Study on modeling of an integrated control and condition monitoring system for nuclear power plants

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Abstract: The relationship between the control system of the nuclear power plant (NPP) and the condition monitoring system which provides support for the operator is very close, but in most nuclear power plant design, these two systems are designed separately, which affects the system compatibility, the utilization efficiency of the system resources, the extendibility of the systems and the real–time nature of the support, and may have some negative impacts on the plant operation. Focusing on this problem, an integrated design concept for the NPP control system and condition monitoring system is proposed in this paper. The overview scheme of the integrated system is given based on the analysis of the functions required. Furthermore, the study for modeling of the integrated control and condition monitoring system using the IDEF(Integration Definition Language) and UCM (Use Case Maps) methods is introduced in this paper.

Keyword: modeling; control and condition monitoring; integrated system; nuclear power plant

1 Introduction

The Three Mile Island accident that occurred in the 1970s revealed that in order to improve nuclear power plant(NPP) safety and automation levels, it is necessary to develop appropriate operation support systems (OSS), helping the operator to adjust plant operation better according to the current plant conditions. Therefore, some operational support and condition monitoring systems have been developed since the 1980s - for example, the reactor accident diagnosis and treatment system (REACOTR) developed by the United States [1], the DISKET system developed by the Japan Atomic Energy Research Institute[2] and the expert system of performance evaluation and diagnosis (ESPED) developed by Korea Electric Power Engineering Company[3]. The development of the OSS system can be seen to provide a greater guarantee for NPP safety. However, previous reports have outlined the fact that the plant control system and the condition monitoring system to provide support for the operator are designed separately in most nuclear power plants at present, which affects the system compatibility, system resources utilization efficiency, the system's extendibility and support for real-time operation, *etc*., and may have a negative impact on the operation of NPPs [4]. Because of the above situation, the general scheme of a system which integrates the NPP control system and the condition monitoring system and considers the structure and function design together is introduced in this paper. A modeling study is also carried out using the IDEF0 (Integration Definition Language 0) and UCM (Use Case Maps) methods for the integrated system.

2 Overall scheme of the integrated control and condition monitoring system

2.1 Function analysis of the integrated system

2.1.1 Control Subsystem function analysis

The control system mentioned in this article is a generalized conceptual model of the power plant control system. It includes the parameter measurement subsystem, manual/automatic control subsystem, protection subsystem and alarm subsystem, among others.

a. Parameter measurement function

The parameter measurement functions include the nuclear parameter measurement and the process parameter measurement. The nuclear parameter measurement includes in-core and ex-core neutron flux and distribution measurements. The process parameter measurements include the variable and the condition measurements of the plant systems and the equipment in normal operation, anticipated operational incidents and accident conditions. The

Received date: July 28, 2012
(Revised date: September 13, 2012)

measured process parameters are temperature, pressure, flow rate, level, *etc*.

b. Manual / automatic control function

The functions include the functions of reactivity control, thermal process parameter control, and so on. Among them, the thermal process parameter control functions include the control of pressure, level, flow, speed, *etc*.

c. Protection and alarm function

The protection function monitors the variables selected by the safety analysis and triggers corresponding protection action when these variables breach the protection setpoint. The alarm function monitors the operating parameters, process parameters and control parameters of the nuclear power plant equipment and system. When these parameters exceed the prescribed values, the corresponding alarm reminder is provided to the operator by way of sound, light, and so on.

2.1.2 Condition Monitoring subsystem function analysis

The function of the NPP condition monitoring subsystem can be divided into three main parts according to the basic operating conditions of the plant: condition monitoring in reactor startup phase, condition monitoring in reactor power operation phase and condition monitoring in reactor shutdown phase.

a. Condition monitoring in the phase of startup

Condition monitoring functions in the phase of the startup include condition monitoring before startup (such as the initial condition monitoring for control switches, control and protection system and the supply voltage monitoring on key equipment, *etc*.), the condition monitoring of temperature, pressure, and the heating rate during the startup, and the critical condition monitoring for the reactor.

