Modeling Goals and Functions of Micro Gas Turbine System by Multilevel Flow Models

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Abstract - Semiotic analysis is often used for describing the inter-relationship of structure, function and behavior of any artifacts as the means for designing various computerized tools for machine diagnosis and operation procedure. In this study, a graphical method called Multilevel Flow Models (MFM) is applied for supporting machine maintenance work of commercially available Micro Gas Turbine System (MGTS), to describe and handle the relationships between goals and functions that exist in various parameters of MGTS including signal, alarm and fault. A new three-step method including alarm validation, fault condition checkup and fault identification is proposed for fault diagnosis based on MFM. A trial software has been developed by using Visual C++ and Excel for monitoring and diagnosing the MGTS based on the proposed fault diagnosis method. And it was tested by several typical actual fault cases, to show that the proposed method is efficient to monitor the running state of MGTS and to diagnose the real reason of fault message from the operation software provided by the vendor of Micro Gas Turbine.

Keywords : Multilevel Flow Models, Micro Gas Turbine System, Monitoring, Fault Diagnosis

1. Introduction

This study proposes a diagnostic technique based on Multilevel Flow Models (MFM) for Micro Gas Turbine System (MGTS). MGTS is a small-scale system, but when runs as a co-generation system it is extremely efficient, has very low concentration of NOx in its exhaust, has low CO_2 emission, and is therefore a product that is highly benevolent to environment. The application of MGTS will strive to achieve sustainable development aimed at symbiosis between social and economic progress, and environmental preservation.

Many monitoring or/and diagnosis methodologies based on intelligent technique have been proposed to aid operator to understand system problems, perform trouble-shooting action and reduce human error under serious pressure. These monitoring or/and diagnosis technologies range from logical reasoning based methods to model based methods and Soft Computing technologies. Logical reasoning based methods [1] usually explore simple production rule to manipulate the relation between signal/alarm and fault. Model based methods such as Petri Net [2], Knowledge/Event Tree [3] and Signed Directed Graph [4] serve the monitoring or/and diagnosis role by establishing a model representing various relations in the target system. Recently, Soft Computing technologies including Fuzzy Logic [5], Artificial Neural Network [6,7], Genetic Algorithms [8] interest researchers greatly. Moreover, some hybrid ways [9,10] by combining two or more of above techniques are also revealed in some researchers' work. Although almost all aforementioned methods have comparable capabilities to find out the real situation and diagnose the real fault of system, there is still a remarkable shortage preventing the operator from processing the fault diagnosis comprehensively in order to reduce human error.

That is to say, these methods only concentrate on the validity of the diagnosis result, but rarely take account into the understandability of the diagnosis process and result. The diagnosis process of these methods usually runs as a "black box" and only diagnosis result is revealed to operator, thus operator can not really realize what happens and how it goes on, which brings potential human error on operation.

A semiotic analysis method based on MFM is specifically applied for proposing comprehensive diagnosis of machine system by understanding machine on the basis of goal-oriented nature of human. The main strategy of MFM provides a multiple graphical representation of the plant based on a dual decomposition principle using means-end and whole-part concepts. MFM decomposes the plant into interrelated functions and synthesize them to structure achieving the goals of plant. Therefore, the diagnostic information provided by MFM explains how the fault results in the loss of the function of physical components could match the types of representation used by operators in order to reduce human error in situations of emergent and high risk tasks. In addition, the function based diagnostic information can be easily explained to operator from the point of view of physical component, for example, using block diagram. In this way, operator even with little knowledge of functional information can really understand what and how the monitoring or/and diagnosis system serves, which will greatly

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enhance the usability of the system and operator's trust in it. Therefore, the operators can improve decision-making skill, respond to changing fault circumstances and initiate creative solution against the fault since they can understand diagnosis process and mechanism easily.

Morten Lind [11] first introduced the basic concepts of MFM and two modeling examples in detail. Then, new algorithms by MFM for measurement validation, alarm analysis and fault diagnosis were proposed by Jan Eric Larsson [12]. Bengt Ohman [13] presented a measurement validation method with MFM. Fredrik Dahlstrand [14] proposed a new approach for performing alarm analysis by using MFM. Akio Gofuku [15] proposed a semantic representation interface that displays diagnostic information from functional viewpoint by MFM.

With the integration of the work of Bengt Ohman [13] and Fredrik Dahlstrand[14], a three-step diagnostic method including alarm validation, fault condition checkup and fault identification is proposed. In addition, it is validated by several actual fault cases of MGTS, a small-scale co-generation system supplying both electricity and heat to the customers' medium-to-small energy demand.

In the future, the proposed method will be applied for developing support software for on-line monitoring and fault diagnosis of the commercially available MGTS. The reason why MGTS is used for this study consists of two aspects. The first is that the versatility of entities of mass flow and energy flow dealt in the MGTS gives apparent difficulty for describing the semiotics by MFM. Although MGTS is a small-scale co-generation system, it consists of several complex flow structures such as gas flow, liquid flow and electricity conversion system similar to a large-scale process plant. The second is the customer's complexity for the operation of MGTS. The customer who will introduce the MGTS may meet the following situation: the Micro Gas Turbine (MGT) as a single machine given by the vendor has already been equipped with various automatic control and diagnosis functions for helping the customer's easy operation. But since the customer will have to connect various equipment and machines to the original MGT for utilization of both electricity and heat from the MGT, the total management system may be prepared at the customer's side. This may be a very cumbersome work for the customer because the vendor-supported operation system in MGT is a kind of "black box" software to the customer.

