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NUCLEAR POWER PLANT PRESSURIZER FAULT DIAGNOSIS USING FUZZY SIGNED-DIGRAPH METHOD

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ABSTRACT

In this study, The Fuzzy Signed Digraph method which has been researched and applied to the chemical process is improved and applied to the fault diagnosis of the pressurizer in nuclear power plants. The Fuzzy Signed-Digraph(FSD) is the method which applies the fuzzy number to the Signed-Digraph(SDG) method. The current SDG methods have many merits as follows: (1) SDG method can directly use the value of sensors not the alarm to the fault diagnosis. (2) This method can diagnose the fault independent on the pattern. (3) This method can diagnose the faults fastly because the method uses the cause-effect relation insteady of the complex control equation among the variables. But, they are not proper to be applied to the diagnosis of the multi-faults and to diagnose faults on real time. It is because the unmeasured nodes in those methods must be connected to each other in order to find out the single fault under the single-fault assumption. These methods need long CPU time and cannot be applied to the multi-faults diagnosis.

We propose a method in which the values of the unmeasured nodes are calculated from the relations between the unmeasured nodes and the measured nodes. By using this method, the CPU time for diagnosis can be reduced. This CPU time reduction makes the real-time diagnosis possible. This method can also be applied for the multi-faults diagnosis. This method is applied to the diagnosis of the pressurizer of the nuclear power plant KORI-2 in Korea.

1. Introduction

The pressurizer and its associated components are very important parts in nuclear power plants to control the pressure of the coolant and to reduce the shock when the turbine power is changed. The correct fault diagnosis of the pressurizer, therefore, is critical to operate nuclear power plants economically and safely. When a trouble is occurred, the operators of the nuclear power plants may be confused by various parameters and alarms and often do not perform the diagnosis of the causal fault properly. More advanced methods in the fault diagnosis by using computers are needed so that the operators decide a proper action.

Generally there are two methods of fault diagnosis using the computer system. One is the experience-oriented method which is based on a list processing algorithm; all the patterns of failures experienced and the corresponding causes are filed and the pattern faced in practice is searched in the list or inferred by some rule. The other is the logic-oriented method which uses a cause-effect algorithm; all the possible cause-effect relations are prepared and the chains of cause-effect relations are used to explain consistently the observed failure pattern.[1]

In this study, Fuzzy Signed-Digraph method, one of the logic-oriented methods, which combines the Signed-Digraph and the Fuzzy-Number is improved for multi-faults diagnosis and is applied to the fault diagnosis of the nuclear power plant pressurizer. We explain the signed-digraph method briefly in section 2 and the Fuzzy signed digraph method is described in section 3. Applications of the improved Fuzzy Signed-Digraph to the pressurizer and the results are given in section 4 and 5, respectively.

2. Signed-Digraph Method

2.1 Signed-digraph

The variables and the components that are interrelated with each other such as pressure, water level, valves, heaters, are called nodes. For applying the signed-digraph to the system, first, we represent all the variables and the components as nodes and connect nodes with the arcs according to their directed cause-effect relations. The picture of the nodes and the arcs of the system is called a digraph. And the arcs have sign '+' or '-' according to whether the relation is positive or negative. For example, if B increases with the increase of A, the arc is from A to B and its sign is '+' as shown in Fig 1.a. If B decreases with the increase of A, the arc is still from A to B but it has '-' sign as shown in Fig 1.b. When two nodes mutually affect each other, i.e. as A increases, B increases, and as B increases, A decreases, which is called a negative feed back loop, their interrelation is shown as in Fig 1.c. Another case in which the nodes have different arcs according to the variables' condition is shown in Fig 1.d.