b. Condition monitoring in the phase of power operation

In the power operation phase, the condition monitoring functions include operation safety monitoring and auxiliary monitoring. At present, the NPP operation safety monitoring can be divided into monitoring based on parameters and monitoring based on the conditions according to the monitoring methods. The safety-critical parameter display system is a typical system based on the parameter monitoring method. A typical system based on the condition monitoring approach is the safety-critical function monitoring system. The condition monitoring approach will be most used in this study to synthesize the condition information related to the running condition of the equipment, control and protection systems, and the other safety-critical parameters which affect the safety function. In this way, the operational safety state of the nuclear power plant can be characterized.

In addition, auxiliary monitoring functions in the phase of the power operation include trend forecasting for parameters and operator plant manipulation guidance.

c. Condition monitoring in the phase of shutdown

The condition monitoring functions in the phase of the shutdown include the temperature and pressure monitoring, cooling rate monitoring, core sub-criticality monitoring and core cooling status monitoring.

2.1.3 The overall function analysis of the control and condition monitoring integrated system

According to the requirements analysis for the nuclear power plant control system and condition monitoring system, combined with the idea of the proposed integrated design of the control system and condition monitoring system, the main functions of the integrated system are as follows:

a. Data acquisition and management

Data acquisition and management are the basis for control and protection, condition monitoring and evaluation and operational decisions. The data acquisition and management function realizes real-time acquisition of site parameter information of an NPP and sends the information to the relevant equipment to be stored and processed. The information can then be used by the various subsystems of the integrated system.

b. Control and protection

The control and protection function implements the corresponding control and protection action according to the site parameter information, plant operation state and operator command in order to assure the safety and reliability of the NPP.

c. Safety-critical function monitoring

Safety-critical function monitoring indicates the current safety state of the nuclear power plant and informs the operator quickly if changes occur that may affect the safe operation of the plant in a timely manner, thus helping the operator to make the decision quickly and accurately. According to the safety principle of "defense in depth" for NPPs, six important safety functions should be maintained simultaneously: reactivity control, core cooling, coolant capacity of the primary side, water capacity of the secondary side, the pressure boundary integrity and the integrity of the containment. In order to monitor the status of the above six safety functions, it is very important to select the correlated parameters properly in the design of the integrated system. The number of the selected parameters should not be too large, but the selected parameters must show the important aspects of the safety state of the NPP.

d. Running status assessment and fault diagnosis

Running status assessment and fault diagnosis execute the functions of the analysis and the feature extraction for the acquisition of process parameters and status parameters, and then determine the system's running condition and carry out fault diagnosis. The integrated system can monitor running status continuously in accordance with set procedures and rules, thus avoiding misjudgment due to the understanding of limitations and omissions of the operator. The system can check the status of the key equipment and engineering safety features (ESF), read the real-time data in the parameter database, evaluate the running status of the NPP and display the analysis results on the human-machine interface. The integrated system can also analyze the parameter changes in the plant systems and equipment operation and generate alarm information when the running state deviates from the normal trajectory，thus reminding the operating personnel to pay attention to the related equipment and system status closely, while executing relevant manipulations if necessary.

e. Operation guidance

The nuclear power plant is a complex system, so maintenance and system testing before startup, after shutdown and in routine operation are intensive but important work. By instructing operating personnel to accomplish these tasks with the integrated system, the burden of operating personnel can be reduced, and status monitoring for the systems and equipment can be realized automatically. These advantages can help to improve the operational safety. In the design of the emergency guidance functions of the integrated system design, the combination of event-driven emergency operating procedures and status-oriented emergency operating procedures should be considered in order to make full use of their respective advantages.

According to the above function analysis, the function composition map of the integrated system is shown in Fig .1.

