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Robust Process Fault Diagnosis with Uncertain Data

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Abstracts This study suggests a new methodology for the fault diagnosis based on the signed digraph in developing the fault diagnosis system of a boiler plant. The suggested methodology uses the new model, fault-effect tree. The SDG has the advantage, which is simple and graphical to represent the causal relationship between process variables, and therefore is easy to understand. However, it cannot handle the broken path cases arisen from data uncertainty as it assumes consistent path. The FET is based on the SDG to utilize the advantages of the SDG, and also covers the above problem. The proposed FET model is constructed by clustering of measured variables, decomposing knowledge base and searching the fault propagation path from the possible faults. The search is performed automatically. The fault diagnosis system for a boiler plant, ENDS was constructed using the expert system shell G2 and the advantages of the presented method were confirmed through case studies.

Keywords Signed Digraph, fault diagnosis, boiler plant, uncertainty, fault-effect tree

1. INTRODUCTION

Steam is the most widely used heat source that supplies energy for the operation of industrial plants such as refinery, petrochemistry and machinery etc.. Boiler produces steam for these plants and is typically a large plant, which has various units. With concern about safety and the environmental problems and the need of energy saving, very complex and automated control system has been introduced to meet severe conditions for operation.

Automatic control system plays the important role in maintaining the plant operation within a desired range against various disturbances. Usually, disturbances consist of the changes of demand or specifications of product, feed, the surroundings such as weather, and noises from sensors, etc. In addition, other serious disturbances which control system can not handle might be occurred. They may threaten the safe operation of plants, and include the physical malfunction of equipment and rapid changes of operation conditions. Automatic trip system should be prepared to protect plants in these disturbances.

The role of operators in the operation of boiler is between these systems. They should understand the status of plants from numerous warnings and signals of control system. They determine the cause of process violation and judge whether the process may run away from the acceptable range of operations or not. However, it is not easy for operators to take correct actions during this procedure due to very numerous, simultaneous warnings and the stress that they have to make proper decision quickly.

Hence, the automated fault diagnosis system is required to aid the operators to reach the correct judgement. This system analyzes the process data on-line, monitors the process status, and diagnoses faults in case of abnormal situation. Then, it provide operators with the information sufficient to help their judgment and decision-making and ultimately assists operators to deal with the problems more efficiently.

Methodologies for fault diagnosis include rule-based expert system, fault estimation, signed digraph, qualitative simulation, neural network, and so on[2]. Recently some hybrid approaches have been studied to overcome the disadvantages of each method.

2. DIAGNOSIS MODEL AND METHODOLOGY

The studied methodology is based on the SDG. The followings are the basic concept of SDG.

2.1. Signed Digraph

SDG is suggested by Iri[3]; this method is a simple and yet efficient method by representing process knowledge with causal relationship among process variables. SDG is consisted of nodes that represent process variables and arcs that show the causal relationships between nodes. The direction of causal relationship is indicated as the sign of the arc. The positive (+) sign is used when the source node and target node move in the same direction, and the negative (-) when reversed. SDG's basic concepts are specified by Mohindra[7].

The SDG is simple and graphical to represent the causal relationship between process variables and/or propagation paths of fault, and therefore easy to understand, and based on the experience and basic principles. These potential merits have made SDG one of the most popular methods in the fault diagnosis.

The methods based on SDG can be classified into two classes: algorithmic approach which assigns the qualitative states of unobserved nodes from the given partial pattern[4], and off-line analysis of SDG[6, 7].

2.2 Practical Problem in SDG-based Methods

One of the difficulties in the fault diagnosis based on SDG comes from the uncertainty of process data. Finch reported in his work that the disturbances rarely followed an exactly predictable pattern in the case of a malfunction propagation through a plant[3]. The dynamics of variables can be influenced by the fault extent-vs-time profile, the exact location of the fault, and noise and decision thresholds. SDG-based methods are based on the consistent path assumption -- that is, each observed symptom is assumed to be connected to its fault by an unbroken path of consistent arcs -- and therefore always fail in case of symptom variation. The discussed problems can be classified into the following three cases.

(1) Sequence variation of symptom detection: the symptoms of process variables do not occur as were expected in the construction of the diagnosis knowledge base. In the SDG, B moves in the same direction with A by the effect of A in the fault propagation path; when B is detected earlier than A, the diagnosis fails.

(2) Diagnostic instability: This is caused by using the limit check method to detect symptoms in the conventional methodologies[5]. In the limit check method, a symptom is generated when a process variable violates a threshold; in the most of previous works, the boundary range is set to be three-times of the steady-state standard deviation. The change is detected when the size of it is as much as the boundary range. However, the diagnosis may fail as the detection is not consistent from the obscuration of symptoms in the process variables due to the sensor noise, etc.

(3) Compensatory and inverse response: The conventional methods mostly use the snap-shot value at a single time point. This snap-shot strategy cannot handle the control action, and the compensatory response or the inverse response in the control loop cannot be explained. Many works have been done on this problem[3,6,8].