The remainder of this paper is organized as follows. A brief introduction of MFM is given in section 2. Section 3 describes how the reference system of this research, MGTS, is modeled and diagnosed based on MFM. The simulated real-time process for monitoring and diagnosing the MGTS by using a trial software is introduced in section 4. Finally, section 5 is conclusions and future work

2. Multilevel Flow Models

MFM is a graphical modeling method to explain the semantics of the process system based on the idea of *goal*, *physical component* and *function*. *Goal* means the objective or purpose that the system or the sub-system is designed or constructed to achieve. *Physical component* is what the system or the equipment consists of. *Function* is the means by which the *physical component* will achieve the *goal*. There are several kinds of *relations* between *goal*, *function* and *physical component*: *realize relation*, *achieve relation*, and *condition relation*.

A *realize relation* affiliates *physical component* to *function* by stressing that a *physical component* is used to realize a specific *function*. Because MFM do not express *physical component* in any explicit way and *function* is the basic

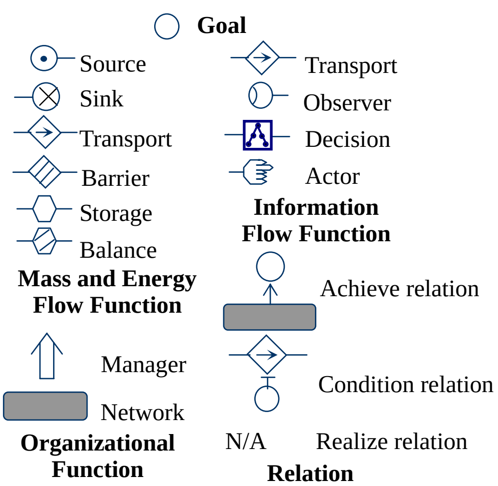


Fig.1 Symbols of Multilevel Flow Models

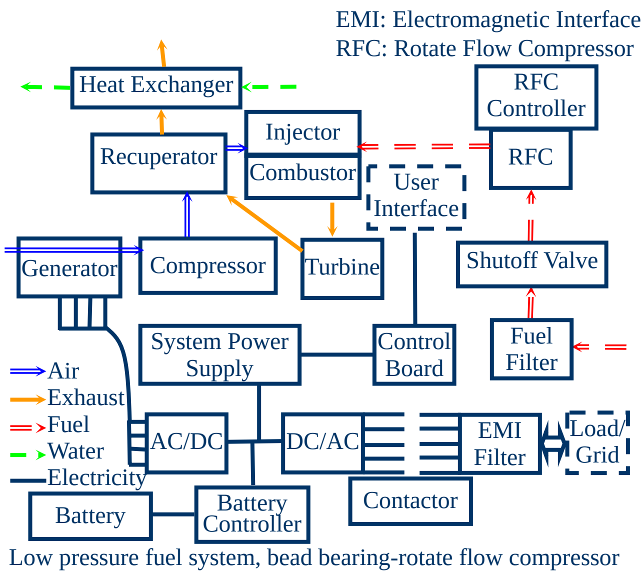


Fig.2 Configuration of Micro Gas Turbine System.

element of MFM, *realize relation* need not be expressed by any symbols. An *achieve relation* connects a group of *functions* to a *goal* by stressing that these *functions* are used to obtain a specific *goal*. A *condition relation* connects a *goal* to a *function* by stressing that the *goal* must be achieved in order to realize the *function*. The symbols that represent *goal*, *functions* and *relations* are shown in Fig.1. MFM describes and handles character and behavior of the process system with a set of interrelated *flow structures*, where the hierarchical structure is constructed by using both *achieve relation* and *condition relation*. There are three kinds of *flow structures*, i.e., *mass flow structure, energy flow structure,* and *information flow structure*.