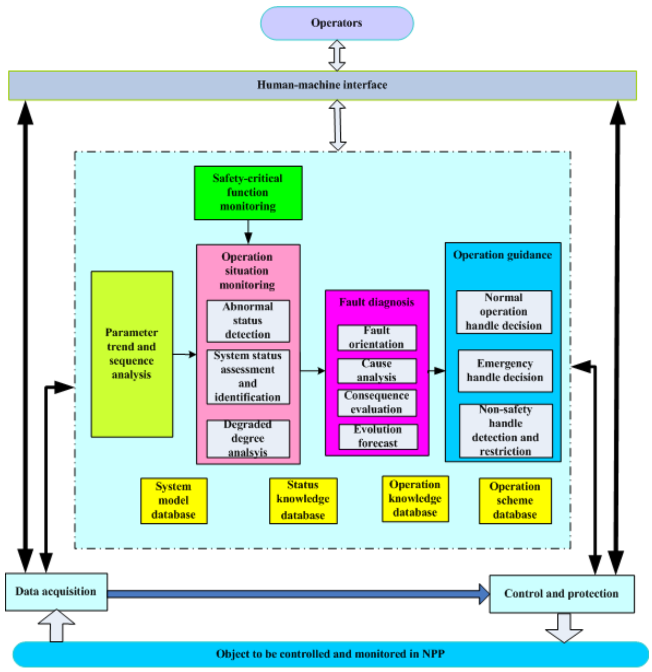

Fig.1 The function composition map of the control and condition monitoring integrated system.

2.2 System hardware and software requirements

The control and condition monitoring integrated system for NPP will implement comprehensive control and condition monitoring of the plant, and give the operator manipulation and operational decision-making support. Its software and hardware systems must meet the following three basic requirements:

1) Reliability requirements

a. The computer used for condition monitoring and its power supply should be covered by redundancies.

b. The integrated system must be in good working condition in normal and abnormal operating conditions.

c. The malfunction of non-safety equipment providing information to the integrated system, should not affect the ability of processing the required safety information of the integrated system.

2) Real-time requirements

The integrated system should have the ability to acquire real-time data from site objects, process data and analyze data, with the ability to respond to abnormal events in a limited time. The data required by the integrated system require online collection. The manner of inputting data manually into the integrated system should be simple and quick. The functions of operational guidance, alarms, and historical data recording should be completed rapidly. The reasoning mechanism of the system must be as simple and efficient as possible and the size of the knowledge database should not be too great.

3) System flexibility and maintenance convenience requirements

Users can query, set the parameters and modify the control rules easily. The system can receive interactive instructions from the operator. When the system fails or in unusual circumstances, the system itself can take the appropriate measures or ask for the introduction of the necessary human intervention.

2.3 Characteristic features of the integrated system and its configuration

The design and development of the integrated control and condition monitoring system will be different from the situation in which the control and condition monitoring systems were designed and developed independently. In the integrated system, the control subsystem completes the functions of measurement and control for the nuclear power plant and provides the necessary information to the condition monitoring system. The condition monitoring subsystem then analyzes and processes information, comparing the information with its own database, and then outputs the corresponding information to indicate the current operating state of the NPP or assist the operator in operational control and emergency response.

Therefore, at the beginning of the integrated system design, the organic combination of control system and condition monitoring system should be considered and operation support functions should be provided. System architecture, human-machine interface, control and condition monitoring policy, subsystem settings and the system functions realization methods must be integrated and unified. In accordance with the above-mentioned design principles, the overall configuration of the integrated system is shown in Fig.2.

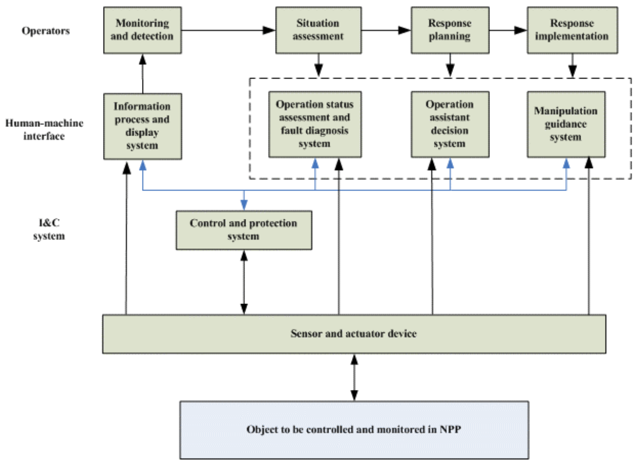

Fig.2 The overall framework scheme of control and monitoring integrated system.

