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Research on Fault Diagnosis of HTR-PM Based on Multilevel Flow Model

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Abstract –*In this paper, we focus on the application of Multilevel Flow Model (MFM) in the automatic real-time fault diagnosis of High Temperature Gas-cooled Reactor Pebble-bed Module (HTR-PM) accidents. In the MFM, the plant process is described abstractly in function level by mass, energy and information flows, which reveal the interaction between different components and capacitate the causal reasoning between functions according to the flow properties. Thus, in the abnormal status, a goal-function-component oriented fault diagnosis can be performed with the model at a very quick speed and abnormal alarms can be also precisely explained by the reasoning relationship of the model. By using MFM, a fault diagnosis model of HTR-PM plant is built, and the detailed process of fault diagnosis is also shown by the flowcharts. Due to lack of simulation data about HTR-PM, experiments are not conducted to evaluate the fault diagnosis performance, but analysis of algorithm feasibility and complexity shows that the diagnosis system will have a good ability to detect and diagnosis accidents timely.*

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I. INTRODUCTION

High Temperature Gas-cooled Reactor Pebble-bed Module (HTR-PM) is one of the major science and technology projects that have been listed in China's national medium and long-term projects for scientific and technological development. At present, it is being constructed cooperatively by INET and other two Chinese corporations in Shandong province, China. Preliminary studies show that the HTR-PM is technologically and economically feasible as one of next generation reactors for electric power generation and process heating applications due to its high thermal efficiency and inherent safety [1]. The most important design feature of HTR-PM is to use inherent safety characteristics and passive safety system to control reactivity, remove core residual heat and limit the release of radioactive materials in the accident.

Unlike the water reactor, HTR-PM utilizes a continuous mode of loading and unloading spherical fuel elements during the reactor operation, and almost two weeks are needed for HTR-PM to reboot once it's tripped. So it is of greatest importance to develop a simulation system that has a good ability of detecting and diagnosing HTR-PM accidents timely before reactor trip, assisting operators to understand plant problems, performing trouble-shooting action and reducing human error and workload. To achieve this, a great deal of research has been made in the design and development of fault diagnosis system. The existing approaches range from fault-tree based methods[2], expert systems[3], to model-based methods[4], and soft computing technologies including fuzzy logic[5], artificial neural network, also interest researchers greatly. However, the problem of above-mentioned technologies is that they only concentrate on the validity of diagnosis results, but not take account of the comprehension of the diagnosis process and outcome, i.e., most of those methods run as a "black box" and only diagnosed results are shown to the operators so that the operators cannot really realize what happens and how it goes on, which brings potential human error during operation. It should be emphasized that, in high-risk processes, the understandability of the diagnosis process and result is crucial to an operator support system, hence, operators need an easy understandable fault diagnosis system in operating the nuclear power plant, which can be directly obtained with the Multilevel Flow Model (MFM), originally developed by Lind in 1992.

The advantage of MFM is that it aims at developing a flexible approach for operating support of various man-made systems and provides a set of formalized symbol language to describe the common properties, including flows and abstraction hierarchy structure of various man-made systems. Thus, people can understand the working principle of a process system, including design intention and internal process based on a formalized and universal way. In the application of fault diagnosis by MFM—a model-based approaches, comparing with other knowledge-based systems, the process of design, construction, and updating of the knowledge database can be more efficient, and the method based on MFM can be used to find any deviation from the working state and not only pre-specified faults—which is the limitation of common rule-based expert systems[6]. This paper applies MFM in the fault diagnosis system design of HTR-PM plant from two aspects, the first is using MFM to build a diagnosis model of HTR-PM process in goal-function-component view[7] to display the plant process in a means-end and part-whole way; second is using the consequence analysis method to perform fault diagnosis of HTR-PM accidents. And a concrete fault diagnosis diagram is also designed.

The rest of this paper is organized as follows: MFM and its model expansion for the consequence analysis algorithm will be presented in Chap. II; introduction of HTR-PM, its system structure and modeling with MFM will be given in Chap. III; detailed process of fault diagnosis for HTR-PM accidents will be performed in Chap. IV; conclusions and future work plan will be mentioned in Chaps. V.