3. DIAGNOSIS FOR A BOILER PLANT

3.1 Process Description

The boiler which fault diagnosis system was developed for, is the drum-type that usually is used for large-scaled plants. Target plant is a typical boiler plant used in refinery/petrochemical complex and consists of five boilers and a steam distribution unit. Each boiler has water supply unit, boiler main unit, air supply unit and fuel supply unit(Fig. 1). The developed system deals with only one boiler and one steam distribution unit.

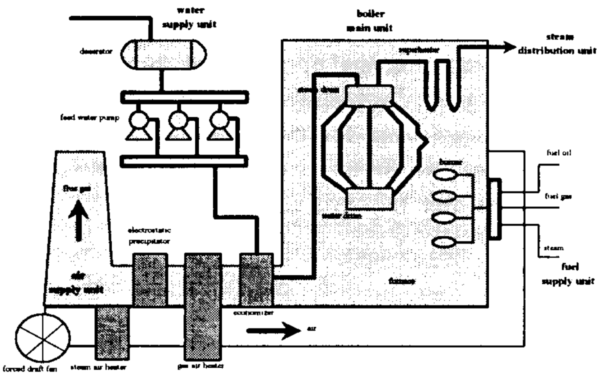

Fig. 1. Process flow diagram of boiler plant.

3.2 System Requirement

To develop the fault diagnosis system for boiler plant, the following specialty must be considered.

- Speed
- Robustness
- Large plant
- Changing processes
- Uncertain mathematical model

4. FAULT DETECTION

The common algorithm for fault detection was the stochastic method such as Shewhart chart or CUSUM

[1]. However, these methods are inadequate for noise. Therefore, this study modified CUSUM algorithm for the stable diagnosis. This method can deal with the transient response such as inverse or compensatory response.

for a decrease:

$$\begin{aligned} T_0 &= 0 \\ T_n &= \sum_{k=1}^{n}\left(x_k - \mu_0 + \frac{\nu_m}{2}\right) \\ M_n &= \max T_k \\ I_n &= \int (M_n - T_n)\,dt \end{aligned} \qquad (1)$$

low alarm when $(M_n - T_n > \lambda)$
and (not in high alarm
or (high alarm and $I_n > i_n$))

for an increase:

$$\begin{aligned} U_0 &= 0 \\ U_n &= \sum_{k=1}^{n}\left(x_k - \mu_0 - \frac{\nu_m}{2}\right) \\ m_n &= \min U_k \\ i_n &= \int (U_n - m_n)\,dt \end{aligned} \qquad (2)$$

high alarm when $(U_n - m_n > \lambda)$
and (not in low alarm
or (low alarm and $i_n > I_n$))

5. FAULT-EFFECT TREE

The suggested model, Fault-Effect Tree, uses the off-line analysis as was done by Kramer and Mohindra[6,7]. Firstly, the fault propagation path from the possible faults is determined off-line from the SDG and is represented in the form of rules. The diagnosis is performed on-line based on these rules.

5.1 FET Development

First, the SDG of the target system is constructed and the cluster of measured variables is constructed. The variable cluster(VC) which is composed of one or more measured variables, increases the credibility of the symptom. But, if the delay time between measured variables in VC is greater than diagnosis interval, symptom detection is delayed. Therefore, the clustering is performed carefully with regard to the process topology and sensor location.

Next, the set of sub-pattern(SP) of each VC is searched through forward chaining. The SP is the qualitative state of each measured variables in VC. The number of the VC's for boiler plant is 33 and the number of the SP is 108.

Finally, the fault propagation path from the (possible) fault is searched by forward search. Only the possible faults were assigned during the development and were able to avoid the unnecessary search in the useless space, while most methodologies assigned faults to every node in SDG. The top node of the FET is a fault and the other nodes are the SP's of VC.

5.2 System Decomposition

The boiler plant may be partially shut down due to the scheduled maintenance or unscheduled events such as equipment failure. To account for these problems, the system may be decomposed into several subsystems[8]. Units which are not shut down alone are also decomposed for the construction and maintenance of the knowledge base as the understanding of the knowledge is facilitated by the decomposition.

The gate variable is introduced between the SDG's of each subsystem. The gate variables preserve the fault propagation paths between subsystems by acting as the input(fault) and the output(measured variable) of each subsystem. The FET is constructed to extract the diagnostic rules for each gate variable by following the procedure explained before. Target plant is decomposed into five subsystems in the developed system. Fig. 2. is the example of the FET's constructed. F_1 is a fault, $GV_{12(+)}$ is a qualitative state of the gate variable, GV_{12}, and VC_1-1, etc. are SP's.

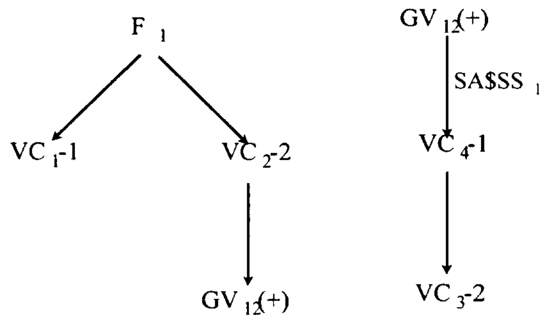

Fig. 2. The example of FET.