As can be seen from Fig.2 and compared with the traditional independent design of the control system and condition monitoring system, the characteristic features of the integrated system will be mainly reflected in the following four aspects:

1) Goal integration: The control systems and condition monitoring systems are designed and developed to ensure the safety, reliability and economic operation of NPPs. In order to achieve this goal and make use of their respective advantages fully, the integrated system should be designed and developed collaboratively.

2) Functional integration: Functional integration includes two aspects. The first aspect is to realize functional integration of certain condition monitoring and operation assistant systems. These systems are functionally different, but overlap and duplication exists. When the integrated system is designed, its functional modules should be selected carefully according to the importance and safety relevance of the modules, and then integrated in a reasonable form. The second aspect is to integrate the functions of the control system and condition monitoring system by taking advantage of advanced technologies such as soft control technology.

3) Physical structure integration: In the integrated system, the structure of the different condition monitoring subsystems and the human-machine interface is uniform, but so is the structure of the

control system and condition monitoring system.Uniformity in the structure avoids duplication and inconsistencies of the system modules, thus ensuring compatibility among man, machines and subsystems.

4) Information integration: The integrated system will undertake more comprehensive information processing and analysis methods to improve information display, transmission and switching modes. In this way, the human-machine interface will be friendlier, the information transmission will be more reliable and the information exchange will be real-time. The information available to the operators will be clear, explicit and direct.

According to the analysis for the characteristics of the integrated system, compared with the separate design of control system and condition monitoring system, the main advantages of the integrated system can be summarized as follows:

1) System resources utilization efficiency is enhanced. The functional integration is considered in the integrated system, thus more equipment can be shared between the control sub-system and condition monitoring sub-system. For example, more sensors or transmitters can be shared on site and the quantities of cables can be reduced.

2) The compatibility between the various sub-systems is improved. Because the physical structure integration is considered at the beginning of the integrated system design, the same or similar platform for the hardware and software will be used in the various sub-systems on the condition that the system requirements are satisfied. So the system compatibility will be enhanced greatly.

3) The system's extendibility is increased. Because both the information integration and physical structure integration are considered in the integrated system, it makes system modification work (for example, adding some new functions to the system) easier and the replacement of hardware and software can be reduced.

3 Control and condition monitoring integrated system modeling

3.1 Modeling methods

3.1.1 Structured modeling methods IDEF0

The structured modeling method is a method oriented system architecture based on data flow and function. It describes the real world as the flow of data in information systems, as well as the conversion of data to information in the data flow process. On the whole, it is a top-down modeling method which depends strongly on the data flow diagram. IDEF modeling method is a typical structured modeling method. IDEF0 (Integration Definition Language 0) is a method of IDEF family and its basic idea is expressing the correlations and limitations among the various system functions clearly and strictly through graphical expression. The user can understand the function and operation of the system by this method. The IDEF0 method has been widely used and discussed in the literature. Bushy and Williams[6], and Bravoco and Yadav[7] provide a comprehensive discussion on the use of IDEF0 in developing manufacturing-oriented models. Sarkis and Lin[8] discuss the application of overall enterprise modeling for CIM (Computer Integrated Manufacturing) strategies. Especially in the nuclear technical fields, Hossam A. Gabbar [9] discusses the modeling of an integrated framework for safety control analysis and design for NPP by using the IDEF0 method. D. van Houtte *et.al* [10] carry out the functional analysis of RAMI (Reliability, Availability, Maintainability, Inspectability) for the ITER(International Thermonuclear Experimental Reactor) using the IDEF0 method. The above mentioned studies indicate that as an analytical tool, IDEF0 can assist the user in identifying the functions performed and then what is needed to perform them. So IDEF0 models are often created as one of the first tasks in system development. As for the integrated system in this study, a relatively complicated interface relationship between the various functions is apparent because the functions requiring implementation are too numerous and the integrated system is made up of subsystems which perform the different functions. Therefore, at the beginning of the design of the integrated system, the interface relationships between the functional modules and between the subsystems should be clarified from the top down and from the whole of the system towards the individual parts by using the appropriate the modeling method. Then the system functions can be allocated to the various moulds and the foundation for the subsequent software programming and hardware realization can be established. So the IDEF0 method is thought of as one suitable method to achieve this intention.

