Method for Designing Alarm System Using DAEs, CE Matrices, and Preference Indices

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A plant alarm system provides critical information to operators as the third layer of independent protection layers when a chemical plant is undergoing an abnormal situation. Therefore, methods for designing plant alarm systems are crucial for plant safety. Because plants are maintained as part of the plant lifecycle, plant alarm systems should be properly managed and adapted to changes that occur throughout the lifecycle. To manage changes, the design rationale of the plant alarm system should be explained explicitly. In the present paper, we explain a design problem for plant alarm systems and propose a method for designing alarm systems by using differential and algebraic equations, cause-effect matrices, and preference indices.

Introduction

In most chemical plants, distributed control systems (DCSs) are installed to simultaneously control thousands of process variables. The main role of operators is to supervise operations to keep plants safe by using process alarms in both normal and abnormal situations. The DCS is an effective means of decreasing the operators' load in normal situations, and the number of operators has recently decreased due to the introduction of advanced control systems. Although the frequency of accidents is very low, the load of operators in abnormal situations has become heavier. Operators face difficult tasks including complex decision making for detection, diagnosis, assessment of urgency, and countermeasure planning in managing abnormal situations. Moreover, the DCS is not effective in abnormal situations because it lacks diagnosis systems or decision-support systems for preventing accidents or disasters. The alarm system becomes more and more important to maintain safe plant operation. Progress of the DCS has made it possible to install many alarms inexpensively. While suitably designed alarm systems can support operators, poorly designed

ones might disrupt operators by alarm floods and nuisance alarms. Therefore, alarm system design must be considered seriously for safe plant operation.

1. IPLs and Alarm Management Lifecycle

To support safe plant operations, the use of independent protection layers (IPLs) has been proposed (CCPS, 1993). A plant alarm system performs a very important role in the initial response to prevent accidents or disasters as the third layer of the IPLs. A plant alarm system consisting of critical alarms must provide useful information to operators. In most cases, alarms lead to confusion as it is not clear whether an alarm is indicating an announcement, alert, caution, or warning. In the present paper, we focus on such critical alarms to design suitable alarm systems.

An alarm system also needs to be properly managed throughout the plant lifecycle because plant modifications regularly occur. A framework and first alarm for managing the alarm system lifecycle was previously proposed (International Society of Automation, 2009), and a revised illustration was proposed in IEC 62682 (IEC, 2014). We focus on "Identification" and "Rationalization" in the alarm management lifecycle (AMLC) in IEC 62682. The AMLC contains three loops: a monitoring and maintenance loop, a monitoring and management of change loop, and an audit of philosophy loop. One problem with designing plant alarm systems is how to design, construct, operate, and maintain plant alarm systems properly throughout the plant lifecycle. For

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example, it is assumed that some alarms are designed based on an existing safety system such as safety valve. However, if the safety valve cannot be used for some reason, the alarms must be modified in this situation. To solve this problem, the design rationale of the plant alarm system should be explained explicitly. Whenever a plant is modified, the plant model must be updated on the basis of the design rationale.

To diagnose system failures in the chemical process, Iri *et al.* (1979) and Shiozaki *et al.* (1985) showed the application of a cause-effect (CE) graph and its effectiveness. For designing a logical and systematic alarm system, we previously proposed a sensor selection method that uses a CE graph (Takeda *et al.*, 2010). In this method, a plant CE matrix G is generated by using a CE graph of the plant on the basis of the directed graph expression of cause-effect relationships among process variables, manipulated variables, and fault origins. A preference index based on reachability matrix R , which is based on CE matrix G , can be used to select alarm source variable candidates.

However, it is difficult to keep consistency in the generation and management of the CE graph of a plant because the interpretation of cause-effect relationships among process variables, manipulated variables, and fault origins may vary depending on the user. Hamaguchi and co-authors proposed a hierarchical CE model and modularized CE model for designing alarm systems (Hamaguchi *et al.*, 2012, 2013; Takeda *et al.*, 2014). However, these models are not enough to solve this problem. To help manage changes in a plant model, a support system for generating and managing the model with consistency is required.