II. MULTILEVEL FLOW MODEL

Multilevel flow model is mainly used in modeling plant process by using a series of standard symbols to present the functions realized by different components and the goals they achieve. Since the goals and functions have been formalized, algorithms can be developed based on them for different applications such as measurement validation, alarm analysis and fault diagnosis [8].

II.A. Basic concepts of MFM

A Multilevel Flow Model consists of three basic concept types: goals, functions and physical components. The goals are the objectives or purposes that the system or sub-system is designed or constructed to achieve, the functions are the means by which the goals are obtained, i.e., the powers or capabilities of the system and the physical components are what the system is constructed from, the equipment of which it consist[8]. These three concept types depend on each other by three kinds of relations: achieve relations, condition relations and realize relations.

An achieve relation connects a set of functions to a goal by emphasizing that these functions are used to obtain that specific goal. A condition relation connects a goal to a function by emphasizing that the goal must be achieved in order to realize the function. A realize relation connects a physical component to a function by emphasizing that the physical component is used to realize the specific function. The MFM symbols of goals, functions and relations are shown in **Fig.1**. Multilevel flow model describes and handles characters of a process system with a group of interrelated flow structures, where the hierarchical structure is constructed by using both achieve and condition relations. Usually, three kinds of flow structures are handled by MFM, i.e., mass flow structure, energy flow structure and information flow structure.

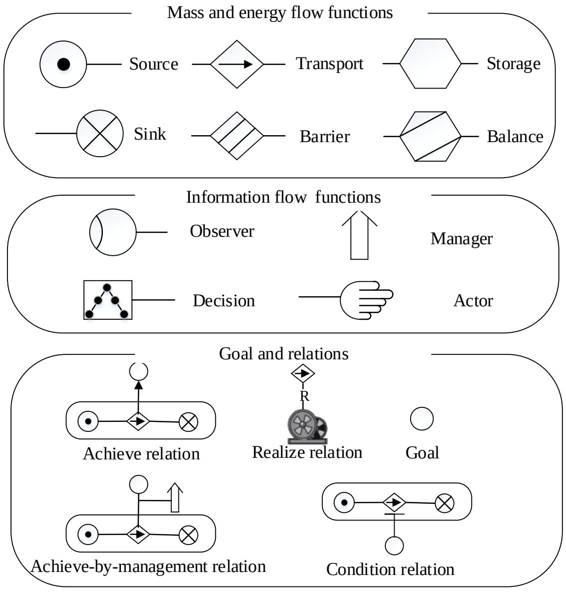
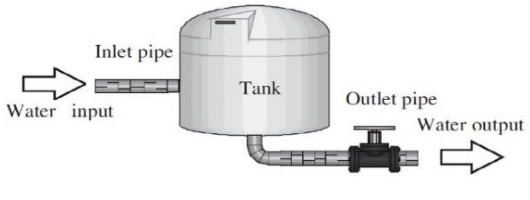


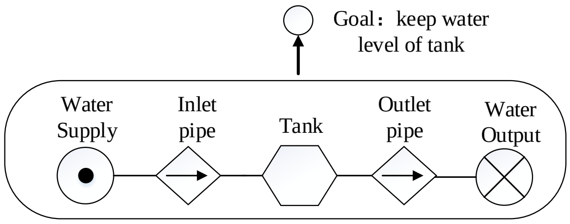
Fig. 1: Symbols of MFM

II.B. An example of a specific process with MFM modeling

An example of MFM modeling is presented in **Fig. 2** for a valve-tank system to show the application of the modeling method[9]. The system consists of an inlet pipe, a tank and an outlet pipe, its goal is to "keep the water level of the tank at a certain value". Suppose three parameters are measured: "water flow of inlet pipe", "water level of tank" and "water flow of outlet pipe". According to those measured values, the alarm states of the responding functions will be determined. For example, in normal situation, the" water flow of inlet pipe" is within a certain range of the flow-rate. If the measured value is less than the lower bound of the range, "low flow alarm" will occur and if measured value is over the upper bound of the range, "high flow alarm" will occur. Alarm states of the valve-tank system can be seen in **Table 1**.