Using the techniques described above a Signed-Digraph of

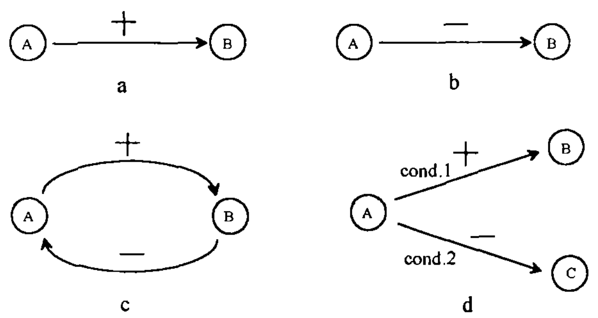

Figure 1. Relations Of Nodes

the system is made by the materials and the experience of the experts before the Fuzzy Signed-Digraph method is applied.

2.2 Fault pattern

The values of the system variables are changed when transients or failures occur in the system. The values of the nodes that indicate the condition of changed variables of the system are called the fault pattern. The value of each node has '+' sign when the variable increases, and '-' sign when the variable decreases, and '0' if the variable is not changed.

The nodes are divided into two groups, measured nodes and unmeasured nodes. The measured nodes are the nodes that are directly known from sensors or indicators and the unmeasured nodes are the nodes that are not directly known from sensors or indicators. When one makes patterns, therefore, the values of unmeasured nodes must be assumed from the measured nodes and from the system information.

The methods of estimating values of unmeasured nodes are as follows: (1) the method of connecting the nodes using the assumption of the single fault. (2) the method assuming the values of unmeasured nodes using the values of measured nodes and the system information.

The merits and demerits of two methods are as follows: In the first method, the values are inferred with digraph even if the values of all unmeasured nodes are not assumed. This method, however, has the premise of single fault assumption and it needs long CPU time when there are many unmeasured nodes. It is, therefore, difficult to diagnose the multi-fault and the causal fault on real-time. In the second method, there should be sufficient information on the system variables and components so that the values of unmeasured nodes are inferred from the values of measured nodes. This method, however, has advantages that it does not need single fault assumption and it can perform real-time diagnosis even with many unmeasured nodes due to its less CPU time required. It can also be used to diagnose the multi-faults.[2]

2.3 Determination of causal fault

For the diagnosis of the causal fault, the nodes that have zero values in the pattern are excluded from the diagnosis process because they are not related to the fault. And the value of an arc from i to j, D_{ij}, is valid if the following equation is satisfied:

$$n_j \neq 0$$
$$n_i \times D_{ij} \times n_j = + \qquad (1)$$

n_i : value of node i
n_j : value of node j
D_{ij} : value of an arc from i to j

The arcs which satisfy the above relations are called consistent arcs and the digraph that consists of these arcs is called a consistent digraph. The diagnosis of the causal fault is performed by back-tracking the arcs of the consistent digraph.[3,4]

However, there are controlled nodes of which the value is appeared to be zeros even though the nodes are related to the fault; the pressure of the pressurizer in nuclear power plants is an example. The values of controlled nodes, therefore, must be estimated from the connected neighboring nodes even if the controlled nodes have zero values. If the node j is a controlled node and i is an input node of the controlled node, the following equation is satisfied:

$$n_i \times D_{ij} = + \Rightarrow n_j = +$$
$$n_i \times D_{ij} = - \Rightarrow n_j = - \qquad (2)$$

If the controlled nodes are appointed initially and its values are assigned from connected nodes using the above equation, we can link the paths leading to the controlled nodes and can find the origins of the failure by means of back-tracking the connected paths.

3. Fuzzy Signed-Digraph method

It is difficult, however, to apply the signed-digraph method to complex systems such as nuclear power plants that have nodes connected to many other nodes. The Signed-Digraph is also inappropriate to be used for the diagnosis of the variables that change in small quantity such as in the regime of control region. There is no way pointing out the severe fault among the faults when multi-faults occur. In order to solve these problems, Fuzzy number is introduced to the values of the arcs and the nodes in the Signed-Digraph method.[4,5]

