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Possibilities of fault tolerant control in thermal power plants

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Abstract: Fault diagnosis and fault tolerant control applications require that the structure of the target process contains certain redundancy in system observability and controllability. Usually the analysis of the existence of these properties is based on the laborious state space model of the process. However, the state space model is not necessary needed for the analysis. In this paper a structural analysis based on oriented bi-partite graphs is applied to analyze the properties of a thermal power plant process to show the redundant structures required for diagnostics and fault tolerant control. The analysis method is demonstrated by analyzing the structure of the secondary and tertiary air system of the boiler.

1. INTRODUCTION

Nowadays a level of process automation is very high taking care of almost everything during the normal operation of a process plant. However, handling of abnormal situations is still based on manual operations, and the success of overcoming the problems depends on the skills of the operators in shift. To automate the handling of abnormal situations, first the abnormal situation must be detected and analyzed and then the control strategy must be updated to meet the new requirements caused by a fault in a process. A control method capable to adapt to the changes caused by faults and maintain the process performance as good as possible is called a fault tolerant control (FTC). The fault tolerant control method is based on a fault diagnosis and redesign of the control algorithm.

The first step towards the automated handling of abnormal situations is fault diagnosis. Fault detection and isolation has been studied actively since 1970's. The pioneers of this research field were among others (Beard, 1971), (Clark, 1975), (Himmelblau, 1978), (Mehra, 1971), and (Willsky, 1976). Since then this area is developed remarkably further by e.g. Frank, Gertler, Isermann and Patton (Gertler, 1998), (Isermann, 1984), (Patton *et al.*, 2000). Fault detection is based on redundant information. The actual measured state of the process is compared with the redundant information to detect any anomalies between the actual and the expected trace of the system. The redundant information may be generated by redundant hardware, e.g. parallel measurements, or computed analytically using models. Fault isolation and identification is based on the analysis of residual information generated from the discrepancy between the measured and reference information. The analysis is carried out by using different kind of searching techniques to match the observed features of the residual to the properties of any known fault possible to take place in the process. So, to be able to isolate and analyze the severity of the fault, effects of all the faults planned to be detected must be modeled. For this reason it is necessary to concentrate on the faults which have the most serious effects on the operation of the process.

The second step in the automated handling of abnormal situations is to automatically adapt the control algorithm to meet the new requirements set by the diagnosed fault. The objective is to maintain process safety and closed loop performance as good as possible by accommodating or reconfiguring the control algorithm. This procedure is called an active fault tolerant control. A passive approach is to design a fixed robust controller, which is not sensitive to the effects of some selected faults (Keating, 1995), (Williams, 1990). The fault tolerant control methods are surveyed e.g. in (Blanke *et al.*, 2000) and (Patton, 1997).

The focus of this paper is to analyze the power plant process and to find the potential targets for fault tolerant control. The analysis is based on a structural analysis. With the structural analysis it is possible to find the interconnections between different process variables and analyze the propagation of faults in the system. Structural analysis is also a tool for analyzing the observability and controllability of the process. It is possible to analyze the existence of the redundant measurement information and redundant control capability needed for fault detection and fault tolerant control.

2. THERMAL POWER PLANT PROCESS

In order to apply FTC in a power plant, the process must be analyzed to find the appropriate control objects. Suitable targets for FTC are sub-processes which have a great influence on the availability and the efficiency of the plant. Also the diagnosability and controller reconfigurability must be taken into account.

The most critical sub-processes according to the availability of the power plant are feed water, fuel feed, combustion air, and flue gas processes. In these processes actuators like pumps, fans, and feeders are typically duplicated and equipped with automatic switching from faulty actuator to reserve actuator. Also fuel transportation from storage silos to

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a boiler house and feeding into the furnace is secured using parallel feeding lines and alternative fuels with alternative combustion equipment. There is also a number of measurements connected with a boiler safety system. E.g. water level in a drum boiler and furnace pressure are this kind of safety related measurements. These measurements are typically multiple and the state of the monitored condition is checked by voting e.g. 2 out of 3 (in case of 3 parallel sensors). So a single faulty measurement does not cause a shut down of the process.