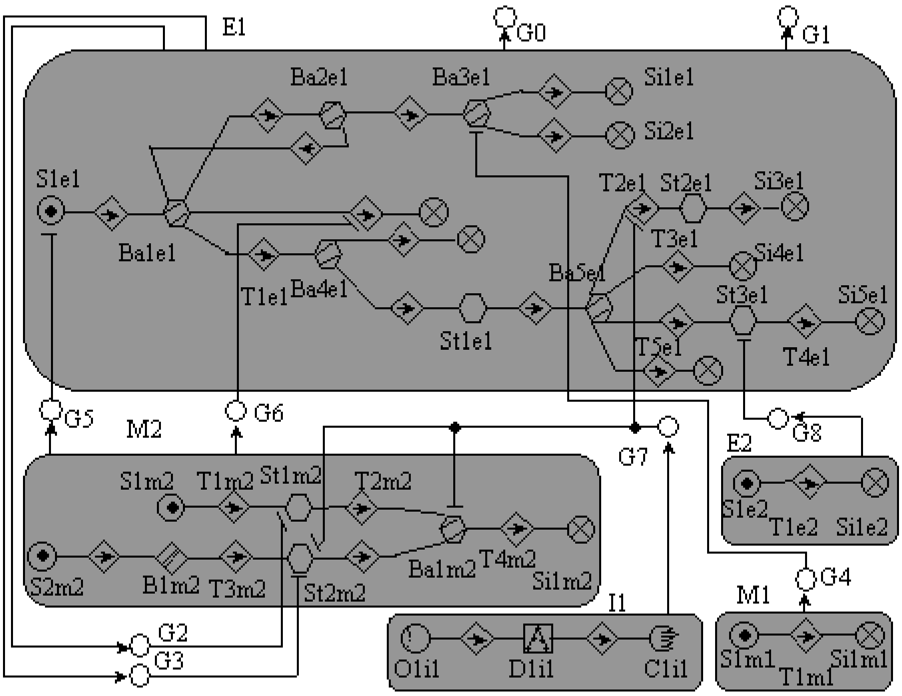
3. Modeling and Diagnosing MGTS by MFM

3.1 Modeling MGTS by MFM

MGTS is a small-scale co-generation of electricity and heat with combining maintenance-free air bearings, low emissions and digital power conversion. The whole configuration of MGTS is depicted in Fig.2. There are five subsystems. Fuel system is an integral fuel delivery and control system available for various fuels. Engine system is a combustion turbine driven by high pressure and high temperature exhaust to generate variable voltage and frequency AC power. Digital Power Controller (DPC) controls the operations of MGTS and performs power conversion functions. Battery system equipped with a large battery is used for unassisted start and for transient electrical load management. Heat exchanger is used for the effective reutilization of high temperature exhaust

Table 1 Explanation of functions in semiotic description

Name	Explanation of Function
S1e1	Provide energy by combustor
Ba1e1	Convert energy by turbine
Ba2e1	Preheat air by recuperator
Ba3e1	Heat water by heat exchanger
Si1e1	Emit exhaust
Si2e1	Emit water
T1e1	Transfer energy by shaft
Ba4e1	Generate electricity by generator
St1e1	Convert AC to DC by AC/DC inverter
Ba5e1	Provide system power by DC bus
T2e1	Transport electricity by DC bus of battery controller
St2e1	Store or supply electricity by battery
T3e1	Transport system power
Si4e1	Consume electricity by digital control system
St3e1	Convert DC to AC by DC/AC inverter
T4e1	Transport electricity by contactor
Si5e1	Consume electricity by Load/Grid
T5e1	Transport electricity by brake resistor
S1m2	Provide air
T1m2	Transfer air by generator
St1m2	Compress air by compressor
T2m2	Transport air by recuperator
S2m2	Provide city gas
B1m2	Remove particulates by filter
T3m2	Transport city gas by shutoff valve
St2m2	Regulate city gas by RFC
Ba1m2	Combust city gas by injector and combustor
T4m2	Transport exhaust by recuperator, heat exchanger
Si1m2	Emit exhaust
S1m1	Provide water
T1m1	Transport water by heat exchanger
Si1m1	Emit water
S1e2	Provide grid power
T1e2	Transport grid power by grid transmitter
Si1e2	Consume electricity by various external loads
O1i1	Receive command by user interface
D1i1	Calculate system parameters
C1i1	Control system by controllers



G0: Generate and output electricity
G1: Heat water in heat exchanger
G2: Drive air compressor
G3: Drive rotate flow compressor
G4: Transport water to heat exchanger
G5: Establish and maintain combustion
G6: Cool engine by inlet air
G7: Regulate air, fuel and battery
G8: Regulate output voltage
E1: Energy flow supported by combustor, compressor, turbine, generator, recuperator, heat exchanger, AC/DC converter, system power supply, DC/AC converter, contactor and so on
E2: Energy flow supported by grid to regulate the output voltage of MGTS
M1: Mass flow of water supported by heat exchanger and so on
M2: Mass flow of air, fuel and exhaust provided by generator, compressor, turbine, recuperator, heat exchanger and so on
I1: Information flow supported by user interface, control board and so on

Fig.3 Semiotic description of Micro Gas Turbine System by MFM to heat water.

When MGT runs under some abnormal condition, its control system or remote control system (Capstone Remote Monitoring System [16]) will report an alarm to the operator. Then, with the help of a text-based trouble shooting manual [17], the operator will try to manually resolve the problem. However, it is a troublesome task for the operator to quickly and accurately identify the real fault because the MGTS is controlled and protected automatically during normal and abnormal operation and therefore becomes a “black box” to the operator.

MFM can provide usable assistance to operators for understanding, monitoring and diagnosing MGTS by modeling the goals and the functions of different components of MGTS. The result of semiotic analysis of MGTS based on MFM is shown in Fig.3 with the explanation of some functions in Table 1. As shown in Fig.3, there are two main goals in MGTS, G0 and G1, seven sub-goals, G2~G8, two energy flow structures, E1 and E2, two mass flow structures, M1 and M2, and one information flow structure, I1.

3.2 Fault diagnosis by MFM

The process of fault diagnosis shown as Fig.4 consists of three steps according to the behavior of MGTS and the character of MFM. They are alarm validation, fault condition checkup, and fault identification, as will be explained in this section.

3.2.1 Alarm validation

The first step is alarm validation for identifying whether the alarm is wrongly activated by the originally implemented diagnosis system of MGT. MGT has fundamental protection function by conditioning values of some important signals. If the value of the signal exceeds the preset limitation for a preset time, a fault code denoting the corresponding alarm will be automatically reported to operators in order that the operators can sense the situation of MGT and perform suitable operation. However, sometimes false alarm and spurious alarm may appear. False alarm usually is caused by the improper setpoint for the alarm. The reason of spurious alarm usually is unknown.