This method transforms the cause-effect relation of variables to Fuzzy values from -1 to +1, which can be accomplished by the opinion of experts on the degree of interrelation among the variables. And the values of nodes that indicate the state of the system are changed to the fuzzy values corresponding to the degree of transition. The values of the controlled nodes defined in the previous section are calculated as in the following procedure: If j is a controlled node,

$$n_j = \bigcup_i [\bigcap \{abs(n_i), abs(D_{ij})\}]$$
$$sign\ of\ n_j = sign\ of\ the\ n_c \times D_{cj}, \qquad (3)$$

i : input nodes of the controlled node j
j : controlled node
c : selected node
n_i : Fuzzy value of the node i

D_{ij} : Fuzzy value of the cause-effect relation from i to j
$abs(n_i)$: absolute value of n_i
$abs(D_{ij})$: absolute value of D_{ij}

If we apply the min-max procedure to this equation, it is expressed as follow:

$$n_j = \max_i[\min\{abs(n_i), abs(D_{ij})\}] \quad (4)$$

In the Fuzzy Signed-Digraph method, the values of unmeasured nodes are estimated by the values of other nodes and the system information as in the previous section. The values of the nodes are not qualitative values, + , 0, -, but fuzzy values in this method.

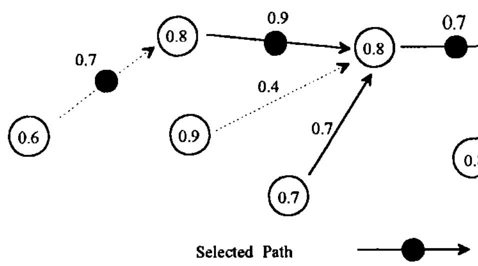

Figure 2. Back-Tracking

After the values of controlled nodes and unmeasured nodes are determined using the above relation, we search the origins of the faults by back-tracking the consistent digraph. During the back-tracking, if we meet the nodes that have multi-input arcs as shown in Fig 2, the path is connected to the node that has the highest fault probability that is estimated using the following fuzzy operation:

$$i = \max_i[\min\{abs(n_i), abs(D_{ij})\}] \quad (5)$$

j : the node that have multi-input nodes
i : the input nodes of the node j
n_i : the value of the node i
D_{ij} : the value of arc from the node i to the node j

In the next search, the path is connected to the node which has the second highest fault probability estimated among the paths, then next, and so on. When multi-faults occur in the system, we can find the fault that has the highest fault probability among the causal faults in order.

4. Application to the pressurizer in nuclear power plants

In this section, we applied the signed digraph method and Fuzzy Signed digraph method to the pressurizer and its associated systems in nuclear power plants. We express the variables(i.e., pressure, water level, temperature, and flow) and the components(i.e., sensors, valves, heaters, and controllers) of the pressurizer as nodes.

The pressure and water level of the pressurizer make many components operate and the variables are influenced with each other. And many connection-conditions of cause-effect arcs of the pressurizer depend on the conditions of the pressure and the water level.

So, we make the digraph that has conditional arcs so that the digraph of the system is represented with different connection arcs according to the range and setpoint of the pressure and the water level.

The nodes are divided into two groups as shown in the section 2, measured nodes and unmeasured nodes. The measured nodes are the sensors such as pressure sensors and water level sensors and temperature sensors and so on., and the unmeasured nodes are the components such as valves and heaters and controllers and other variables such as flow. The values of measured nodes are given directly from the sensor outputs, and the values of unmeasured nodes are given from the information of the digraph or the values of measured nodes.

In this work, we use the method in which the values of unmeasured nodes are inferred from measured nodes such as sensor outputs because there are enough measured nodes to infer the value of the unmeasured nodes in the pressurizer and its associated systems. For example, the state of the relief valve of the pressurizer is known from the temperature of the line connected from the valve to the relief tank. The value of the valve, therefore, could be inferred by the temperature as long as