The most important sub-processes according to the efficiency of the boiler process are combustion control and steam temperature control. The objective of the combustion control is to maintain the optimal fuel-air ratio both in steady state and transient modes. To achieve optimal circumstances for combustion, combustion air should be distributed optimally as a primary, secondary and tertiary air flows. The performance of the combustion control is directly related to the amount of flue gas and fuel losses, temperature stability in the furnace, and generated NO_x and CO emissions.

The objective of the steam temperature control is to stabilize live steam temperature entering the turbine. Live steam is typically superheated in three stages and the temperature is controlled by two attemperators connected between the superheating stages. In condensing power plants there is also steam reheating and temperature control between the high and the intermediate pressure stages of the turbine. Temperature is tried to get as high as possible, because the higher the temperature, the higher the efficiency of the steam turbine. The maximum allowed temperature is limited by the material properties.

3. FAULTS, DIAGNOSIS, AND FAULT TOLERANT CONTROL

A fault changes the operation of a technical system so that it can no more produce the required services. Faults can be classified as process component faults, sensor faults, and actuator faults. Process component faults effect on the dynamics between process inputs and outputs. Sensor faults influence on the measured information of the states of the process and they can lead to incorrect control actions. Actuator faults distort or totally cut the control action from the controller to the process. Faults can be classified also according to their sizes and dynamics. Faults can be abrupt, incipient, or occasional.

Fault diagnosis can be understood as an inverse simulation. In the simulation the behavior of the process is studied on the base of the structure and the functionary of the process, but in the diagnosis the structure and the functionary are studied according to the behavior of the process. The diagnosis system extracts features from the behavior of the process and according to these features the system tries to classify the observed behavior. The classification methods can be based on pattern recognition, model based reasoning, and model matching.

The objective of the FTC is to maintain the operability and controllability of the process in case of a fault. First the fault must be detected and isolated and then the controller must be redesigned. The adaptation of the controller can be done either by retuning the controller (accommodation) or by changing the configuration e.g. by choosing new sensors and/or actuators to the control loop (reconfiguration). Reconfiguration of the controller requires that there exist some redundancy in the structure of the process. The process must contain alternatives to get the required information or to put the control actions to the process.

4. STRUCTURAL ANALYSIS

A detailed presentation of the structural analysis can be found from (Blanke *et.al*, 2003). The structural analysis is based on the structure model of the system. The structure model is an abstraction of the behavior model of the analyzed system in the sense that only the existence of links between system variables and parameters is considered. The structure model represents the links between a set of variables Z and a set of constraints C. The system equations are called constraints, because the behavior of system variables is constrained by the system equations. The constraints can be expressed in several different forms as algebraic and differential equations, rules, etc. In a structure graph each variable is connected by an edge with all the constraints where this variable is present.

Structure models provide useful information for fault diagnosis and fault tolerant control design, since structural analysis is able to identify those components of the system which are or are not monitorable, to provide design approaches for analytical redundancy based residuals, and to identify those components whose failure can or cannot be recovered through control system reconfiguration. State space model based system analysis requires that model equations and their parameters are known. E.g. in order to be able to analyze the ranks of the controllable and the monitorable canonical forms of the system model, the equations must be known. By using structural analysis the exact model equations are not needed. It is enough to know which variables are interacting with each other by system equations.

4.1 Analysis of the secondary air system

The use of structural analysis is demonstrated in the analysis of the secondary and tertiary air process of the boiler. The function of this process is to distribute a part of combustion air to the upper parts of the furnace to complete the combustion of fuel. The basic demand for the secondary and tertiary air flows is determined by the load of the boiler. The desired fuel-air ratio of the combustion process is controlled by correcting the secondary and tertiary air flow demands according to the oxygen content measured from the flue gases in the back part of the furnace before air preheaters. The structure of the process is depicted in fig. 1. Normally the pressure of the air in the channel is controlled by the secondary air fan, and the secondary and tertiary air flows are controlled by dampers.