In order to validate the alarm, their corresponding MFM functions and the preset ranges of the signals will be stored in advance. Usually, the preset range is represented as an inequation with an upper limit and a lower limit such as $v_l \le v \le v_h$. As soon as an alarm is reported, its relevant MFM function and signal will be accessed, and then the values of the signal will be compared with preset range in order to validate whether the alarm is wrongly activated. If a high value alarm is activated, the actual value of signal will be compared with the upper limit. If the actual value of signal exceeds the upper

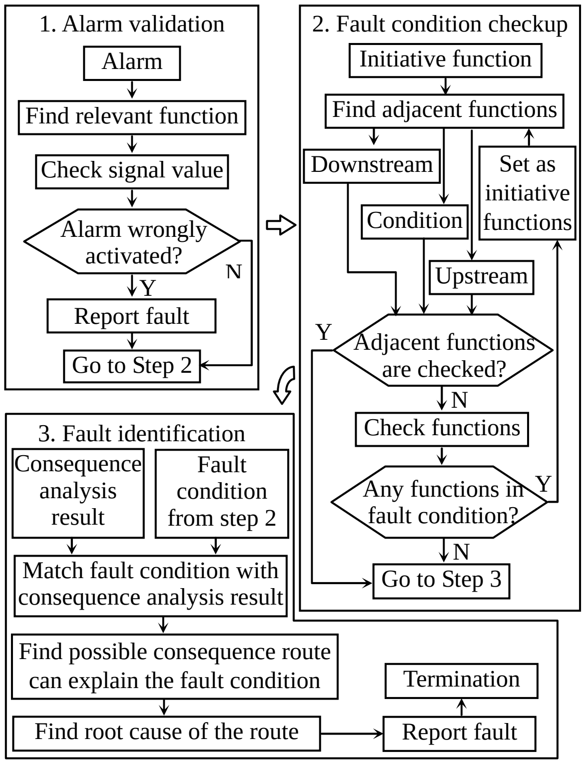


Fig.4 Three-step method for fault diagnosis by MFM

limit, it can be concluded that the alarm is rightly activated, otherwise not.

3.2.2 Fault condition checkup

After alarm validation, the second step for fault condition checkup will find all functions in fault condition. The function in fault condition means its relevant signal is in abnormal state even if the abnormal state of the signal does not bring on the appearance of an alarm. Usually, a signal is affiliated with a preset range represented by an inequation like $v_l \le v \le v_h$, where v_h denotes the upper limit and v_l denotes the lower limit. The fault condition checkup of a single function compares the value of its relevant signal with the preset range. If the signal of this function exceeds the preset limit, the function will be marked with a fault condition, otherwise not.

How fault condition checkup searches the MFM structure is an essential issue that should be carefully considered especially in a complex MFM model representing a large-scale system. If the fault condition checkup is carried out in a pervasive way which means all functions in the MFM structure are accessed to identify whether they are in fault condition, it will become a time-consuming task and its efficiency sometimes can not fulfill the requirement of the real-time monitoring and diagnosis system. If the fault condition checkup appears as a too abbreviated one, the comprehension of the system after fault condition checkup will become too cursory to serve its necessary role for understanding the situation of the system.

According to the characters of flow model, the abnormities in MFM structure usually are propagated through the flow structure so it can be concluded that the functions in fault condition always are connected into a self-consistent route. In this way, a propagation search for fault condition checkup is adopted in order to find all functions in fault condition efficiently and completely. As the first step of the propagation search process for fault condition checkup, it is necessary that at least one function in fault condition should be obtained to play an initiative role in order that the propagation process can start. In our study, the function that directly relates to the alarm is considered as the initiative function with which the checkup process will start.

The fault condition checkup is a propagation search process circularly checking the signal values of the adjacent functions adjoining the initiative functions. The flow chart of the fault condition checkup is shown in the section “2.Fault condition checkup” of Fig.4. An initiative function is the one that directly relates to an alarm or is found in fault condition in the last checkup cycle. An adjacent function is the one that adjoins the initiative function downstream, upstream or with condition relation. After one checkup cycle is finished, the adjacent functions in fault condition will become initiative functions of next checkup cycle. The fault condition checkup will be terminated until all adjacent functions in a checkup cycle are either checked or in normal state.

The lack of signal for function checkup should also be considered. Because there are many components in a system or equipment, sometimes it is impossible to install many sensors to provide enough signals for checking the condition of all functions. We call this situation “uncheckable”. If an function is “uncheckable”, this function will be skipped and the adjacent functions of it will be checked alternatively.

3.2.3 Fault identification

The third step “Fault identification” finds the real fault by using a consequence analysis method. Consequence analysis described by Fredrik Dahlstrand [14] is a sound way to find the root cause (fault) of fault condition in a process plant by comprehensively manipulating the goal-function and cause-result relations. Because the fault of a function usually results in an aberration of the signal of the same function, the real fault can be found by searching all possible faults of the functions in fault condition.

Firstly, the consequence analysis in this paper will analyze the cause-result relations between possible faults and fault condition not only based on the rules of flow model but also based on the actual behavior of the target system. We suppose the occurrence of a possible fault, and then infer the possible state of functions in the MFM structure according to rules of flow model and behavior of target system. For example, if we suppose a fault “Leak of tank” will result in the low water level of a storage representing this tank, a MFM rule “Low level of storage may result in low flow of downstream transport” will be applied to infer that the flow of downstream valve should be in low state. In this way, all consequence relations between the possible faults and their consequential fault conditions, called as consequence analysis result, will be obtained and stored for further usage.

It should be mentioned that sometimes the cause-result relation derived from the actual behavior of the target system is different from that derived from the rules of the flow model. In this situation, we consider that the cause-result relation from actual behavior of the target system has higher priority than that from the rules of the flow model. When carrying out the consequence analysis on the target system, the cause-result relations based on the rules of flow model will be adopted firstly, and then they will be modified according to the actual behavior of the target system if necessary. In this way, the consequence analysis method in this paper not only makes use of the MFM’s advantage of automatic knowledge generation but also considers the actual situation of the target system.

