Process description

Let us consider the pilot process whose global view is shown on figure 1. This installation is mainly constituted of four subsystems: a receiver with the feed water supply system, a boiler heated by a 60kW resistor (steam generator), a steam flow system, and a complex condenser coupled with a heat exchanger.

In the present paper is considered only a part of the pilot process composed of the steam generator and the steam flow system as shown on Figure1. The dynamic global model can be consulted in [6].

The feed water flow, taken from the receiver tank, is pressurized via the feed pump which is controlled by a relay to maintain a constant water level inside the steam generator. The heat power is determined based on the available accumulator pressure. When the accumulator pressure drops below a minimum pressure, the heat resistance delivers maximum power; on the contrary, when the accumulator reaches a maximum pressure, the electrical feed of the heat resistance is cut off.

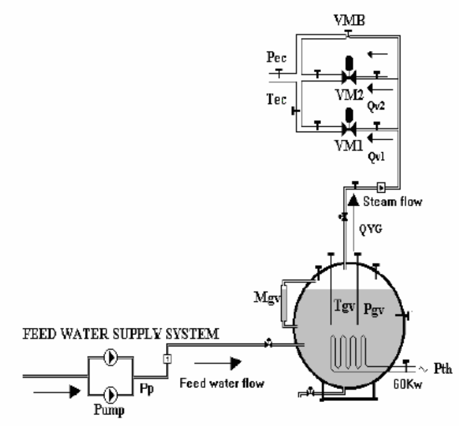

Fig 1 Technological schematic of the model

As inputs are used: the inlet feedwater flow Q_{AL}, the heating power P_{TH}, the ambient temperature (disturbance) T_{EX}, the pressure imposed by the external system (condenser) P_{EC} and the control signals O_{VC} and O_{VT} acting respectively on the valves V_{M1} and V_{M2}.

The basic equations of the system are the following:

2.1.1 Mass conservation law in the boiler

$$\dot{M}_{GV} = Q_{AL} - Q_{VG} \tag{1}$$

where Q_{VG} is the outlet steam flow from the boiler:

$$\begin{aligned} Q_{VG} &= Q_{V1} + Q_{V2} \\ &= K_{V1}(Z_{V1})(P_{GV} - P_{EC}) + K_{V2}(Z_{V2})(P_{GV} - P_{EC}) \end{aligned}$$

$K_{v1}(Z_{v1})$ and $K_{v2}(Z_{v2})$ are the nonlinear flow characteristics of valves V_{M1} and V_{M2} respectively and are identified experimentally as polynomial functions of the stem positions Z_{V1} and Z_{V2}.

Since the thermodynamic regime in the boiler is saturated, those pressure and temperature are dependant and can be expressed as polynomial functions:

$$P_{GV} = f(T_{GV}) = \frac{T_{GV}}{9} - 10 \tag{2}$$

2.1.3 Energy conservation law of the boiler

$$\dot{H}_{GV} = \dot{H}_{AL} + P_{TH} - Q_{VG} h_V(P_{GV}) - K_{MG}(T_{GV} - T_{MG}) \qquad \textbf{(3)}$$

where K_{GM} represents the global heat transfer from the fluid to the body of the boiler, h_V is the specific enthalpy of the steam.
The specific enthalpy of the mix (liquid-vapor)

$$h_{GV} = h_l(P_{GV}).(1 - X) + h_v(P_{GV}).X \qquad \textbf{(4)}$$

The specific volume of the mix :

$$\rho_{GV} = \rho_l(P_{GV}).(1 - X) + \rho_v(P_{GV}).X \qquad \textbf{(5)}$$

P_{GV}, and T_{GV}. can be deduced from these two equations

$\overset{\bullet}{H}_{AL}$ is the enthalpy flow convected by the inlet feed water flow:
$\dot{H}_{AL} = M_{AL} T_{AL} C_{p_{AL}}$
T_{AL} and C_{pAL} represent respectively the temperature of the inlet water (considered constant) and the thermal capacity. Also, $Q_{AL} = M_{AL}$

2.1.4 Energy conservation law for the body of the boiler

$$\dot{Q}_b = M_{MG} C_{p_{MG}} \dot{T}_{MG} = K_{MG}(T_{GV} - T_{MG}) - K_{EX}(T_{MG} - T_{EX}) \qquad \textbf{(6)}$$

where M_{MG} is the total mass of the metal body of the boiler, C_{pMG} the specific heat capacity of the metal. K_{EX} represents the global heat transfer from the metal to the environment.