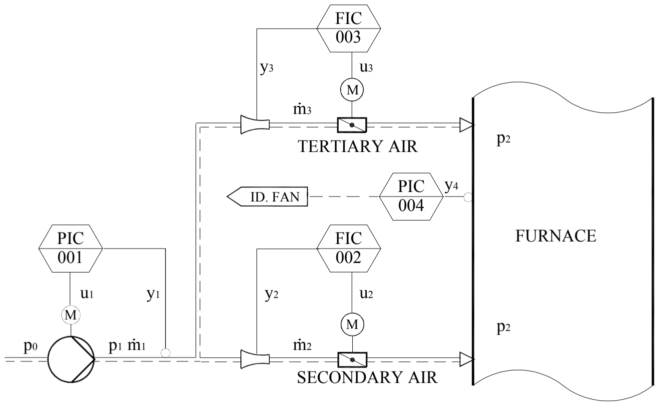

Fig. 1. Structure of the secondary air process.

The system equations constraining the behavior of the process variables are

$$c_1: \quad p_1 = p_0 + a_1\dot{m}_1^2 + a_2\dot{m}_1u_1 + a_3u_1^2 \tag{1}$$

$$c_2: \quad \dot{m}_2 = u_2k_1\sqrt{p_1 - p_2} \tag{2}$$

$$c_3: \quad \dot{m}_3 = u_3k_2\sqrt{p_1 - p_2} \tag{3}$$

$$c_4: \quad \dot{m}_1 = \dot{m}_2 + \dot{m}_3 \tag{4}$$

$$c_5: \quad y_1 = p_1 \tag{5}$$

$$c_6: \quad y_2 = \dot{m}_2 \tag{6}$$

$$c_7: \quad y_3 = \dot{m}_3 \tag{7}$$

$$c_8: \quad y_4 = p_2 \tag{8}$$

p_0 is normal air pressure, p_1 is air pressure after the fan, $\dot{m}_1$ is air flow rate through the fan, a_i are fan model parameters, u_1 is control signal for the fan, $\dot{m}_2$ is secondary air flow rate, u_2 and u_3 are damper positions, p_2 is furnace pressure, k_i $i = 1,2$ are damper capacities, y_i $i = 1,\ldots,4$ are process measurements. The structure model can be presented as a graph. The graph consists of nodes and connecting edges. The nodes represent either the variables (circles) or the constraints (bars) of the system. If a certain variable is introduced in a certain constraint c_i, the variable node and the constraint node are connected together by an edge. Fig. 2 depicts the structure graph of the secondary air process.

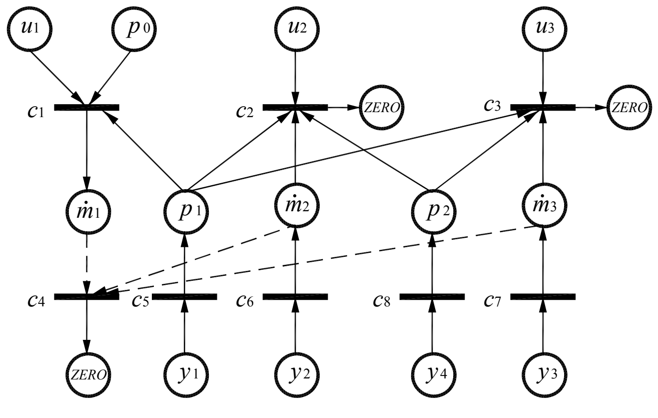

Fig. 2. Structure graph of the secondary air process.

The incidence matrix of the structure model depicts the links between the system variables and the constraints. If there is a connection between the variable and the constraint, the corresponding element of the incidence matrix is "1". The variables are classified as known variables (control signals, measured signals, and some constants) and unknown variables (internal process variables).

Table 1. Incidence matrix of the structure model of the air process.

	Known variables								Unknown variables				
	u_1	u_2	u_3	y_1	y_2	y_3	y_4	p_0	p_1	p_2	$\dot{m}_1$	$\dot{m}_2$	$\dot{m}_3$
c_1	1							1	1		1		
c_2		1							1	1		1	
c_3			1						1	1			1
c_4											1	1	1
c_5				1					1				
c_6					1							1	
c_7						1							1
c_8							1			1			

Initially the edges of the structure graph have no direction. They just describe that a certain variable is introduced in a certain constraint. Defining a matching on a structure graph introduces some orientations of the edges. Matching is a subset of edges of the graph such that any two edges have no common node, neither in constraints nor in variables. A maximal matching is a matching such that no edge can be added without violating this "no common node" property. Since the set of matchings is only partially ordered, it follows that there is in general more than one maximal matching.