IDEF0 model is made up of graphics, text, vocabulary tables and mutual cross-reference tables, of which the graphics is the main component. The activities, information and interface conditions are taken into account simultaneously in IDEF0 graphics. The boxes represent activities and arrows represent data and interfaces in IDEF0 graphics. IDEF0 graphics are therefore always made up of an activity model, an information model and a user interface model, when they are used to express a current operation, functional description or design[11]. The graphical structure diagram is shown in Fig.3.

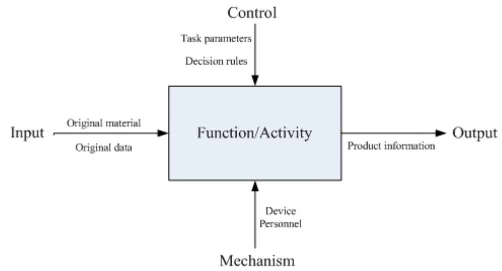

Fig.3 The graphical structure diagram of IDEF0 model.

In Fig.3,

Input: resource changed or consumed by the activities, Answer the question about "what” and “when”.

Control: restrictions in activities operating.

Output: the output result of the activity, answer the question about "what" and "why".

Mechanism: the person, things, objects and so on, which execute or actuate the activities. This answers the questions about "who" and "how".

The main modeling steps using IDEF0 method are as follows：

1) Select the scope, the views or purpose;

2) Establish the internal and external relationship diagram (A-O diagram);

3) Draw the top-level diagram (A0 diagram);

4) Establish a series of graphics;

5) Create a text description.

3.1.2 Based on scene modeling method UCM

UCM (use case maps) is a typical modeling method based on scenarios. UCM describes the behavior and composition of the system, as well as the relationships between the parts in one chart that gives a view of the entire system. When UCM is used for system modeling, the level of abstraction is relatively high, on the other hand, the implementation details within the system are not fully hidden. Therefore, this gray box approach allows UCM to have considerable flexibility in the expression of the system architecture.

The basic elements of the UCM modeling methods are the path, the components and responsibility.

1) Path: the ordered sequence of causal responsibility. It is a visual representation of the scenario.

2) Components: refers to software or hardware components. It can also be human participants or other systems.

3) Responsibility: the abstraction of actions, activities, operations and tasks performed by the component.

The basic idea of the UCM modeling method is based on the causal relationship of the responsibility executed by components to describe the scenario path [12]. The basic symbols in the UCM model are shown in Fig.4.

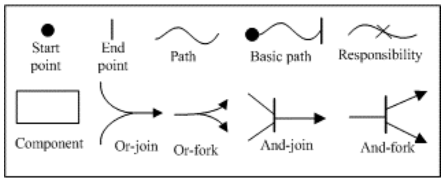

Fig.4 The elementary symbols of the UCM model.

3.1.3 IDEF0/UCM integrated modeling methods

The model established by the IDEF0 method is a static functional description model, which is suitable to describe the system function composition and flow of information within the system. However, it lacks the expression capability for describing a dynamic model (such as the description of information processes in the system) and designing the system from the top-level, and can not describe the implementation process of a specific function.

UCM method describes the system behavior, structure and relationships between them in one diagram simultaneously in the view of the entire system. It can describe the dynamic behavior of the system clearly and make the designer understand the system overall. However, it is not suitable to describe the flow of information within the system. It is better to model and analyze the system by integrating the two methods, using the UCM method to describe the dynamic behavior of the system, and describing the system functions and information flow by the IDEF0 method.