2.1.5 Dynamics of the valves

The identical dynamics of the electromechanical valves are identified using experimental data from the process. Their models are given under first order form:

$$\begin{aligned} \dot{Z}_{V1} &= -\lambda_5 Z_{V1} + O_{VC} \\ \dot{Z}_{V2} &= -\lambda_5 Z_{V2} + O_{VT} \end{aligned} \qquad \textbf{(7)}$$

After restructuring the equations and with the hypothesis that KEX=0 (no temperature exchange with outside), the model can be written under nonlinear form 1. Consider the following simplified nonlinear state-space model of the steam generator and steam flow system:

$$\begin{cases} \dot{h}_{GV} = \lambda_1 \dfrac{Q_{AL}}{M_{GV}} - \lambda_2 \dfrac{(T_{GV} - T_{MG})}{M_{GV}} + \dfrac{P_{TH}}{M_{GV}} \\ \qquad - \dfrac{1}{M_{GV}} \left(\begin{array}{l} (K_{V1}(Z_{V1}) + K_{V2}(Z_{V2})).\left(\dfrac{T_{GV}}{9} - 10\right) \\ + (K_{V1}(Z_{V1}) + K_{V2}(Z_{V2})).P_{EC} \end{array} \right).(h_V - h_{GV}) \\ \dot{T}_{MG} = \lambda_3 (T_{GV} - T_{MG}) \\ \dot{Z}_{V1} = \lambda_4.(-Z_{V1} + O_{VC}) \\ \dot{Z}_{V2} = \lambda_4.(-Z_{V2} + O_{VT}) \\ \dot{M}_{GV} = (K_{V1}(Z_{V1}) + K_{V2}(Z_{V2})).\left(\dfrac{T_{GV}}{9} - 10\right) + (K_{V1}(Z_{V1}) + K_{V2}(Z_{V2})).P_{EC} + Q_{AL} \end{cases}$$

with

$\lambda_1 = C_{PAL} T_{AL}$, $\lambda_2 = K_{MG}$, $\lambda_3 = \dfrac{K_{MG}}{M_{MG} C_{PMG}}$, λ_4 is proportional to the water gate opening $K_{V1}(Z_{V1}) = 0.007 * Z_{V1}$, $K_{V2}(Z_{V2}) = 0.0028$ is a constant, since the position of valve V_{M2} is manually fixed.

The values of that parameter can be found on table 1:

Table 4. Nomenclature and numerical values

Parameters	Values
Thermal capacity of water C_{PAL}	4180 (J/K)
Temperature of input water T_{AL}	300 (K)
Coefficient of heat exchange between the mixture (vapour-water) and the boiler K_{MG}	1000 (kg.m².s^{-3})
Mass of boiler M_{MG}	100 (kg)
Thermal capacity of the boiler C_{PMG}	640
Time-constant of the mechanical valve	0.3 (sec)

2.2. State space representation of process

The state representation of the boiler show as:

$$\dot{x}(t) = f(x(t)) + g(x(t)).u(t) \tag{8}$$

With

$$x(t) = \begin{pmatrix} h_{GV} & T_{MG} & Z_{V1} & Z_{V2} & M_{GV} \end{pmatrix}^T ,$$

$$u(t) = \begin{pmatrix} P_{EC} & P_{TH} & Q_{AL} & O_{VC} & O_{VT} \end{pmatrix}^T$$

$$f(x) = \begin{pmatrix} \lambda_2 \dfrac{(T_{GV} - T_{MG})}{M_{GV}} - \dfrac{(hv - h_{GV})}{M_{GV}}.(K_{V1} + K_{V2}).\left(\dfrac{T_{GV}}{9} - 10\right) \\ \lambda_3 (T_{GV} - T_{MG}) \\ -\lambda_4 Z_{V1} \\ -\lambda_4 Z_{V2} \\ (K_{V1} + K_{V2}).\left(\dfrac{T_{GV}}{9} - 10\right) \end{pmatrix} \qquad \mathbf{(9)}$$

And:

$$g(x) = \begin{pmatrix} -\dfrac{(hv - h_{GV})}{M_{GV}}.(K_{V1} + K_{V2}) & \dfrac{1}{M_{GV}} & \dfrac{\lambda_1}{M_{GV}} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \lambda_4 & 0 \\ 0 & 0 & 0 & 0 & \lambda_4 \\ (K_{V1} + K_{V2}) & 0 & 1 & 0 & 0 \end{pmatrix} \qquad \mathbf{(10)}$$

3. Reachability analysis

Reachability analysis analysis allows us to know if the system keeps reachable when actuator failures occur.