Defining a matching on a structure graph introduces some orientations of the edges. Once a matching is chosen each matched constraint is now associated with one matched variable and some none matched ones. The edges connected with matched constraints are provided with an orientation: the non-matched variable is an input of the constraint and the matched variable is an output of the constraint. If there is no matching associated with a constraint, all the variables are considered as inputs, and a ZERO node is added to a graph as an output of the constraint. The matching represents some causality assignment by which the constraint c is used to compute the variable x assuming that the other variables are known. The structure graph in fig. 2 is drawn using the matching presented in table 2.

Table 2. Matched incidence matrix of the secondary air system.

	Unknown variables				
	p_1	p_2	$\dot{m}_1$	$\dot{m}_2$	$\dot{m}_3$
c_1	1		M		
c_2	1	1		1	
c_3	1	1			1
c_4			1	1	1
c_5	M				
c_6				M	
c_7					M
c_8		M			

A matching is complete with respect to constraints if every constraint in the graph is matched. A matching is complete with respect to variables if every variable in the graph is matched. In the incidence matrix the matching between a variable and a constraint is represented by "M". Table 2 shows one possible matching of the unknown variables of the secondary air process.

Any structure graph can be decomposed into three subgraphs; over-constrained, just-constrained, and under-constrained subsystems. A graph is called over-constrained if there is a complete matching on the system variables but not on the constraints. A graph is called just constrained if there is a complete matching on the variables and the constraints. A graph is called under-constrained if there is a complete matching on the constraints but not on the variables.

Matching of the secondary-tertiary air process described in table 2 is complete with respect to variables, but there are still three non-matched constraints (c_2, c_3, c_4), so the secondary air system is over constrained.

By rearranging the system variables and constraints, the incident matrix shown in table 2 is decomposed in the just constrained and under constrained subsystems. The decomposed incidence matrix is shown in table 3.

Table 3. Decomposed incidence matrix of the secondary air system.

	Unknown variables				
	p_1	p_2	$\dot{m}_1$	$\dot{m}_2$	$\dot{m}_3$
c_5	M				
c_8		M			
c_1	1		M		
c_6				M	
c_7					M
c_4			1	1	1
c_2	1	1		1	
c_3	1	1			1

The just-constrained subprocess of the secondary air process is $\{c_1, c_5, c_6, c_7, c_8\}$, $\{p_1, p_2, \dot{m}_1, \dot{m}_2, \dot{m}_3\}$. Air flow $\dot{m}_1$ can be calculated from the measured air pressure after the fan, p_1, and the control signal for the rotation speed of the fan u_1. The other variables are measured directly. Subsystem $\{c_2, c_3, c_4\}$, $\{p_1, p_2, \dot{m}_1, \dot{m}_2, \dot{m}_3\}$ is under-constrained. It means that there is no unique solution for this subsystem, because the number of variables is greater than the number of constraints.

4.2 Fault tolerant control of the secondary air system

However, this non-matched under-constrained subsystem contains redundant information for the matched variables. This redundant information can be used for diagnosing the sensors of the secondary air system. Table 3 shows that for the secondary and tertiary air flow measurements $\dot{m}_2$ and $\dot{m}_3$ it is possible to compute two redundant values using constraints c_2 and c_4 for $\dot{m}_2$ and c_3 and c_4 for $\dot{m}_3$. For flow $\dot{m}_1$ it is possible to compute only one redundant value using constraint c_4. These redundant input-output relations form so called parity relations for the system. These relations can be used for fault detection and identification (Gertler, 1998).

If any of these measurements is diagnosed faulty, the faulty measurement can be replaced by the redundant computed estimate of the signal. So it is possible to reconfigure the flow controller to continue the control task even if the measurement connected to the control loop is found faulty.