A valve-tank system



MFM of the valve-tank system

Fig.2: A valve-tank system and its MFM

Functions	Alarm status				
Inlet pipe	Excessively low flow	Low flow	Normal	High flow	Excessively high flow
Tank	Excessively low level	Low level	Normal	High level	Excessively high level
Outlet pipe	Excessively low flow	Low flow	Normal	High flow	Excessively high flow

Table. 1: Alarm status of valve-tank system

II.C. Consequence analysis algorithms

In the fault pattern of a system, some certain alarms are directly connected to the primary source of the system failure, which is called root cause, but other alarms may be secondarily caused by the primary failures' consequential effect. The purpose of fault diagnosis is to find the root cause of the failure by selecting the primary alarms from the secondary alarms. Based on the MFM, the "causal dependency graph"[10] is first deduced from the MFM model of the plant process as a set of rules, and then it is compared with the occurred alarms to find the possible path of fault propagation, i.e., which alarm is root cause and how the alarms spread. For the tank leakage of the valve-tank system in Fig.2, its causal dependency graph can be described as **Fig.3**.

In Fig.3, the solid line A with arrow indicates a causal relationship between the two states of "high flow of inlet pipe" and "high water level in tank.", which means that "high flow of inlet pipe" will result in "high water level in tank." And also the broken lines, B and C, mean that "low water level of tank" will result in "high flow of inlet pipe" and "low-flow of outlet pipe."

In the case of "small leakage in tank", three alarms would occur almost at the same time as shown by shaded circles in Fig. 3: "high flow of inlet pipe," "low water level of tank" and "low flow of outlet pipe." The reason of "low flow of outlet pipe" is as follows: if small tank leakage happens, the water level of tank will decrease and then the water flow of outlet pipe will decrease, while the reason of "high flow in inlet pipe" is because the control action of tank level controller will increase the water flow of inlet pipe to keep the goal of this valve-tank system so that the water level of tank could be maintained. Comparing these three alarms with the whole "causal dependency graph," it becomes clear to know that the "low water level of tank" is root cause (Note: real cause is, of cause, "small leakage in tank"), and that the other two alarms are secondary nature caused by this root cause. Broken lines B and C in Fig.3 show the causal path which indicates how the alarms would spread.

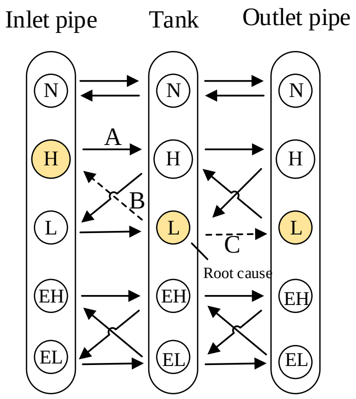


Fig.3: Causal dependency graph of the sample MFM

III. HTR-PM AND ITS MODELING WITH MFM

III.A. Introduction of HTR-PM

HTR-PM is made up of two reactors, two steam generators and a steam turbine. One reactor and one steam generator, located in the same power plant, form a standard unit. The primary loops of the two reactors are independent with the same construction design, but the two reactors share the fuel handling system, helium purification system and other auxiliary facilities. The total thermal power is 500 MW, i.e., 250 MW from each reactor. Electrical power of HTR-PM is 210 MW and each reactor is composed of pebble bed filled with fuel elements, graphite and carbon bricks, metal reactor internals, control rods and their drive mechanism, the absorber sphere shutdown system and the reactor pressure vessel, etc. Its structure overview can be seen in Fig.4 [11].