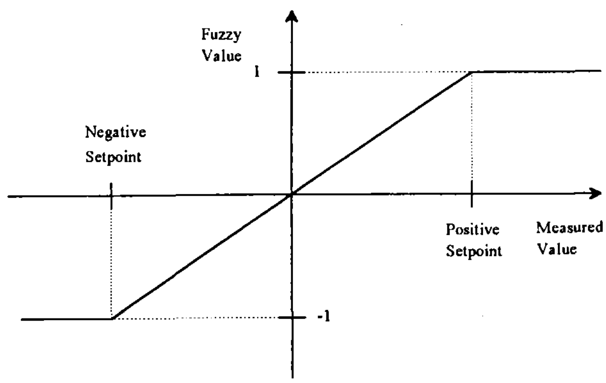

Figure 3. Fuzzy Value

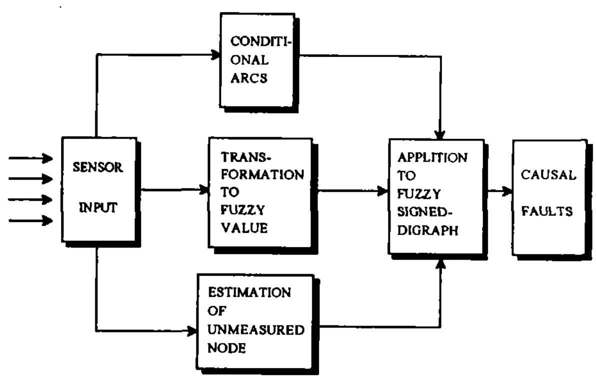

Figure 4. The Schame Of Diagnosis

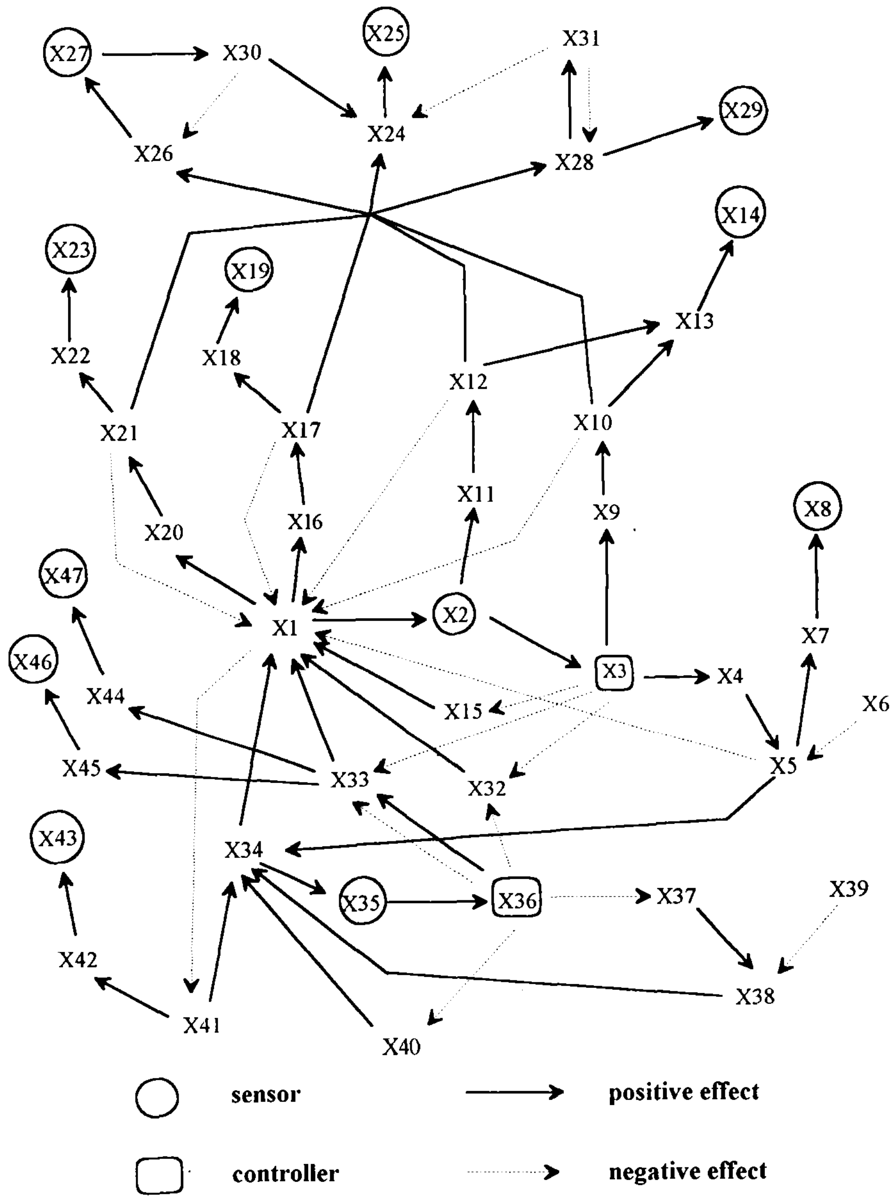

Figure 5. Application To The Pressurizer Of Kori-2 Nuclear Power Plant

the sensor is not failed. And the value of a measured node is given +1 when the indicated value of the node is higher than positive alarm setpoint and is given with linearly increasing value from zero to +1 up to the positive alarm setpoint as shown in Fig.3. It is given -1 when the value of the node is lower then negative alarm setpoint and is given with linearly decreasing value from zero to -1 up to the negative alarm setpoint as shown in Fig.3.

In this work, the Fuzzy Signed-Digraph of the pressurizer and its associated systems is made up of 47 nodes and many arcs as shown in Fig.5 and in Table 1. The digraph is made using the components and variables related to the system. And the scheme that performs diagnosis of causal faults is in shown Fig.4. The examples of which we diagnose the faults using this method are shown in the next section.

5. Result and Conclusion

The Fuzzy Signed-Digraph was applied to the single-failure of the pressurizer in which the relief valve was leaking. It is also applied to a multi-failure case in which the relief valve was leaking and the control valve was overly open. The data used for the diagnosis of the failures are shown in Tables 2 and 3. The consistent digraph used for the diagnosis of the failures and the causal faults are shown in Fig. 6 and Fig. 7. We can find out the