Table 2. Reachability Analysis of the Boiler Process

State x_j \input u_i	u_1 P_{EC}	u_2 P_{TH}	u_3 Q_{AL}	u_4 O_{VC}	u_5 O_{VT}
x_1 (T_{GV})	1	1	1	1	0
x_2(T_{MG})	1	1	1	1	0
x_3(Z_{V1})	0	0	0	1	0
x_4 (Z_{V2})	0	0	0	0	1
x_5 (M_{GV})	1	1	1	1	0
v_i	3	3	3	4	1

In table 2, x_j is generically reachable by the input u_i if and only if the cellular corresponding to the line of x_j and to the column of u_i is equal to 1.

Table 2 shows that state x_3 and x_4 are respectively generically reachable only by input u_4 and u_5. Also, u_4 can generically reach the state x_1, x_2 and x_5. So inputs u_4 and u_5 are necessary and sufficient to generically reach the state and therefore have to be detected and isolated without false alarms. So, the set of actuators $\{u_4, u_5\}$ is a minimal set of actuators. All sets of actuators which don't contain both actuators u_4 and u_5 are neither minimal or redundant. Finally, all sets of 3 actuators or more and containing actuators u_4 and u_5 are redundant. The choice of set of actuators containing u_4 and u_5 depend on the desired weak redundancy degree [5]. For instance, if the desired weak redundancy degree is greater or equal to 1, $\{u_1, u_2, u_4, u_5\}$, $\{u_1, u_3, u_4, u_5\}$, $\{u_2, u_3, u_4, u_5\}$, $\{u_1, u_4, u_5\}$, $\{u_2, u_4, u_5\}$, $\{u_3, u_4, u_5\}$ could be chosen. A reliability study could be computed in order to give the set of actuators having the best reliability. The loss of actuator 1, 2 or 3 from the nominal system yields to a reachable state. Thus, in these cases, a reconfiguration of the process can be considered.

4. Structural analysis

However, in presence of actuator fault, the first step is to detect and isolate this fault. FDI process is in charge of this detection and localization. Fault detection and isolation (FDI) by structural analysis to conceive FDI process from the nominal mode, an offline study must be developed. The aim of this analysis is to find the system's structural properties. We can define four sets from the model: the set of the equations F, the set of the unknown variables X, the set of the known variables C and the set of the variables $Z=X\cup C$.

We can define a bipartite graph $G=(F,Z,U)$ whose set of the nodes is $F\cup Z$, and set of arcs is U. An arc u_{ij} between F_i and Z_j exists only if the constraint F_i is followed by the variable Z_j (or if the variable Z_j is present in the equation F_i). In the steam generator vapour model, the constraints F_i are given by:

$$F_1 : \left(\begin{array}{l} \dot{h}_{GV} - \lambda_1 \dfrac{Q_{AL}}{M_{GV}} + \lambda_2 \dfrac{(T_{GV} - T_{MG})}{M_{GV}} - \dfrac{P_{TH}}{M_{GV}} \\ + \dfrac{(h_V - h_{GV})}{M_{GV}} \left(\begin{array}{l} (K_{V1}(Z_{V1}) + K_{V2}(Z_{V2})).\left(\dfrac{T_{GV}}{9} - 10\right) \\ + (K_{V1}(Z_{V1}) + K_{V2}(Z_{V2})).P_{EC} \end{array}\right) \end{array}\right) = 0$$

$$F_2 : \quad \dot{\mathrm{T}}_{\mathrm{MG}} - \lambda_3(\mathrm{T}_{\mathrm{GV}} - \mathrm{T}_{\mathrm{MG}}) = 0$$

$$F_3 : \quad \dot{\mathrm{Z}}_{\mathrm{V1}} + \lambda_4 \mathrm{Z}_{\mathrm{V1}} - \lambda_4.\mathrm{O}_{\mathrm{VC}} = 0$$

$$F_4 : \quad \dot{\mathrm{Z}}_{\mathrm{V2}} + \lambda_4 \mathrm{Z}_{\mathrm{V2}} - \lambda_4.\mathrm{O}_{\mathrm{VT}} = 0$$