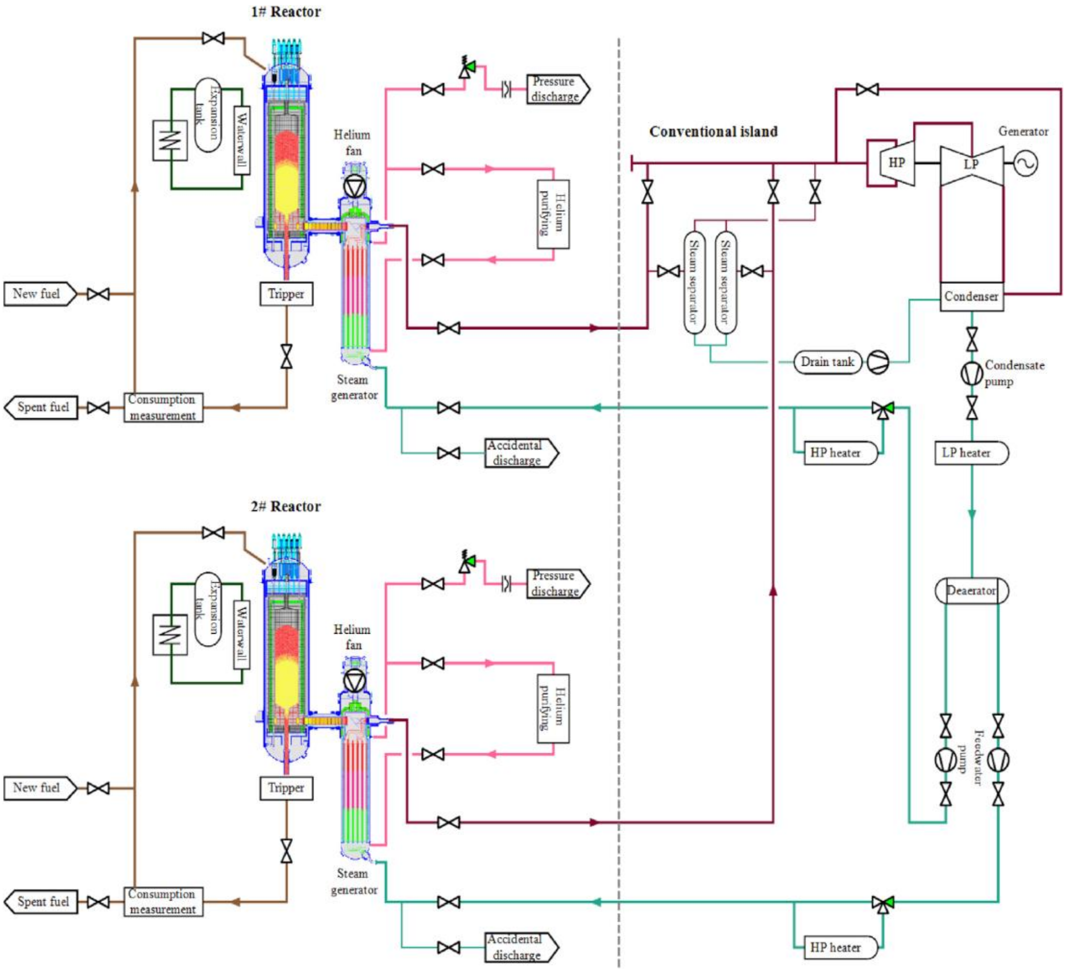


Fig. 4: Overview of HTR-PM thermal system

The reactor coolant system of HTR-PM consists of systems and relevant equipment for helium flows including pressure vessel, steam generator shell, hot gas conduct shell, and all the pipes (up to and including the first isolation valve). Normally, the helium coolant, driven by the primary helium circulator, passes the heat generated in reactor core to steam generator to heat up the 200C feed water into 570C superheated steam in the secondary loop. Then the superheated steam is sent into the turbine to generate electricity.

Different from water reactor, helium is used as the coolant and heat-carrier in the HTR-PM. To reduce the erosion of the fuel elements, graphite and other structural materials, the helium must be purified, which can be realized by the helium purification auxiliary system, whose function is to control the level of chemical impurities in the helium and maintain its purity. The system is made up of helium purification system, helium regeneration system, oxygen supply and storage system, liquid nitrogen supply and storage system, etc.

In order to prevent pressure from exceeding the design limits, HTR-PM uses a primary circuit pressure relief system to ensure the integrity of the primary circuit pressure boundary, i.e., exhaust part of the coolant gas before the pressure of primary loop reaches the design limit.

Fuel handling and storage system is designed to guarantee the safety and reliable continuous operation of HTR-PM, in which fuel elements repeatedly run through the reactor core during operation, circulating, handling, distributing and storing. With fuel burn-up measuring device, the system can distinguish whether fuel elements, emitted from the core bottom discharge pipes, have reached the final burn up, and then deliver them to respective target site through distribution equipment, or return to the core. The total number of recycled fuel elements in each reactor is about 6000 per day, in which 400 fresh fuel elements are added and 400 spent are unloaded.