Table 1. The Name of Nodes in Figure 5

NODE	NAME	NODE	NAME
X_1	Pressure	X_2	Pressure Sensor
X_3	Pressuer Controller	X_4	Spray valve
X_5	Spray line Flow	X_6	Spray line Tube
X_7	Spray line Temp.	X_8	Spray line Temp. Sensor
X_9	PORV1	X_{10}	PORV line Flow
X_{11}	PORV2	X_{12}	PORV2 line Flow
X_{13}	PORV Temp.	X_{14}	PORV Temp. Sensor
X_{15}	PORV Interlock Valve	X_{16}	SRV1
X_{17}	SRV1 flow	X_{18}	SRV1 line Temp.
X_{19}	SRV1 line Temp. Sensor	X_{20}	SRV2
X_{21}	SRV2 flow	X_{22}	SRV2 line Temp.
X_{23}	SRV2 line Temp. Sensor	X_{24}	Pressurizer Relief Tank(PRT) Level
X_{25}	PRT Level Sensor	X_{26}	PRT Temp.
X_{27}	PRT Temp. Sensor	X_{28}	PRT Pressure
X_{29}	PRT Pressure Sensor	X_{30}	PRT coolant
X_{31}	Rupture Disc	X_{32}	Proportional Heater
X_{33}	Backup Heater	X_{34}	Level
X_{35}	Level Sensor	X_{36}	Level Controller
X_{37}	Charging Valve	X_{38}	Charging Flow
X_{39}	Charging line Tube	X_{40}	Let down Valve
X_{41}	Surge Flow	X_{42}	Surge line Temp.
X_{43}	Surge line Temp. Sensor	X_{44}	Water Temp.
X_{45}	Water Temp. Sensor	X_{46}	Vapor Temp.
X_{47}	Vapor Temp. Sensor		

causal faults from the consistent digraphs if we use the method of the back-tracking which starts from the nodes not possessing the output arcs such as RTls, RTps, POts, Sts, Hp, Hb, and Cf as shown in Fig. 7. In the causal faults, the two relief valves appeared to be failed even though one of them is working well. This is because the two relief valves have only one temperature sensor. Thus, if there is temperature sensor at each relief valve line, we can find the failed relief valve among the two valves using the Fuzzy Signed-Digraph method.