Secondly, the fault condition obtained from the second step “Fault condition checkup” will be applied to match the consequence analysis result in order to find the consequence route resulting in the same fault condition. Then the root cause of the consequence route, which denotes the possible fault, will be considered as the diagnosis result.

Finally, the consequence route denoting how the identified fault results in the alarm/signal situation will be demonstrated to operator in a graphical way. In addition, the consequence route can be explained to operator from the point of view of block diagram together with the signal/alarm. In this way, why and how the diagnostic method identify the fault according to alarm/signal, MFM rules and behavior of target system will be explained to operator in order that operator can comprehend real fault situation easily.

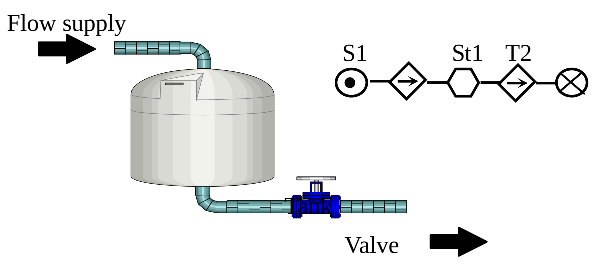


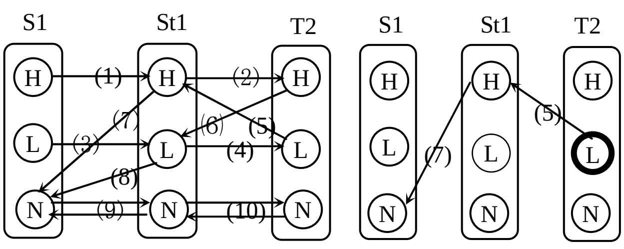
Fig.5 Simple example for fault diagnosis by MFM

3.3 A simple example of fault diagnosis

Fig.5 shows a simple system consisting of a flow supply, a tank and a valve and its corresponding MFM model, which will be utilized to explain the three-step method mentioned above. The source function S1 represents the flow supply, the storage function St1 represents the tank and the second transport function T2 represents the valve. Totally, it is supposed that there are three signals: flow of flow supply, water level of tank and flow of valve that indicates the flow after the valve; and four possible faults: “Loss of flow supply”, “Leak of tank”, “Valve is closed or blocked” and “Flow supply is overflow”. The consequence relations adopted in this MFM model are shown as follows:

(1)High flow supply may result in high water level of tank.
(2)High water level of tank may result in high valve flow.
(3)Low flow supply may result in low water level of tank.
(4)Low water level of tank may result in low valve flow.
(5)Low valve flow may result in high water level of tank.
(6)High valve flow may result in low water level of tank.
(7)High water level of tank may cause normal flow supply.
(8)Low water level of tank may result in normal flow supply.
(9)Normal flow supply may cause normal water level of tank
Normal water level of tank may cause normal flow supply.
(10)Normal valve flow may cause normal water level of tank.
Normal water level of tank may cause normal valve flow.

These consequence relations are derived according to rules of MFM and actual behavior of the example system under a single fault situation. For example, if a fault existing in S1 results in low flow of it, it can be inferred that St1 should be low level state. The consequence analysis result according to them is illustrated as Fig.6(a). After alarm validation and fault condition checkup, fault condition that indicates the states of the functions is manipulated to find the matching self-consistent consequence route in the consequence analysis result. Then the fault indicated by the root cause of this consequence route will be considered as the diagnostic result.



(a) (b)

Fig.6 Consequence analysis result of example system

Here, a simple fault case will be discussed. We can suppose that an alarm “High water level of tank” appears during the operation of the system. After alarm validation and fault condition checkup, it can also be supposed that fault condition is St1 “High water level of tank” and T2 “Low valve flow”. During fault identification, fault condition indicating S1 “Normal source flow”, St1 “High water level of tank” and T2 “Low valve flow” is applied to match the consequence analysis result shown as Fig.6(a). Finally, it can be easily found that only one self-consistent route shown as the real line in Fig.6(b) is fit for this fault condition. The fault “Valve is closed or blocked” indicated by the rout cause of this consequence route can be identified in a graphical manner. In this way, from this consequence analysis graph, operator can know that the fault “Valve is closed or blocked” will cause “Low valve flow”. Then, “Low valve flow” results in “High water level of tank”.