During normal operations, qualified steam from the nuclear island steam generator is delivered to the turbine's high-pressure cylinder through main steam system of conventional island. And the main steam pipe is set with a “2-l-2” arrangement. Two steam pipes from the two nuclear reactor steam generators merge into one main pipe after entering the turbine room. Then the main pipe is divided into two branch pipes at the head of the room and connect with two main steam valves. Apparently, the conventional island thermodynamic system of HTR-PM is almost the same with that of water reactor power plant.

III.B. MFM model for HTR-PM

In the modeling of HTR-PM, the loop where 1# reactor lies is called A-loop, while the other one is named B-loop. Then we can get an overview of the HTR-PM MFM at the high abstraction of goal and function level as shown in **Fig.5.** Meanings of the symbols used are listed in **Table 2**.

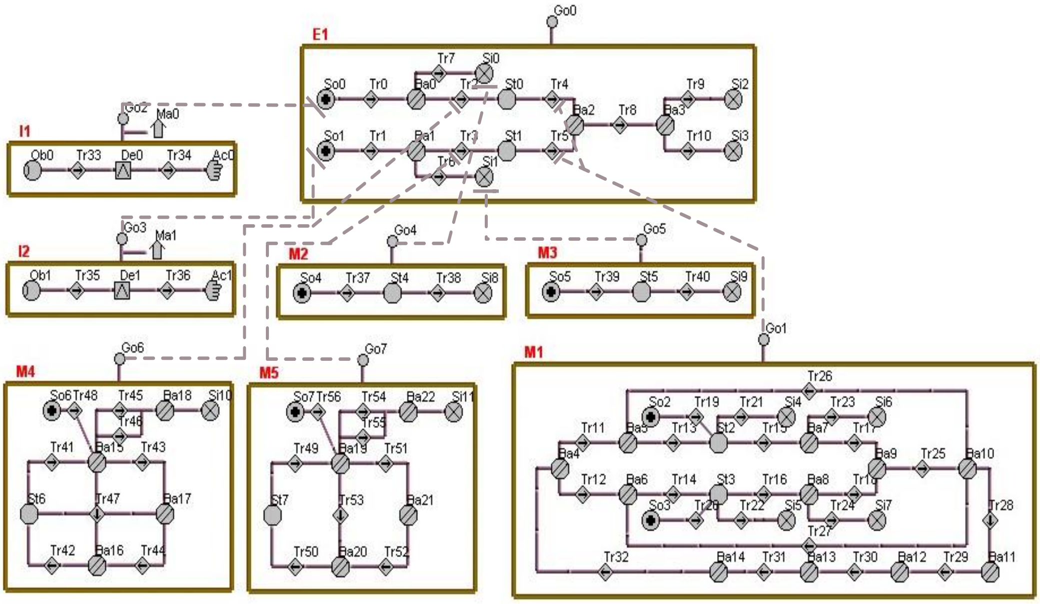


Fig.5 MFM of HTR-PM

Concepts		Symbols	Explanation
Structure		E1	Energy flow of HTR-PM
		M1	Mass flow of the secondary cooling system
		I1	Information flow realized by sensors, PID or operators
		M2	Mass flow in the waterwall (A-loop)
		M4	Mass flow of the primary cooing system (A-loop)
Goals		Go0	Generate power
		Go1	Transfer energy in secondary loop
		Go2	System control (A-loop)
		Go5	Transfer energy in waterwall (A-loop)
		Go6	Transfer energy in primary loop (A-loop)
Functions	Source	So0	Energy production by fission (A-loop)
		So2	Water supply by condensation storage tank (A-loop)
		So4	Energy obtained through heat transfer (A-loop)
		So6	Helium storage and supply system (A-loop)
	Transport	Tr0	Energy transfer from the core (A-loop)
		Tr2	Energy transfer to the SG (A-loop)
		Tr4	Energy transfer by the steam (A-loop)
		Tr7	Energy transfer to the environment through waterwall (A-loop)
		Tr8	Energy transfer through main steam line
		Tr9	Energy transfer to the condenser
		Tr10	Energy exchange in generator