5.3 Fault Likelihood

The fault candidates for the given partial pattern are suggested according to the fault likelihood after evaluating each fault. The fault likelihood is the extent of agreement of the propagation path of each fault to the set of given data. To obtain the fault likelihood, the likelihood which is the credibility of each measured variable is calculated first.

The likelihood, ML_i of each measured variable is calculated using the sigmoid-type belief function. And the cluster likelihood, SL_i is calculated as the normalized sum of the likelihood of each measured variable in VC_i.

$$SL_i = \frac{\sum ML_i^j}{N_{MVC_i}} \qquad (3)$$

MVC_i is the set of the measured variables in VC_i and ML_i^j is the likelihood of the jth measured variable in VC_i.

The path likelihood PL_{ij} is for the fault propagation of SP_j from fault i.

$$PL_{ij} = \frac{\sum_k SL_{ij}^k}{NP_{ij}} \qquad (4)$$

NP_{ij} is the number of the SP's between fault i and SP_j.

Finally, the fault likelihood of each fault is calculated from equation (5).

$$FL_i = \frac{\sum_k PL_i^k}{N_{P_i}} \frac{N_{P_i}}{N_{SVC}} \qquad (5)$$

P_i is the set of the SP related to fault i and SVC is the set of VC in which the SP is detected.

6. CASE STUDY

The case happened in the target plant at 1992. This fault is difficult for the previous methodologies to diagnose because of the failed sensor and the broken path due to symptom variation. However, the developed system suggested the true solution simply and quickly. The user interface screen for this case study is shown in figure 3, and includes process diagram, graphs relating major variables, and messages for faults.

7. CONCLUSION

A new methodology for fault diagnosis is suggested based on the SDG to develop the fault diagnosis system of a boiler plant. This methodology uses the new model, FET. The FET utilizes the advantages of SDG and covers the problems which conventional SDG-based methods cannot handle. The off-line test of the developed system has been performed from December 1995.

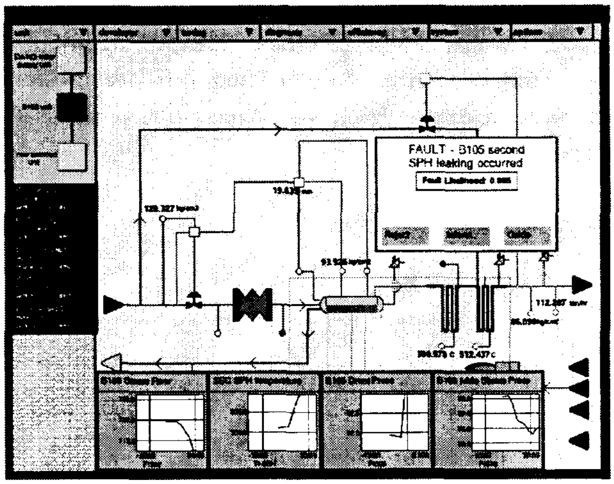

Fig. 3. The user interface screen for case study.

REFERENCES

[1] Basseville, M, "Detecting Changes in Signals and Systems-A Survey," *Automatica*, vol.24, pp. 309-326, 1988.

[2] Becraft, W.R., D.Z. Guo, P.L. Lee and R.B. Newell, "Fault Diagnosis Strategies for Chemical Plants : A Review of Competing Technologies," *Proc. 4th Intl. Symp. on Process Systems Engineering*, vol. 2, pp. 12.1-12.15, 1991.

[3] Finch, F.E., Automated Fault Diagnosis of Chemical Process Plants Using Model-based Reasoning., *Sc.D. Thesis*, Massachusetts Institute of Technology, 1989

[4] Iri, M., K. Aoki and E. O'Shima, "An Algorithm for Diagnosis of System Failures in the Chemical Process," *Computers chem. Engng.*, vol.3, pp. 489-493., 1979.

[5] Kramer, M.A., "Malfunction Diagnosis Using Quantitative Models with Non-Boolean Reasoning in Expert Systems," *AIChE*, vol.33, pp. 130-140, 1987.

[6] Kramer, M.A. and B.L. Palowitch, "A Rule-Based Approach to Fault Diagnosis Using the Signed Directed Graph," *AIChE*, vol.33, pp. 1067-1078, 1987.

[7] Mohindra, S. and P.A. Clark, "A Distributed Fault Diagnosis Method based on Digraph Models: Steady-State Analysis," *Computers chem. Engng.*, vol. 17, pp. 193-209, 1993.

[8] Nam, D.S., Fault Diagnosis using the Extended Symptom-Fault Association Model in the Continuous Chemical Processes, *Ph.D. Thesis*, Department of Chemical Engineering, Seoul National University, 1995.