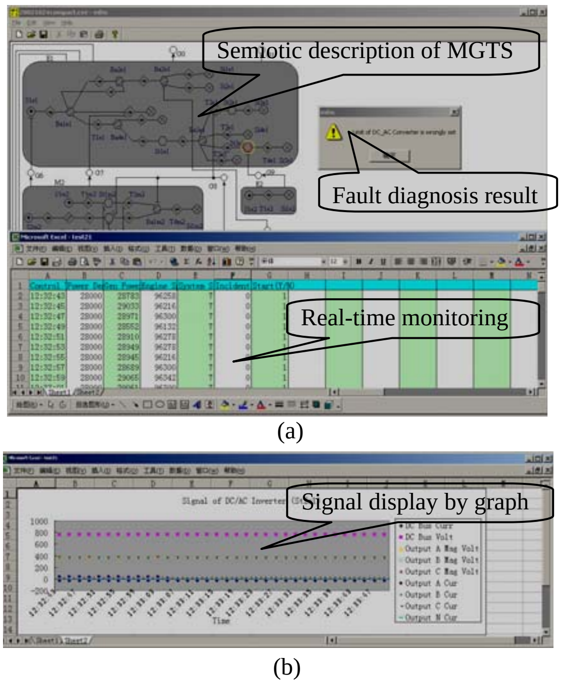


Fig.7 Interface of trial software and graph display of signal

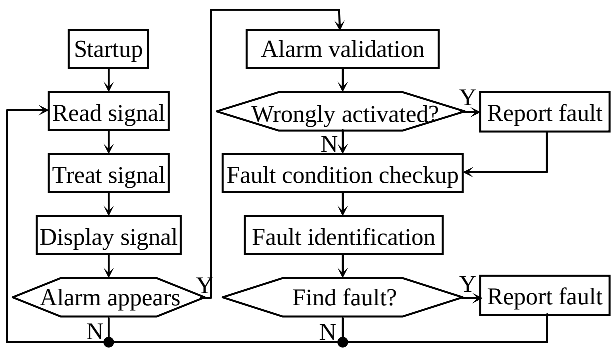


Fig.8 Flow chart of trial software for monitoring and diagnosis

4. Test by Fault Cases

4.1 Brief introduction of software

A trial software for monitoring and diagnosing MGTS was developed by using Visual C++ and Excel based on MFM. Fig.7 (a) shows the main interface of the software and Fig.7 (b) shows the graph display of signal.

Table 2 Signals used in monitoring and diagnosis software

No.	Signal Name	No.	Signal Name
1	Control Time	34	Output Current Phase B (A)
2	Engine Speed (rpm)	35	Output Current Phase C (A)
3	DPC Gen Power (W)	36	Output Current Neutral (A)
4	Turbine Exit Temp #1 (℃)	37	Output Voltage Phase A (V)
5	Turbine Exit Temp #2 (℃)	38	Output Voltage Phase B (V)
6	Turbine Exit Temp (℃)	39	Output Voltage Phase C (V)
7	Compressor In Temp (℃)	40	Gen Command Value (V)
8	Air to Fuel Ratio	41	Gen DC Bus Voltage (V)
9	Want Air (pph)	42	Brake Temp (℃)
10	Ambient Pressure (psia)	43	Gen Temp (℃)
11	Want Energy (btu/sec)	44	Gen Current Limit (A)
12	Incident Record	45	Gen Current Feedback (A)
13	System Severity Level	46	Brake Voltage Command (V)
14	System State	47	Gen Speed Command (rpm)
15	Power Enable	48	Gen Direct Current (A)
16	DPC Board Temp (℃)	49	Gen Direct Voltage (V)
17	Power Demand (W)	50	DPC Inv Temp (℃)
18	Power Supply Voltage (V)	51	Output Power (W)
19	Start Command (0/1)	52	Output Power Phase A (W)
20	RFC Command	53	Output Power Phase B (W)
21	Fuel Inlet P LP (psig)	54	Output Power Phase C (W)
22	Fuel Outlet P LP (psig)	55	Bat Charge Curr Dmd (A)
23	RFC Temp (℃)	56	Bat Charge Volt Dmd (V)
24	RFC Speed (rpm)	57	Charge Type
25	RFC Current Feedback (A)	58	BC DC Bus (V)
26	RFC Injector State	59	Bat Avg Curr (A)
27	Inv DC Bus Volts (Vdc)	60	Bat Leg A (A)
28	Inv Direct Curr (A)	61	Bat Leg B (A)
29	Output Frequency (Hz)	62	Bat Leg C (A)
30	Output Phase A Mag (V)	63	BC Board Temp (℃)
31	Output Phase B Mag (V)	64	BC Heatsink Temp (℃)
32	Output Phase C Mag (V)	65	Bat PM Temp (℃)
33	Output Current Phase A (A)	66	Bat Temp (℃)

This software simulates the real-time monitoring of MGTS by periodically reading the offline signal file and displaying those signals in text and graph. The offline signal file totally consists of 119 signals, 112 signals are captured by Capstone Remote Monitoring System (CRMS) [16] and 7 signals are obtained from the sensors added by Mitsubishi Electric Corporation. 66 signals out of the 119 signals listed in Table 2 are used in this software. CRMS is a software system that can control and monitor MGT directly or remotely. When MGT runs in an abnormal situation, CRMS reports a corresponding alarm and controls MGT if necessary. However, CRMS is short of an efficient diagnosis function so the operator has to manually find the real fault. In addition, sometimes CRMS wrongly reports the alarm, which will confuse the operator for proper operation. Therefore the developed software which has the ability of alarm validation and fault diagnosis will play an important role for the operation of MGTS.

The flow chart of this trial software is shown as Fig.8. Firstly, the trial software reads, treats and displays the signal of MGTS. The software senses the situation by conditioning one signal "Incident Record" which is a serial number indicating a corresponding alarm. For example, value "10008" of the signal "Incident Record" indicates the alarm "DC/AC inverter phase A overvoltage" [17]. Then, the trial software validates the alarm and diagnoses the fault according to the fault diagnosis method mentioned in section 3.

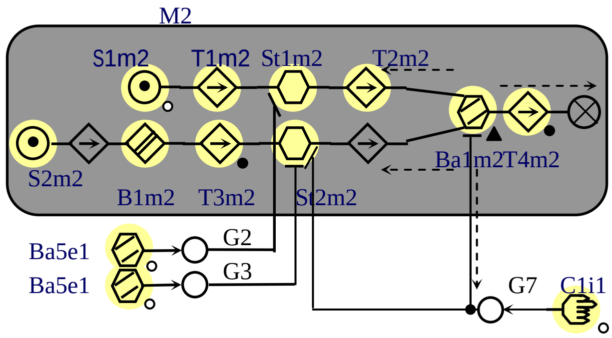


Fig. 9 Alarm validation and fault condition checkup for case 1 "Engine fails to light"

4.2 Test by two actual typical fault cases

Here, two actual typical fault cases are introduced for the simulated monitoring and diagnosis by the trial software.