		Tr11	Water transfer to HP heater (A-loop)
		Tr13	Water transfer to SG (A-loop)
		Tr15	Steam transfer to steam line 1 (A-loop)
		Tr17	Steam transfer to steam line 2 (A-loop)
		Tr19	Auxiliary feedwater transfer to SG (A-loop)
		Tr21	Wastewater transfer to wastewater tank
		Tr23	Steam transfer through release valve
		Tr26	Steam transfer to HP heater
		Tr40	Helium transfer to the primary loop (A-loop)
		Tr41	Helium transfer through heat gas duct (A-loop)
		Tr42	Helium transfer outside the heat gas duct (A-loop)
		Tr43	Helium transfer to SG (A-loop)
		Tr44	Helium transfer powered by the main fan (A-loop)
		Tr45	Helium transfer to the 1st safety valve (A-loop)
		Tr46	Helium transfer to the 2st safety valve (A-loop)
		Tr47	Helium purification system (A-loop)
	Storage	St0	Energy storage in SG (A-loop)
		St2	Feedwater storage in SG (A-loop)
		St5	Water storage in waterwall (A-loop)
		St6	Helium storage in the core (A-loop)
Functions	Sink	Si0	environmental heat sink
		Si2	Energy absorption by sea
		Si3	Energy absorption by power grid
		Si4	Wastewater tank (A-loop)
		Si6	Steam absorption by containment (A-loop)
		Si8	Water tank of waterwall (A-loop)
		Si10	Helium absorption by containment (A-loop)
	Balance	Ba0	Heat transfer from core to the coolant and waterwall (A-loop)
		Ba2	Energy convergence of A-loop and B-loop
		Ba3	Energy exchange in turbine
		Ba4	Transfer feedwater to feedwater line of the two loops
		Ba5	Heat water in the HP heater
		Ba7	Steam release
		Ba9	Steam convergence of A-loop and B-loop
		Ba10	Part of steam enters the HP
		Ba11	Steam flows through turbine
		Ba12	Steam condensation in condenser
		Ba13	Heat water in LP heater
		Ba14	Heat water in desecrator
		Ba16	Transfer helium into the primary loop after purification (A-loop)
		Ba17	Helium flows through SG (A-loop)

Table. 2: Explanation of Symbols in the MFM of HTR-PM

IV. FAULT DIAGNOSIS OF HTR-PM ACCIDENTS BY USING MFM

The algorithm of fault diagnosis based on MFM was firstly proposed by Larsson, and was applied in a Guardian project[7]. The "consequence analysis theory" for alarm analysis and fault diagnosis, proposed by Dahlstrand[10], was exclaimed that it is a universal algorithm for MFM model and the old algorithm is just a special case of "consequence analysis theory." This study applies the consequence analysis algorithm in the fault diagnosis of HTR-PM and propose a concrete fault diagnosis diagram, providing a realization of the algorithm.

IV.A. Diagram of fault diagnosis

According to the structure of the MFM model of HTR-PM, a "causal dependency graph" will be obtained from the interconnection of functions, achieve relations and condition relations as shown in Chap. IV.B. In every second interval after the fault occurs, operating parameters will be read in and each function will have a status (excessively high, high, excessively low, low or normal) according to the measured values and then alarm occurs. By using consequence analysis algorithm, the alarm propagation path will be searched in the "causal dependency graph"—which is a set of pre-defined alarm propagation rules. Once a path is found in the "causal dependency graph" that passes through all the alarms occurred, the start point of the path can be considered as the primary alarm and a certain function can be located. Then by using realize relation, the failed physical component will be located. The fault diagnosis will be performed before the trip of the HTR-PM and the diagram is shown in **Fig.6**.

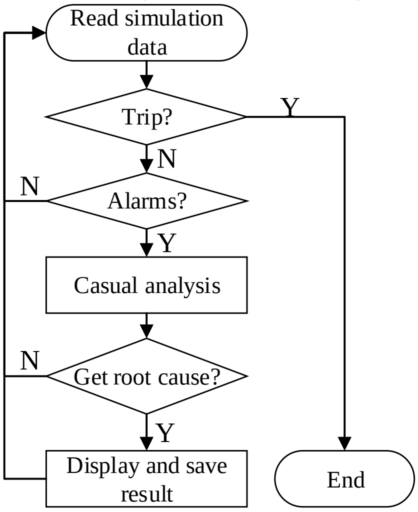


Fig.6 Flowchart of the fault diagnosis

IV.B. Implement of consequence analysis algorithm

The algorithm of consequence analysis is to find the possible root cause from a set of alarms. In the view of the computer data structure, the algorithm is going to find a path which passes through all of the alarms in the "causal dependency graph" and then the start point of the path can be considered as the root cause. The algorithm is performed in a recursive way and is called "depth-first search" traversal of the graph. The flowchart of judging whether a function with alarm is a root cause is shown in **Fig. 7.**