If the PORV opening is caused from insurge flow, the fault pattern is different from table 2. Under this situation, the pattern is appeared such as the level sensor is high and the pressure sensor is high. The causal fault, therefore, is that surge flow is high.

If PORV is open for other cause not PORV leaking, the fault pattern is appeared differently from the pattern of PORV leaking. For example, PORV valve is open when the pressure of the pressurizer is over the setpoint of "PORV OPEN" due to insurge flow to pressurizer from the coolant system. If the pressure is increasing for above situation, the pressure sensor indicates "high", and the level sensor indicates "high" and then the arcs in consistent digraph indicate surge flow as the causal fault.

The merits of the Fuzzy Signed-Digraph method developed in this work are as follows: (1) This method is better than the method of using binary output alarms in the fact that the values of sensors are directly used in the FSD method. The method using the alarm at the fault diagnosis is able to diagnose the fault

Table 2. The Data Of Single-Failure (PORV1)

Measured node	Sensor's (normal) value	Fuzzy value
2	2207(2235) pisa	-1.0
8	536(536) ^oF	0
14	656.7(86) ^oF	+1.0
19	86(86) ^oF	0.0
23	86(86) ^oF	0.0
25	78(75) %	+0.375
27	258(100) ^oF	1.0
29	44.1(14.7) pisa	1.0
35	64.1(60) %	0.8
43	615.42(615.42) ^oF	0.0
45	656.7(656.7) ^oF	0.0
47	656.6(656.7) ^oF	0.0

Table 3. The Data Of Multi-Failure (PORV 1+Spray valve)

Measured node	Sensor's (normal) value	Fuzzy value
2	2201(2235) psia	-1.0
8	551(536) ^oF	1.0
14	656.7(86) ^oF	+1.0
19	86(86) ^oF	0.0
23	86(86) ^oF	0.0
25	78(75) %	+0.375
27	258(100) ^oF	1.0
29	44.1(14.7) psia	1.0
35	64.5(60) %	0.9
43	615.42(615.42) ^oF	0.0
45	656.7(656.7) ^oF	0.0
47	656.6(656.7) ^oF	0.0

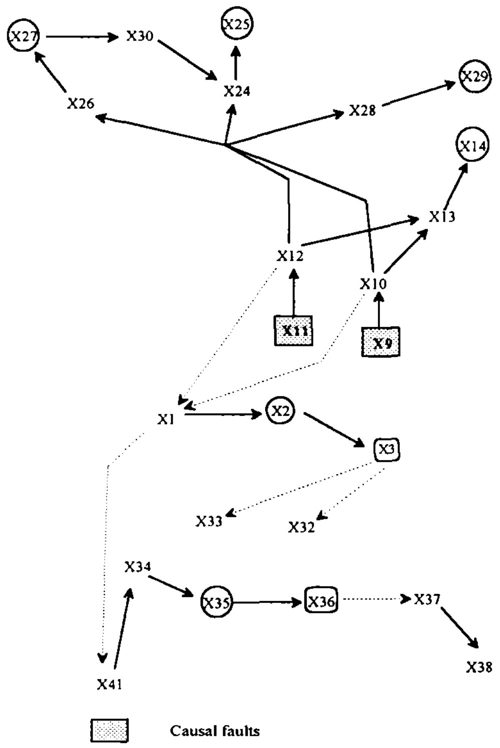

Figure 6. The Consistent Digraph Of The Single-Fault (PORV Leaking)