The integrated control and condition monitoring system for NPPs is a more complex system. The system functions are various and there are a multitude of exchanges of information between the various subsystems. So in the design and development， the relevant model should be established firstly to describe the system architecture with the system information exchange relationship between the input and output of each functional module within the system, thus providing guidance for the subsequent detailed design and development work for the integrated system. According to the needs of the integrated system modeling, this study will use IDEF0 and UCM integrated methods to establish the system model. The IDEF0 method is used to analyze the overall system, express system activity and data flow as well as the links between them, and describe the system functional requirements. UCM method is used to describe the system behavior and composition as well as the relationships between them. That is to say, the overall function models are established by the IDEF0 method firstly, and then the search path of the typical scenarios/activities can be established by the UCM method. By this means, the causal relationship between function and responsibility and the corresponding relationship between activities and the implementation objects can be clarified, thus forming the system modeling framework from whole to parts and from outline to detail.

3.2 Modeling study for the integrated system based on the IDEF0/UCM integrated methods

3.2.1 The overall system model

According to the integrated system functional diagram shown in Fig.1 and the overall configuration shown in Fig.2, the internal and external relationship diagram (A-O diagram) which indicates general function of the integrated system is established firstly by using the IDEF0 method, as shown in Fig.5.

In Fig.5, I1, I2 and I3 denote input parameter information, including I1 for the nuclear parameters and process parameters, I2 for the operator manipulation information and I3 for the various databases required.

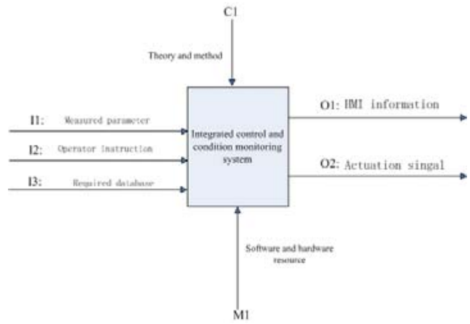

Fig.5 The internal and external relationship diagram of the integrated system.

C1 represents control, which shows a variety of theories, techniques and methods (such as state detection methods, fault diagnosis methods, *etc*.).

M1 indicates that the mechanism mainly refers to the system hardware and software environment, such as computers, sensors, instrumentation and information transmission network.

O1 and O2 denote output information, including system parameter information, status information, fault information, manipulation and control information.

On the basis of the above-mentioned A-O diagram, the dynamic causal relationship between the activities of the various functions of the integrated system is analyzed. The UCM model of the overall system is shown in Fig.6.

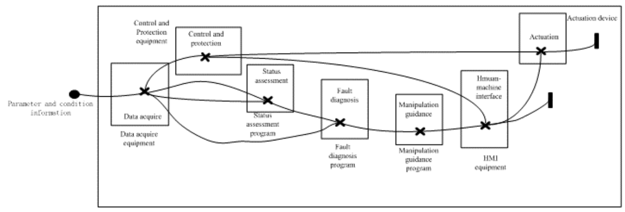

Fig.6 The overall UCM model diagram of the integrated system.

Combined with the internal and external relationship A-O diagram, the components in the UCM model diagram of the overall integrated system are mapped to corresponding functional modules expressed by the IDEF0 model, and then the top-level IDEF0 model diagram of the system - theA0 diagram - can be established, as shown in Fig.7. The A0 diagram is a real top-level model diagram, which reflects the characteristics of the models from the perspective of the overall structure. As seen in Fig.7, the system is divided into six sub-modules.

In Fig.7,

I1 and I2, I3: correspond to the three inputs of the A-O diagram.

C1 and M1: correspond to the control and mechanism in the A-O diagram.

O1 to O6: correspond to the output of the six modules, including O1 and O2 in the A-O diagram.