We previously proposed a method for generating and checking alarm configurations using CE matrices (Hamaguchi *et al.*, 2015). For this method, we introduced an alarm configuration matrix A , alarm loop model GA , and reachability matrix R for generating and checking alarm configurations. Although the method was useful for rejecting bad alarm configurations, more information is needed to select better alarm configurations. A method was proposed for generating a plant CE matrix based on differential and algebraic equations (DAEs) for a plant-wide control loop configuration design tool (Kojima *et al.*, 2014) and for dividing the zones of a process control network to improve cyber security (Moritani *et al.*, 2014). Moritani *et al.* (2016) proposed a method of generating fault trees for ICS safety and security by using DAEs. A fault tree is a useful tool for process hazard analysis (PHA). Therefore, DAEs can be used as the basis of the design of an operator support system, considering the management of change throughout the plant life cycle.

To develop a support system for generating and managing a plant model with consistency for alarm system design, we applied a DAE method of modeling a plant model for alarm system design. Moreover, we modified the controller configuration method based on CE matrices for systematic alarm system design.

2. Problem with Designing Alarm Systems

An alarm system should be properly managed throughout the plant lifecycle. To properly manage a system, the activities concerning the system and information flows between the activities during the plant lifecycle should be explicitly expressed. Furthermore, “constraints,” “inputs,” and “outputs” of each activity and information flow in the form of a business process model (BPM) have been proposed. Takeda *et al.* (2015a, 2015b) proposed an alarm management business process model (AMBPM) and derived business flows. A part of an activity tree of the AMBPM concerning the alarm system design process is shown in **Figure 1** because the whole AMBPM is very large. Important activities corresponding to alarm system design are filled in with yellow.

Fig. 1 Part of activity tree of AMBPM concerning alarm system design process

A42, “Plan and design overall operational design philosophy,” is applied to the basis of alarm system design. One of the core activities of the alarm system design process of the AMBPM is A44533, “Perform PHA.” The key information of alarm system design, such as the information required for operators and the reasons that such information is required, must be gained from the PHA. Another core activity of the alarm system design process of the AMBPM is A44553, “Develop detailed design for plant alarm system.” For this activity, another activity, A445533, “Develop alarm source signals,” selects or newly designs alarm source signals. This paper corresponds to this activity. Assume that suitable countermeasures must be prepared for accidents. A countermeasure may be suitable for one accident, but it might be worse for another accident. Therefore, assumed accidents must be grouped in terms of effective countermeasures, and an alarm must be useful to distinguish them. The alarm system must be considered systematically. A detailed design such as of the threshold of the alarm and filtering corresponds to A445534 and A445535. These activities are out of the scope of the present study.

The purpose of an alarm must be considered to design an alarm system. In the present paper, we consider that alarms can be divided into two modes for critical accidents identified by PHA because suitable countermeasures might differ depending on the mode. Mode 1 is for detecting the occurrence of fault origins before the effects of the origins reach each condition for accidents. Mode 2 is for detecting the occurrence of each condition for accidents. For example, there are two fault origins and two fault trees, as shown in **Figure 2**. Accident 1 of fault tree 1 has arisen from abnormal values of nodes 6 and 7. Accident 2 of fault tree 2 has arisen from abnormal values of nodes 7 and 8. The propagation is based on the CE model. Fault origins 1 and 2 can cause the values of nodes 1 and 2 to be abnormal, respectively. The effect of fault origin 1 can reach node 6 via node 3. The effect of fault origin 2 can reach nodes 7 and 8 via nodes 4 and 5. If fault origin 2 occurs, then accident 2 might arise from only the effect of fault origin 2, but accident 1 does not arise because the effect cannot reach node 6. In this example, the yellow zone is mode 1, and the blue zone is mode 2, as shown in **Figure 2**. The difference in suitable countermeasures, allowances, and so on must be considered for generating and

Fig. 2 Fault origins, fault trees, and modes

checking alarm configurations. However, an algorithm for generating and checking the configurations can be used for both modes. The CE model might change for abnormal situations. If the liquid level decreases in a reactor and a cooling pipe does not contact the liquid, then the cooling water flow rate cannot affect the temperature of the liquid. Therefore, the CE model can generate configurations systematically for various situations with consistency.