$$F_5 : \left(\begin{array}{l} \dot{M}_{GV} - (K_{V1}(Z_{V1}) + K_{V2}(Z_{V2})).\left(\dfrac{T_{GV}}{9} - 10\right) \\ - (K_{V1}(Z_{V1}) + K_{V2}(Z_{V2})).P_{EC} - Q_{AL} \end{array}\right) = 0$$

$$F_6 : \quad y_1 - f(x_1, x_5) = 0$$

$$F_7 : \quad y_2 - x_3 = 0$$

$$F_8 : \quad y_3 - x_4 = 0$$

$$F_9 : \quad y_4 - x_5 = 0$$

And Z_j is composed of x_1, x_2, x_3, x_4, x_5, y_1, y_2, y_3, y_4, u_1, u_2, u_3 and u_4

From these constraints, the bipartite graph is drawn in Figure 7:

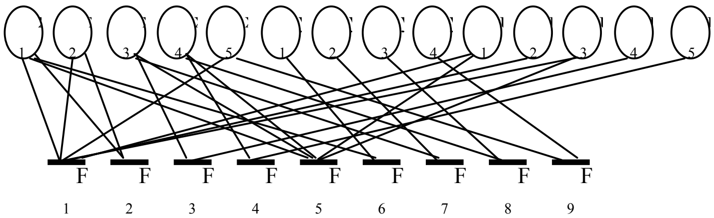

Fig.2: Bipartite graph

Residuals are computed from the constraints equation

$$\begin{aligned}
R_1 &= \begin{pmatrix} \ddot{h}_{GV}\, M_{GV} + \dot{h}_{GV}\, \dot{M}_{GV} + \lambda_2\, \dot{T}_{GV} - \dot{P}_{TH} + \dot{Q}_{AL}\, T_{GV} \\ + Q_{AL}\, \dot{T}_{GV} - \lambda_1\, \dot{Q}_{AL} - \lambda_3 R_{1a} + R_{1b} \end{pmatrix} \\
R_2 &= \dot{Z}_{V1} + \lambda_5 . Z_{V1} - \lambda_5 . O_{VC} \\
R_3 &= \dot{Z}_{V2} + \lambda_5 . Z_{V2} - \lambda_5 . O_{VT} \\
R_4 &= \begin{pmatrix} \dot{\mathrm{M}}_{\mathrm{GV}} + (\mathrm{K}_{\mathrm{V1}}(Z_{v1}) + \mathrm{K}_{\mathrm{V2}}(Z_{v2})).\left(\dfrac{\mathrm{T}_{\mathrm{GV}}}{9} - 10\right) \\ - (\mathrm{K}_{\mathrm{V1}}(Z_{v1}) + \mathrm{K}_{\mathrm{V2}}(Z_{v2}))\mathrm{P}_{\mathrm{EC}} - Q_{AL} \end{pmatrix}
\end{aligned} \qquad \textbf{(11)}$$

with

$$R_{1a} = P_{TH} + \lambda_1 Q_{AL} - M_{GV}\, \dot{h}_{GV} - (h_V - h_{GV}).\begin{pmatrix} (K_{V1}(Z_{V1}) + K_{V2}(Z_{V2})).\left(\dfrac{T_{GV}}{9} - 10\right) \\ + (K_{V1}(Z_{V1}) + K_{V2}(Z_{V2})).P_{EC} \end{pmatrix}$$

$$\begin{aligned}
R_{1b} = {} & \left(\dot{h}_V - \dot{h}_{GV}\right).\left((K_{V1}(Z_{V1}) + K_{V2}(Z_{V2})).\left(\frac{T_{GV}}{9} - 10\right) + (K_{V1}(Z_{V1}) + K_{V2}(Z_{V2})).P_{EC}\right) \\
& + (h_V - h_{GV}).\begin{pmatrix} \left(\dot{K}_{V1}(Z_{V1}) + \dot{K}_{V2}(Z_{V2})\right).\left(\dfrac{T_{GV}}{9} - 10\right) + (K_{V1}(Z_{V1}) + K_{V2}(Z_{V2})).\dfrac{\dot{T}_{GV}}{9} \\ + \left(\dot{K}_{V1}(Z_{V1}) + \dot{K}_{V2}(Z_{V2})\right).P_{EC} + (K_{V1}(Z_{V1}) + K_{V2}(Z_{V2})).\dot{P}_{EC} \end{pmatrix}
\end{aligned}$$

In these equations, there are only known variables and the table 3 shows the fault signature in which the monitorability (possibility of detection and isolation of failures) of only the actuator faults is analyzed. The set of residuals generates a binary sequence where "0" represents a null residual and "1" a non-null residual. Those binary sequences are called signatures. By comparing those signatures with theoretical, known signatures representing the faults, faulty could be deduced.