4.2.1 Case 1 "Engine fails to light"

The first case "Engine fails to light" is a typical fault existing in a mass flow. When MGT detects that the engine has not been able to begin combustion, it declares the alarm "Engine fails to light".

The alarm validation and the fault condition checkup of this case are shown in Fig. 9. In this kind of figure, a function that directly relates with the alarm is marked with a small triangle. A white triangle indicates that the alarm is wrongly activated, whereas a black triangle indicates that the alarm is rightly activated. A function marked with a white circle indicates that the function is in normal condition whereas a black circle indicates that the function is in fault condition.

Input signals, checkup rules and checkup results in this case are depicted in Table 3. During alarm validation, the

Table 3 Input signals, checkup rules and checkup results for case 1 "Engine fails to light"

Function	Signal	Checkup rule	Value	Result
T3m2	P_F Fuel Inlet P LP (KPa)	$34.5KPa \le P \le 103KPa$	$P = 0KPa$	Low Pressure
S1m2	P_A Ambient Pressure T Compressor In Temp (℃)	$P_A \ge 50000Pa$ $-20°C \le T \le 50°C$	$P_A = 100700Pa$ $T = 14°C$	Normal Pressure Normal Temperature
T4m2	T_{TET} Turbine Exit Temp (℃)	$T_{TET} \ge 193°C$	$T_{TET} = 63°C$	Low Temperature

temperature of exhaust is very low that means the combustion is not established in the combustor so the alarm “Engine fails to light” is rightly activated. Three functions are found in fault condition: T3m2 is low pressure, Ba1m2 fails to light and T4m2 is low temperature.

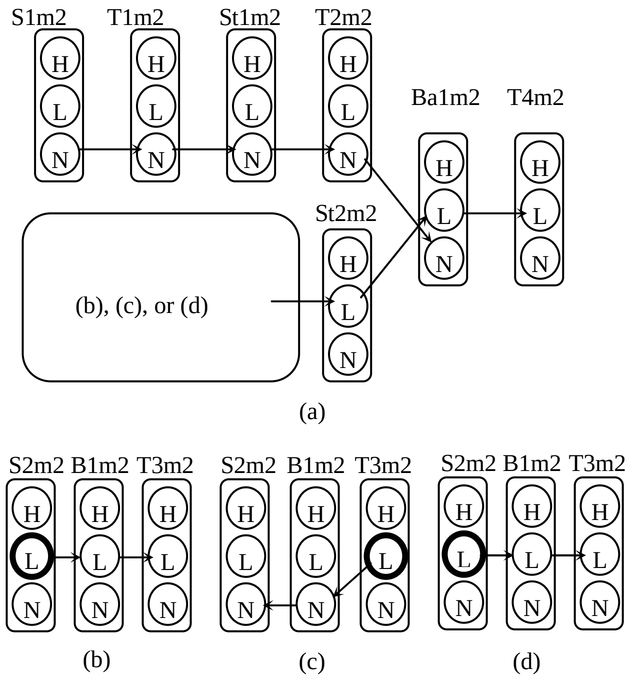


Fig.10 Fault identification for case 1 “Engine fails to light”

Fault identification by the consequence analysis is shown in Fig.10. Here, the overall consequence analysis result is neglected in order that we can concentrate on the consequence route for the possible fault. Fig.10 (a) shows the consequence route that matches the fault condition obtained from fault condition checkup. The consequence route in the rectangle consists of three independent consequence routes shown as Fig.10(b), Fig.10(c) and Fig.10(d) respectively. The root causes of these three consequence routes, “Fuel is not provided”, “Filter is blocked” and “Shutoff valve is closed or blocked”, are possible faults of this case. Table 4 summarizes

Table 4 Result of three-step fault diagnosis method for case 1 “Engine fails to light”

Step	Function	Alarm, fault condition or fault
1	Ba1m2	“Engine fails to light” rightly activated
2	Ba1m2	Alarm “Engine fails to light”
	T3m2	Low fuel pressure
	T4m2	Low exhaust temperature
3	T3m2	Shutoff valve is closed or blocked
	B1m2	Filter is blocked
	S2m2	Fuel is not provided

the result of these three steps.

4.2.2 Case 2 “Battery DC bus overvoltage”

The second case “Battery DC bus overvoltage” is a multi-fault case that includes an alarm wrongly activated fault and an electrical circuit fault. To protect the system, MGT declares an overvoltage alarm when input voltage of battery DC bus exceeds the DC bus overvoltage limit in any sample.

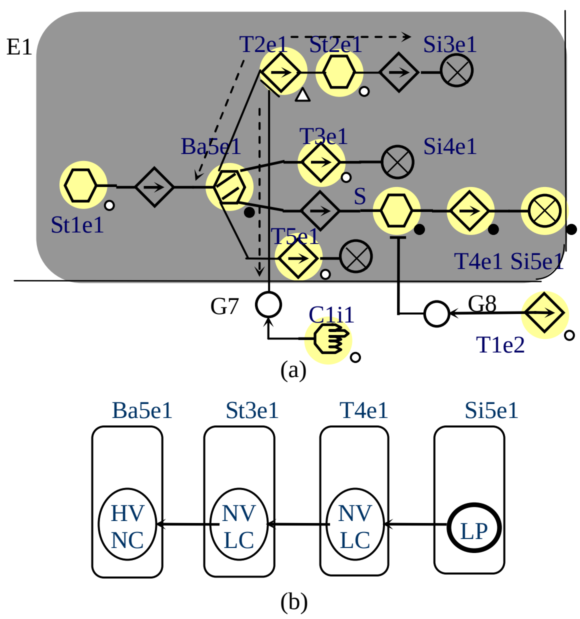


Fig.11 Alarm validation, fault condition checkup and fault identification for case 2 “Battery DC bus overvoltage”