Let M be a set of all measured variables that can be used for alarm source variables, process variables, and manipulated variables on a DCS. Let C be a set of fault origins to be distinguished by use of the alarm system. Therefore, C is a subset of all assumed fault origins in a plant. We assume that C can be given by PHA, such as the fault tree, HAZard and Operability (HAZOP) study and so on. In the present paper, we define the alarm system design problem as how to select alarm source variables from M to distinguish each fault origin of C .

3. Basic Method for Alarm System Design Using DAEs, CE Matrices, and Preference Index

3.1 Example plant and DAEs

An example plant and Eqs. (1)–(5) as DAEs are shown in **Figure 3**. In this example, the boundary conditions are given as system outside pressure P_1 and P_2 and atmospheric pressure P_0 . The inlet flow rates F_1 and F_2 and the outlet flow rate F_3 are determined in accordance with the valve openings V_1 , V_2 , and V_3 . The tank level, cross-sectional area, and bottom pressure are respectively L_1 , S_1 , and P_3 . The others, α , k_1 , k_2 , and k_3 , are proportionality constants. In this example, V_1 and V_3 are assumed to be elements of C , and F_1 and F_3 are assumed to be elements of M .

3.2 Generation of plant CE matrix G from DAEs

Step 1: The matrix in **Table 1** is generated from the DAEs in **Figure 3**. The rows in the matrix correspond to the equations. The columns correspond to variables in the DAEs. x , u , and z , respectively, mean state variables in the differential equations, input variables, and variables determined by algebraic equations. This method is based on Kojima *et al.* (2014). In the present paper, we divide the z into measured (F_1 and F_3) and unmeasured (F_2 and P_3) variables, as shown in **Table 1**. Element “1” in the matrix means the entry of the variables in the equations, while a blank element indicates “0” elements.

Step 2: In Eq. (5), to explain the differential pressure

Fig. 3 Example plant and DAEs

Table 1 Step 1 for generating G

State variables in differential equations		Variables determined by algebraic equations					Input variables					
dx/dt	$x(t)$	$z(t)$					$u(t)$					
		Measured variables		Unmeasured variables								
dL_1/dt	L_1	F_1	F_3	F_2	P_3		V_1	V_2	V_3	P_1	P_2	P_0
(1)	1	1	1	1								
(2)			1			1				1		1
(3)				1		1			1			1
(4)					1		1				1	1
(5)		1				1						1

Table 2 Step 2 for generating G

dx/dt	$x(t)$	$z(t)$					$u(t)$					
dL_1/dt	L_1	F_1	F_3	F_2	P_3		V_1	V_2	V_3	P_1	P_2	P_0
(1)	1	1	-1	1								
(2)			1			1				1		-1
(3)				1		1			1			-1
(4)					1		1				1	-1
(5)		1				1						-1

Table 3 Step 3 for generating G

dx/dt	$x(t)$	$z(t)$					$u(t)$					
dL_1/dt	L_1	F_1	F_3	F_2	P_3		V_1	V_2	V_3	P_1	P_2	P_0
(1)	1.722	1	-1	1								
(2)			1.859			0.890				1		-1
(3)				1.870		1			1.449			-1
(4)					0.846		0.918			1		-1
(5)		1.320				1						-1

Table 4 Step 4 for generating G

dx/dt	$x(t)$	$z(t)$					$u(t)$					
dL_1/dt	L_1	F_1	F_3	F_2	P_3		V_1	V_2	V_3	P_1	P_2	P_0
(1)	1.722	1	-1	1								
(2)			1.859			0.890				1		-1
(3)				1.870		1			1.449			-1
(4)					0.846		0.918			1		-1
(5)		1.320				1						-1

P_3-P_0 , the relationship is expressed in Table 1. Therefore, the element of P_0 is modified from "1" to "-1." The relationship is boxed off, as shown in Table 2. In the same way, the elements of F_3 in Eq. (1) and P_0 in Eqs. (2)–(4) are modified from "1" to "-1."