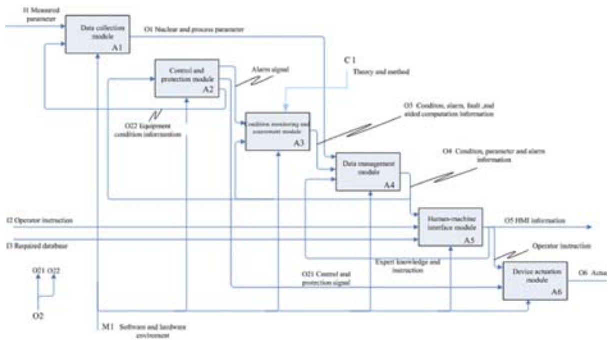

Fig.7 The top-level A0 function diagram of the integrated system.

In the A0 diagram, the data acquisition module is responsible for data collection and transmission. The control and protection module is responsible for nuclear reactor power control, pressurizer pressure control and monitoring of the variables selected by the safety analysis. When the assumed event prescribed by the safety analysis appears and the related parameters exceed the protection setpoint, the appropriate protection action will be triggered. The condition monitoring and assessment module monitors the work conditions of the equipment and the important systems, and carries out the corresponding auxiliary computing and fault diagnosis. the data management module is responsible for making the various kinds of data management systematic, standard and automatic. The human-machine interface module provides the interactive interface between the system and the operator. The device actuation module receives the control and protection information from the control and protection module as well as the operator manipulation information from the human-machine interface module, and then produces actuation signals.

3.2.2 IDEF0 and UCM model of the system module

The top-level A0 diagram shown in Fig.7 is the description of the system as a whole. In order to analyze the functional modules in the A0 diagram in more detail, the further decomposition of the various modules is needed to get the IDEF0 model sub-graph. The modules in the sub-graph which can not be broken down further by the IDEF0 method will be modeled by the UCM method. The condition monitoring and assessment module, which is shown in Fig.7, is taken as an example to describe this process in the following text.

The function of the condition monitoring and assessment module A3 in the A0 diagram is to improve the perception ability of the operators to enable them to identify the operating state of the NPP more quickly and easily. This module has the ability to calculate, analyze and filter the raw data and information. The decomposition map of the module is shown in Fig.8.

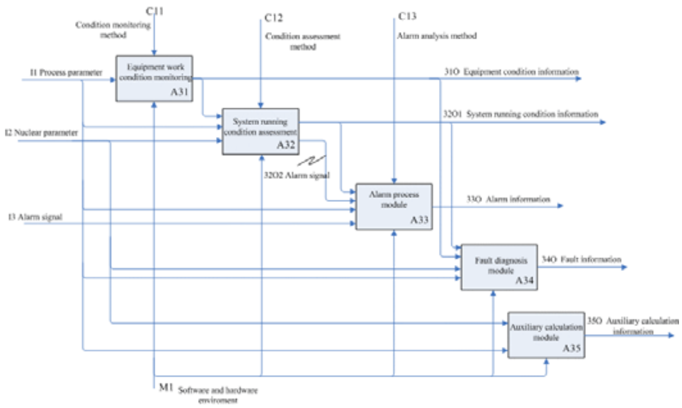

Fig.8 The diagram of the condition monitoring and assessment module.

In Fig.8, the functions of the each functional module are as follows:

The equipment work condition monitoring module is responsible for monitoring the work condition of the system equipment, such as valves, pumps, electric heaters, *etc.*;

The system running condition assessment module is responsible for evaluating whether the running state of the system is normal or not, according to the system operating parameters and equipment work conditions, and giving an alarm if abnormal conditions are detected.

Alarm process module is auxiliary to filter, compress, and sort the alarm information.

Auxiliary calculation module is responsible for the calculation of the critical rod position, Iodine well, burnup and subcooling in the core during reactor operation.

The fault diagnosis module is responsible for induction, reasoning and other automatic processing for the complex system information under accident conditions, thus helping the operator understand the system state, detect the early symptoms of the fault in a timely manner and determine the possible nature of the failure or malfunction position of the equipment as accurately as possible.