Table 5 Input signals, checkup rules and checkup results for case 2 “Battery DC bus overvoltage”

Function	Signal	Checkup rule	Value	Result
St3e1	U_A, U_B, U_C Output Phase A,B,C Mag (V) I_A, I_B, I_C Output Curr Phase A (A)	$U_A, U_B, U_C \le 480 \times 1.02\sqrt{2}/\sqrt{3}V$ $U_A I_A + U_B I_B + U_C I_C = \sqrt{2} P_{Demand} (\pm 10\%)$	$U_A, U_B, U_C = 365,360,354V$ $I_A, I_B, I_C = 3,3,3A$ $P_{Demand} = 25000W$	Normal Voltage Low Current
Ba5e1	U_d Inv DC Bus Volts (V) I_d Inv Direct Curr (A)	$U_A I_A + U_B I_B + U_C I_C \approx I_d U_d (0 \sim 10\%)$ $750V \le U_d \le 760V$	$U_d = 761V, I_d = 3.5A$	High Voltage Normal Current
T4e1	U_a, U_b, U_c Output Current Phase A (V) I_a, I_b, I_c Output Voltage Phase A (A)	$U_G \le U_a, U_b, U_c \le 480 \times 1.02/\sqrt{3}V$ $\sqrt{2}(U_a, U_b, U_c) \approx U_A, U_B, U_C$ $U_a I_a + U_b I_b + U_c I_c = P_{Demand} (\pm 5\%)$	$U_a, U_b, U_c = 255,253,250V$ $I_a, I_b, I_c = 3,3,3A$	Normal Voltage Low Current
Si5e1	P_{Out} Output Power (W)	$P_{Out} = P_{Demand} (\pm 5\%)$	$P_{Out} = 2477W$ $P_{Demand} = 25000W$	Low Power

The alarm validation and the fault condition checkup for the second case are shown in Fig.11 (a). Some important input signals, checkup rules and checkup results are shown in Table 5. In the alarm validation of the second case, the voltage of Battery DC bus is found in normal range so the alarm should be wrongly activated. The alarm "Battery DC bus overvoltage" is a spurious alarm since its reason is unknown (maybe transient disturbance or shortcoming of alarm trigger mechanism). Four functions are found in fault condition: Ba5e1 is normal electric current but high voltage, St3e1 is normal voltage but low electric current, T4e1 is normal voltage but low electric current and Si5e1 is low output power.

In this case, fault identification cooperated with simple knowledge for electrical circuit is shown as Fig.11 (b). The fault condition of the consequence route shown in Fig.11 (b) matches the fault condition obtained from fault condition checkup. Therefore, the root cause of this consequence route, "MGTS is in offload state", is a real fault of this case. In summary, two faults are found in the second case, "Alarm 'Battery DC bus overvoltage' is wrongly activated" and "MGTS is in offload state". The result of the three-step fault diagnosis method in the second case is summarized in Table 6.

Table 6 Result of three-step fault diagnosis method for case 2 "Battery DC bus overvoltage"

Step	Function	Alarm, fault condition or fault
1	T2e1	"Battery DC bus overvoltage" wrongly activated
2	Ba5e1	High voltage; Normal electric current
	St3e1	Normal voltage; Low electric current
	T4e1	Normal voltage; Low electric current
	Si5e1	Low output power
3	Si5e1	MGTS is in offload state

4.3 Discussions

The mentioned fault identification technique can be easily applied to the small-scale system like Micro Gas Turbine System. During the test of these actual fault cases, the trial software can quickly and rightly find the real cause of the fault message reported by the vendor-supported automatic diagnosis function as soon as the alarm appears. Fault can be identified by comparing the fault condition of possible fault obtained from consequence analysis with the fault condition gotten from the inter-comparison between actual signal value and preset limit. In addition, by comparing the corresponding signal of the alarm with the preset limit, it is also possible to validate spurious alarm and false alarm.

This fault identification technique cannot be applied to changeable physical structure due to automation or manual work. For example, when MGTS runs in shutdown state because of fault, grid power will be transmitted through a transformer to MGTS in order to maintain the rotation of turbine for emitting the remainder heat. New features need be introduced to MFM in order to cope with the changeable physical structure. For the large-scale process system like Nuclear Power Plant, the proposed fault identification technique has to take account into the transient condition in order to capture the right consequence pattern.

5. Conclusions and future work

Based on MFM a semiotic description for MGTS is accomplished. A new three-step method including alarm validation, fault condition checkup and fault identification is proposed for comprehensive diagnosis of MGTS. A trial software is developed to simulate real-time monitoring and diagnosis of MGTS based on the semiotic description and proposed fault diagnosis method. The simulated fault diagnosis using the proposed method is conducted for actual typical fault cases during the operation of MGTS, and the result shows that the proposed method is an efficient and promising method for diagnosing the fault of MGTS.

In the future, a prototype software which accesses the signal of MGTS in real-time mode and carries out the three-step diagnosis in an interactive manner will be programmed for the final purpose of developing an actual usable monitoring and diagnosis system. In this software, the process and result of alarm validation, fault condition checkup and fault identification like Fig. 9, Fig.10 and Fig.11 will be shown to operators. Then, the process and result will be explained from the point of view of block diagram together with related signal/alarm in order to help the operators understand the abnormal situation.

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