Step 3: The rest of the variables are assigned positive random numbers, as shown in Table 3. The random numbers should not be integers; otherwise, unexpected elements may be swept out in Step 5.

Step 4: For Step 5, the inverse matrix of F_2 and P_3 of Eqs. (4) and (5) is generated, as shown in Table 4.

Step 5: The generated inverse matrix is multiplied by the

Table 5 Step 5 for generating G

dx/dt	$x(t)$	$z(t)$					$u(t)$					
dL_1/dt	L_1	F_1	F_3	F_2	P_3		V_1	V_2	V_3	P_1	P_2	P_0
(1)	1.722	1	-1	1								
(2)			1.859			0.890				1		-1
(3)				1.870		1			1.449			-1
(4)					1		1.421				1.548	-1.548
(5)		1.320				1						-1

Table 6 Result of Step 5

dx/dt	$x(t)$	$z(t)$					$u(t)$					
dL_1/dt	L_1	F_1	F_3	F_2	P_3		V_1	V_2	V_3	P_1	P_2	P_0
(1)	1.722	1	-1	0	0		-1.421			-1.548	1.548	
(2)			1.859	0	0	0.890				1		-1
(3)		-1.320		1.870	0	0			1.449			
(4)				1			1.421				1.548	-1.548
(5)		1.320			1							-1

Table 7 Step 6 for generating G

dx/dt	$x(t)$	$z(t)$					$u(t)$					
dL_1/dt	L_1	F_1	F_3	F_2	P_3		V_1	V_2	V_3	P_1	P_2	P_0
(1)	1	1	1	0			1			1	1	
(2)			1				1			1		1
(3)		1		1	0			1				
(4)				1			1			1	1	
(5)		1			1							1

Table 8 Plant CE matrix G

		Causes											
Effects	g	L_1	F_1	F_3	F_2	P_3	V_1	V_2	V_3	P_1	P_2	P_0	
	L_1	1	1	1				1			1	1	
	F_1		1				1			1		1	
	F_3	1		1					1				
	F_2				0			1			1	1	
	P_3	1				0						1	
	V_1						1						
	V_2							1					
	V_3								1				
	P_1									1			
	P_2										1		
	P_0											1	

three boxed matrices in Table 4. Equations (4) and (5) are converted into (4)' and (5)', respectively. The elements of F_2 and P_3 in Eqs. (1) and (3) are swept out by Eqs. (4)' and (5)', as shown in Table 5. The result is shown in Table 6.

Step 6: All elements without "0" in Table 6 are modified to "1," as shown in Table 7.

Step 7: The column of dL_1/dt is added as Boolean to the column of L_1 , and then deleted. The elements of unmea-

Table 9 R and preference index

R	Fault origins to be distinguished				Preference index			
	V_1	V_2	V_3	V_4	1	2	3	4
Measured variables	F_1	1			○			
	F_2	1	1		○			

Preference Index 1

Preference Index 2

Preference Index 3

Preference Index 4

Table 10 A_1 for V_1 - F_1

A_1	L_1	F_1	F_2	F_3	P_1	P_2	P_3	V_1	V_2	V_3	P_0
L_1	1										
F_1		0									
F_2			1								
F_3				1							
P_1					1						
V_1		1						1			
V_2									1		
V_3										1	
P_1						1					
P_2							1				
P_3											1

measured variables (F_2 and P_3) of Eqs. (4)' and (5)' are modified to "0." The rows corresponding to u are added to the matrix. The submatrix corresponding to u is modified to a unit matrix. The matrix then becomes a square matrix. Equations (1)'–(5)' are modified to L_1 , F_1 , F_3 , F_2 , and P_3 , and then, the rows and columns of the square matrix correspond to the same variables. This is a CE matrix G that explains the plant model, as shown in Table 8.

The CE matrices have elements "0" or "1." The blank element indicates "0" elements, too. Column variables and row variables correspond to causes and effects, respectively. When the (i, j) element of the CE matrices is 1, the j -th column variable affects the i -th row variable. The 1 at the (F_1, V_1) element of Table 7 shows that the fault origin V_1 affects the measured variable F_1 .