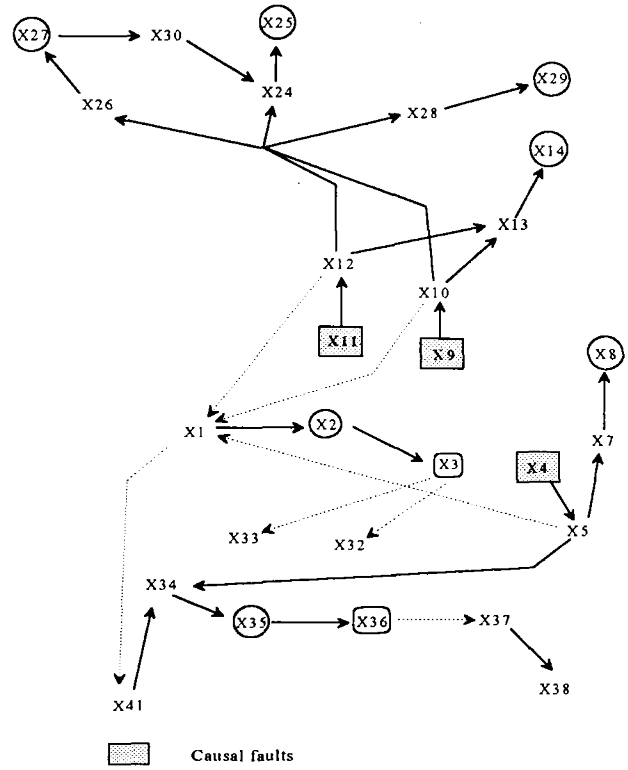

Figure 7. The Consistent Digraph Of Multi-Faults (PORV + Spray valve)

only when the values of sensors exceed the alarm setpoint, but this Fuzzy Signed-Digraph method can diagnose the fault regardless of the range of the sensors. (2) This method is not restricted by the fault patterns unlike the method using the neural networks. The new method can find the origin of the faults independent of the patterns, whereas the neural networks methods require all the possible fault patterns in the learning procedure. (3) The FSD method searches causal faults more quickly than other signed digraph methods because it does not need to estimate the values of unmeasured nodes, which are given from the values of sensors and indicators. (4) It can find the multi-faults because the values of unmeasured nodes are given from the information of the system and the measured nodes. Additionally, it can find the causal fault which has the highest failure probability among causal faults because it can back-track along the path which has high probability of fault. The pressurizer, however, is often affected from the failure of other system not the pressurizer itself, such as insurge flow to the pressurizer from the coolant system. In further study, the method which can diagnose the faults of wide system should be investigated.

REFERENCE

1. M. IRI, K. AOKI, E. O'SHIMA, H. MATSUYAMA, "An Algorithm for Diagnosis of System Failutes in the Chemical Process" Computer & Chemical Engineering, Vol.3. pp.489, 1979

2. J. SHIOZAKI, H. MATSUYAMA, E. O'SHIMA, M. IRI, "An Improved Algorithm for Diagnosis of System Failure in Chemical Process." Computer & Chemical Engineering, 9, 285, 1986

3. MASASUMI KOKAWA, SATOSHI MIYAZAKI, SADANDORI SHINGAL, "Fault Location Using Digraph and Inverse Direction Search with Application" Automatica, Vol.19. No. 6 pp.729, 1983

4. GANCHO VACHKOV, KAORU KIROTA, "Fuzzy Method for Finding Fault Propagation Way in Industrial Systems" Fifth IFSA Word Congress. pp 1114, 1993

5. GANCHO VACHKOV, STOYAN STOYANOV, "Application of Fully Directed Graphs to Fault Diagnosis and Approximate Reasoning Problems" Proc. of the Int. Conf. IIZUKA'90. pp 295, 1990

6. M. A. KRAMER, B. L. PALOWITCH, JR."A Rule-Based Approach to Fault Diagnosis Using the Signed Directed Graph" AIChE Vol.33. No. 7. pp 1067, 1987

7. S. MOHINDRA, P.A. CLARK, "A Distributed Fault Diagnosis Metheod Based on Models: Steady-State Analysis" Computer chem. Engng. Vol 17. No 2. pp 193, 1993