The columns of Db and Ib respectively represent the detectability and isolability of faults. A value of 1 appears in the table, if it is detected or isolated. We can see that all faults are detected and isolated. So, the fault of blocked valve OVC can be isolated based on the sign of the residual R2. That means if R2>0 more than a certain threshold, there exists an actuator fault of valve O_{VC} caused by the blockage. If we want to monitor leakage of valve, one more mass flow sensor needs to be added and then we can generate a redundancy sensitive to leaks, i.e., if the inlet sensor value is different to the outlet that means there is leakage on the valve.

Table 3. Fault Signature Matrix

Actuator Faults	Db	Ib	R1	R2	R3	R4
u_1	1	1	0	0	0	1
u_2	1	1	1	0	0	0
u_3	1	1	1	0	0	1
u_4	1	1	0	1	0	0
u_5	1	1	0	0	1	0

Assuming that only actuator faults can occur, no signatures are identical. So according to the real time computed residuals, the faulty actuator can be detected and isolated. For instance, if in real time, $(R_1,R_2,R_3,R_4)=(0,1,0,0)$, it means, by comparison to the fault signature matrix of table 2, that actuator 4 is faulty. So, in this case, for reconfiguration, only actuator $\{u_1, u_2, u_3\}$ will be used.

5. Simulation results

The figure 3shows the evolution of actuator commands. At time 20 s, valve Z_{v1} is completely opened however valve Z_{v2} is maintained constant at 40%. The figure 9 shows the residuals responses. These residuals are near zero when we suppose that any faults affect the actuators. If we assume that valve Z_{v1} is blocked, the command O_{VC} is sent to open this valve and the residual R_2 is different from zero, then we conclude this valve is faulty.

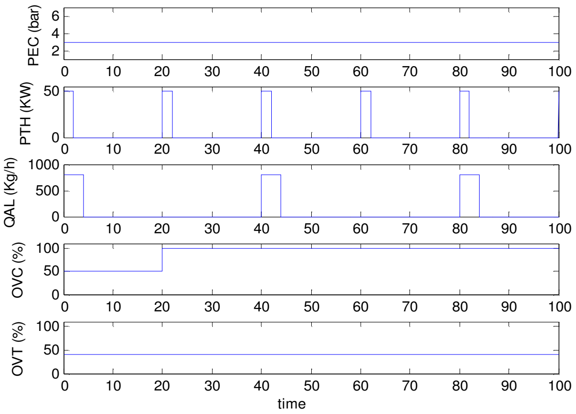

Fig 3. Evolution of commands

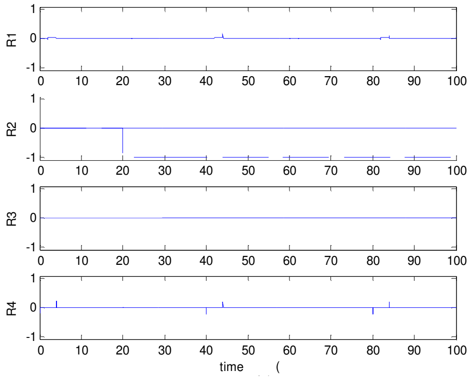

Fig 4 Evolution of residuals

After this structural analysis which shows us that each faulty actuator can be detected and isolated, the reconfiguration is possible if the system is still reachable

6. Conclusion

Reachability studies in case of faulty actuators are used to determine minimal and redundant sets of actuators to keep the functional reachable and then to know the maximal number of actuators which can be lost while keeping the system reachable or controllable. Our approach depends on isolation of faulty actuators. We have presented a structural analysis for fault detection and isolation of a actuator faults of steam generator vapour. The results of structural monitorability of this system show that all actuator faults can be detected and isolated. To isolate other failures, we just need to add sensors, i.e., for valve leakage, a mass flow sensor could be added.

The experimental results show that those faults can be detected and isolated if the residual exceeds the threshold which is fixed experimentally. In further work, a reconfiguration algorithm in future could be used and the only the best healthy actuators that satisfy the properties of fault tolerant control are used to reconfigure the system.

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