The equipment work condition monitoring module in Fig.8 can be decomposed further by using IDEF0 method, as shown in Fig.9.

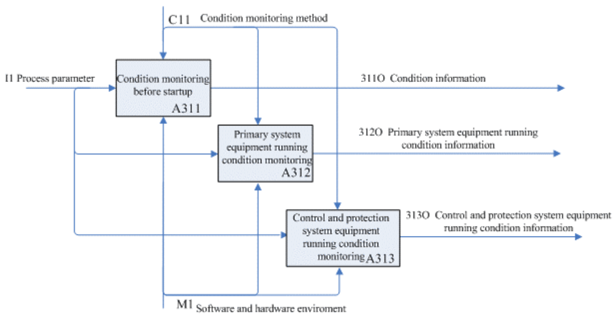

Fig.9 The diagram of the equipment work condition monitoring module.

The equipment work condition monitoring module should complete the following functions:

1) Status check before reactor startup

Check the important switch positions and status of the system valves and determine the correctness. If the current position of the switch and status of the valve are consistent with the correct position and status, it sends signals which indicate the switch position and valve status are correct, and then the operator can carry out the next work. If not, the system alerts the operator, reminding the operator to reset the corresponding switches and valves.

2) Supply voltage check for the important equipment

The important equipment includes three categories: pumps, valves, electric heaters. The equipment work condition monitoring module will check the power supply voltage of the key equipment automatically.

3) Working condition signal check of the control and protection system

Check the working condition signal of the nuclear instrumentation system, process parameter measurement system, process control system, reactor power control system, reactor protection system, *etc*.

The primary system equipment running condition monitoring module A312 and the control and protection system equipment running condition monitoring module A313, which are shown in Fig.9, as the basic functional units cannot be decomposed further. Their activities can be described by the UCM method. The UCM model diagram of the module A312 is shown in Fig.10.

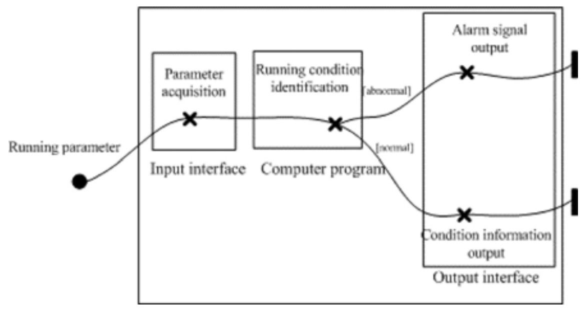

Fig.10 The UCM diagram of the primary system equipment condition monitoring model.

4 Conclusion

In this paper, the integration of control functions and condition monitoring functions of NPP are studied for the function composition, information requirements and the overall scheme of control and condition monitoring integrated system is demonstrated. Based on the structural and functional characteristics of the integrated system, a modeling method combining IDEF0 and UCM is selected to establish a system model for analyzing design performance.

The corresponding method and analysis process in this study can provide a reference for the development of an integrated system for a real NPP. Furthermore, the modeling results in this study can be used in the detailed design of the integrated control and condition monitoring system of an NPP.

On the other hand, because the study is still at a preliminary stage, the following work should be done in the next stage:

1) Based on the specific objects of an NPP, the further refinement for the model should be completed in order to describe the relationship between input and output of the system modules in detail;

2) The appropriate software and hardware should be selected to establish the prototype or demonstration system to verify the correctness and rationality of the analysis and design results;

3) Based on the above selected environment of hardware and software, specific realization methods, especially the programming method and interface, need to be studied in order to develop the integrated system smoothly.

Nomenclature

A-O diagram	internal and external relationship diagram
CIM	Computer Integrated Manufacturing
ESF	Engineering Safety Features
IDEF0	Integration Definition Language 0
ITER	International Thermonuclear Experimental Reactor
NPP	Nuclear Power Plant
OSS	Operation Support Systems
RAMI	Reliability, Availability, Maintainability, Inspectability
UCM	Use Case Maps

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