3.3 Alarm source variable selection using CE matrices and preference index

Preference index 1: A measured variable is also a fault origin.

Preference index 2: A measured variable can be reached from one fault origin.

Preference index 3: A measured variable can be reached from two or more fault origins.

Preference index 4: A measured variable cannot be reached from any fault origins.

The submatrix of the reachability matrix of G is called R in the present paper. The rows and columns of R respectively correspond to measured variables and fault origins to be distinguished, as shown in Table 9.

Table 11 GA_1 .

GA_1	L_1	F_1	F_2	F_3	P_1	P_2	P_3	V_1	V_2	V_3	P_0
L_1	1										
F_1		1									
F_2			1								
F_3				1							
P_1					1						
V_1		1									
V_2								1			
V_3									1		
P_1										1	
P_2											1
P_3											

Table 12 R' based on A_1 and preference index

R' based on A_1	Fault origins to be distinguished			Preference index			
	V_1	V_2	V_3	1	2	3	4
Measured variables	F_1	1			○		
	F_2	0	1		○		

The effect of fault origin V_1 arrives at the measured variables at F_1 and F_3 . The effect of fault origin V_3 arrives at the measured variables at F_3 . Therefore, the preference indices of F_1 and F_3 are 2 and 3, respectively. The number of fault origins that can affect the measured variables may be different. If the distinguishability of measured variable sets is equal, fewer fault origins that can affect the sets are preferred. Only one preference index is added to a measured variable from the preference indices 1 to 4 using the reachability matrix of G .

We propose the following usage of the preference index for designing an alarm system. First, a measured variable that has preference index 1 should be selected for an alarm source variable. In this example, none of the measured variables have preference index 1. Next, a measured variable that has preference index 2 should be selected for an alarm source variable. In this example, the preference index of fault origin V_1 is index 2, so the fault origin V_1 is paired with F_1 . The alarm configuration matrix A_1 explains the alarm configuration between the fault origin V_1 and alarm source variable F_1 . Therefore, the element of (V_1, F_1) is "1," that of (F_1, F_1) is "0," and all other diagonal elements are "1," as shown in Table 10. V_1 does not affect the lower stream of F_1 because matrix A_1 is used.

An alarm loop matrix GA_1 is calculated by the Boolean multiplication of two matrices, G and A_1 . An alarm loop matrix GA_1 based on A_1 is shown in Table 11. The column of F_1 is changed from G in Table 8.

The submatrix of the reachability matrix of GA_1 is called R' , as shown in Table 12. By using A_1 , the effect of fault

Table 13 A_2 for V_1 - F_1 and V_3 - F_3

A_2	L_1	F_1	F_3	F_2	P_3	V_1	V_2	V_3	P_1	P_2	P_0
L_1	1										
F_1		0									
F_3			0								
F_2				1							
P_3					1						
V_1		1				1					
V_2							1				
V_3			1					1			
P_1									1		
P_2										1	
P_0											1

origin V_1 does not reach the measured variables at F_3 . Therefore, the preference index of F_3 is modified to index 2.

As a result, the measured variable F_3 is selected as an alarm source variable for V_3 . The alarm configuration matrix A_2 is shown in Table 13.

Conclusion

In the present paper, we proposed a sequential method for designing alarm systems using DAEs, CE matrices, and preference indices. Even if a plant is designed properly for the preliminary conditions, plant operation conditions might be changed. The result of change might cause the check points for an alarm system to change. The PHA and CE matrices can be regenerated from DAEs, so the difficulty of management of change should be easier.

Our design method is the first step to bridging the discontinuity between plant alarm system design and alarm management.

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Nomenclature

A	= CE matrix for alarm configuration	[—]
C	= a set of fault origins to be distinguished	[—]
G	= CE matrix for plant model	[—]
GA	= CE matrix for alarm loop model	[—]
F	= flow rate	[—]
L	= liquid level of tank	[—]
M	= a set of all measured variables	[—]
P	= pressure	[—]
R	= reachability matrix	[—]
S	= cross-sectional area of tank	[—]
T	= temperature	[—]
V	= valve	[—]

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