The secondary air process holds also some actuator related redundancy. It can be seen from the constraints c_2 and c_3 that the secondary and tertiary air flows depend both on the damper positions (u_2, u_3) and the inlet pressure p_1 to the dampers (also on the furnace pressure p_2 , but it is not a free variable). In case of a damper fault, e.g. a jammed actuator or an irregular movement of a register plate, control signal u cannot be used any more for controlling the flow. E.g. a sticky movement of the damper may cause oscillations to the whole combustion air system degrading the combustion efficiency and increasing the amount of harmful emissions (CO, NO_x). Also thermal stresses in the furnace are increased due to the fluctuations of the furnace temperature.

In this case it is possible use a redundant control signal, the inlet pressure p_1 to control the air flow. Pressure p_1 is controlled by the secondary air fan. So it is possible to reconfigure the flow control loop to change the actuator of the loop from the damper to the fan, and freeze the position of the faulty damper to a suitable position. The position of the faulty damper must be chosen so that the flow resistance of the channel is matched with the capacity of the fan to guarantee the required amount of combustion air for all loads. The control result will be degraded because with this configuration the non-faulty damper cannot operate in the optimal range regardless of the boiler load. That is because the channel pressure is not controlled independently anymore to keep the actuators in the desired range. The new configuration of the secondary air process due to the actuator fault in tertiary air channel is shown in fig. 3.

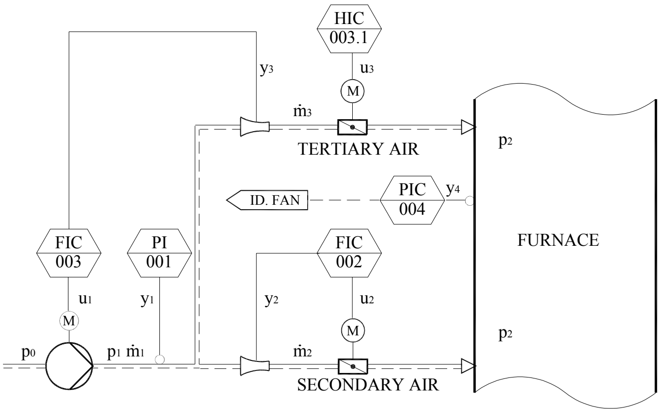

Fig. 3. The reconfigured control structure of the secondary air process due to the faulty actuator in the tertiary air channel.

CONCLUSIONS

Applications of FTC require that faults can be diagnosed reliably and there exist sufficient redundancy in the process to enable an alternative control configuration. One major problem with applications of fault diagnosis is that there is not a general method available but every case must be tailored as a special case. As a result the diagnosis system applications are typically very expensive and laborious to maintain.

The applied fault detection and identification methods should be chosen according to the properties and the possible faults of the monitored process. Structural analysis based on structure graphs and incident matrixes is a suitable tool to analyze the properties of the process. A detailed model is not required, only the existence of the connections between different process variables is needed to build a structure model. The structure model can be used to analyze the monitorability and controllability properties of the process. This information is needed for designing the fault diagnosis and fault tolerant control systems. Structural analysis gives also valuable information to improve the fault tolerance of the process by means of process design.

Structure models can be applied to fault propagation analysis. Fault propagation analysis is used to isolate the detected fault. In case of a fault the structure model helps to analyze how the observed symptoms are connected with different process variables. With the help of the model it is possible to match the observed symptoms with a possible fault in a certain process component.

Structural analysis was demonstrated in the analysis of the secondary air process of the boiler. The structure of the process was decomposed to just-constrained subsystem and under-constrained subsystem. The under-constrained subsystem contained redundant information for the just constrained subsystem. This redundant information is needed to diagnose the process. The existence of this redundant information makes it possible to comprise the parity equations for the system. These equations are used to generate residual information for fault detection.

The structure of the secondary air process contained also redundant control capabilities. It was shown, that the air flows can be controlled either with the dampers or with the fan. In case of the damper fault it is possible to reconfigure the control loop to use the fan instead of the damper. However, the control performance may be degraded because the remaining damper cannot operate in the optimal range through the whole load range.

The structure analysis can be used to analyze also the other important sub-processes like steam superheating and feed water control to find out the possibilities of applications of fault tolerant control.

In the future, the reconfiguration of the controller is demonstrated using a model predictive controller as a platform of the fault tolerant control application.

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