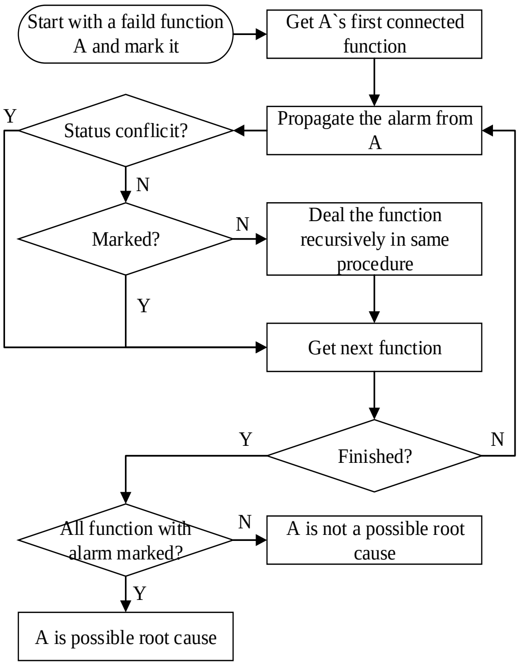


Fig. 7 The flowchart of judging whether a function with alarm is root cause

IV.C. Complexity of the algorithm

The complexity of the computation is decided by the functions' number, alarms' number and the structure of the model. Supposing the number of functions is "n" and the number of alarms is "m," the whole fault diagnosis process will perform "m" times traversal in the model (all alarms should be judged). The complexity of one traversal is $O(n)$~ $O(n^2)$ [12], so the complexity of the whole process is,

$$\mathrm{m}(O(n)\sim O(n^2)),\qquad (m \le n)$$

Since "m" is not greater than n, so in the worst case, the complexity is $O(n^3)$.

The complexity has been discussed is the case that all of the function can be measured, while in the case that some functions are immeasurable, the unmeasured function will be checked two times. Supposing the number of unmeasured function is "k," the complexity of the whole process is,

$$(\mathrm{m}+2\mathrm{k})(O(n)\sim O(n^2)),\qquad (m+k \le n)$$

In the worst case that "k=n" and "m=0", the complexity is also $O(n^3)$. Actually, the worst case of the traversal is in the situation that each function has connection with every other function in the model and all functions have alarm. In MFM model, this situation is impossible since that most types of function such as source, sink and transport can only have one or two connections (this character makes the complexity of one traversal be near to $O(n)$), so the complexity of the algorithm in dealing the MFM model will be far less than $O(n^3)$. and in rest cases will be closed to $O(n^2)$ .. In the best case the complexity is O(n) with no branches in the structure of model and alarms will not increase with the scale of model. So it can be concluded that in the algorithm can achieve the requirement of real-time calculation in principle.

V. CONCLUSION

In this paper, a symbolic modeling approach—Multilevel Flow Model (MFM) is used in the fault diagnosis of HTR-PM to build a three layer MFM model for HTR-PM and present its intricate relations and mutual interactions among flow behaviors of mass, energy and information with the conception of means-end and part-whole. Furthermore, theoretical analysis of algorithm feasibility and complexity, detailed process of fault diagnosis are also given. Due to lack of simulation data about HTR-PM, simulation experiments are not conducted. But once those data are obtained, the author have confidence that the diagnosis system will have a good ability to detect and diagnosis accidents timely before reactor trip.

To make the diagnostic process more accessible for HTR-PM operators, a user interface for HTR-PM supervisory and control will be developed in goal-function-component view with MFM. And methods dealing with unmeasured flow parameters, multiple causes and automatic operation for HTR-PM will also be the future focus of the author.

VI. ACKNOWLEDGMENTS

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