Design of an operator support system for online maintenance at nuclear power plant

CHU Yong-yue[1], LI Hu-wei[2], GAO Qiang[3], YANG Ming[4], and YI Yan[5]

1. Nuclear and Radiation Safety Center, Ministry of Environmental Protection of the People's Republic of China, 100082 China (chuyongyue17@126.com)

2. Nuclear and Radiation Safety Center, Ministry of Environmental Protection of the People's Republic of China, 100082 China (lihuwei@chinansc.cn)

3. Nuclear and Radiation Safety Center, Ministry of Environmental Protection of the People's Republic of China, 100082 China (quagmire.gao@gmail.com)

4. "111 project" Nuclear Power Safety and Simulation, Harbin Engineering University, 150001 China (yangming@ hrbeu. edu. cn)

5. Nuclear and Radiation Safety Center, Ministry of Environmental Protection of the People's Republic of China, 100082 China (nscyiyan@126.com)

Abstract: Online maintenance based on reliability centered management is pivotal for the safe and economical operation of Nuclear Power Plant (NPP). This paper presents an operator support system through which the operators can effectively manage plant configuration and identify the weaknesses in plant operation. The proposed operator support system is based on the GO-FLOW, which is a success-oriented availability analysis methodology and can be used for evaluating phased missions. In this paper, the design of the proposed operator support system is introduced through a case study of the Auxiliary Feed Water System (AFWS).

Keyword: reliability centered maintenance; reliability analysis; operator support system; nuclear power plant

1 Introduction

The prime objective of operating a nuclear power plant is to obtain maximum economic profit on the premise of ensuring nuclear safety. The Online and Reliability Centered Maintenance (ORCM)[1][2]provides a systematic consideration of system operation and maintenance. In other words, the ORCM maintains the plant within an acceptable level of efficient and cost-effective manner on one hand, while operating the system under an acceptable level of operability on the other hand. Therefore, the ORCM directs maintenance efforts towards those parts and units which are critical from the point of view of reliability, safety and production regularity.

Plant configuration management forms the basis of the ORCM. For this purpose, many reliability analysis methodologies have been proposed, in which the Fault Tree Analysis (FTA)[3] is the most prominent technology and has been widely applied in many domains. However, FTA is also criticized owing to its limitation of processing phased missions.

This paper presents an operator support system [4] to help safety engineers evaluate maintenance plan and identify the weaknesses in plant operation. In addition, we extend the application of plant configuration from offline to online by connecting it with a fault diagnosis system. Therefore, the operators in main control room can also use the support system to monitor whether the plant system is operating under acceptable level and pre-evaluate the actions they will take. In this way, the support system can not only help operators identify the operating status, but also reduce human flaws which will be greatly meaningful to ensure the online maintenance activities.

The proposed operator support system is based on the GO-FLOW[5-8] which is a success-oriented reliability analysis methodology and can be used for evaluating phased missions. Compared with the FTA, the GO-FLOW models are more compact and easier to build and update. In addition, the reliability calculation by the GO-FLOW is fast, which makes it possible to apply the proposed operator support system in an online and real-time mode.

The rest of this paper will be organized as follows: Section 2 gives a brief introduction of the GO-FLOW and illustrates how to build the GO-FLOW model, based on a case study of the Auxiliary Feed Water System (AFWS) at Pressurized Water Reactor (PWR) of NPP. The design of proposed operator support system will be introduced in detail in Section 3, and a

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discussion as well as pending future works will be given and summarized in the final session.

2 Modeling the nuclear power plant with GO-FLOW

2.1 Basic conception of GO-FLOW methodology

The GO-FLOW (Matsuoka and Kobayashi, 1988) methodology is a success-oriented systems analysis method developed from the GO methodology[9]. The GO-FLOW analysis consists of a GO-FLOW chart and reliability calculation algorithm. The GO-FLOW chart can be directly built by referring to the system physical layout using a set of operators which are shown in Fig. 1. The operators in the GO-FLOW chart are connected together by signal lines which identify output(s) and/or input(s) of each operator and represent time transition, control signals, physical variable conditions, *etc*. The operators can model various transitions and logic gates, including OR, AND, and NOT, which are used to describe the logical combinations of component states. The GO-FLOW chart can be further setup with time points to depict the dynamic reliability behavior of a system with phased missions and in different operating states.

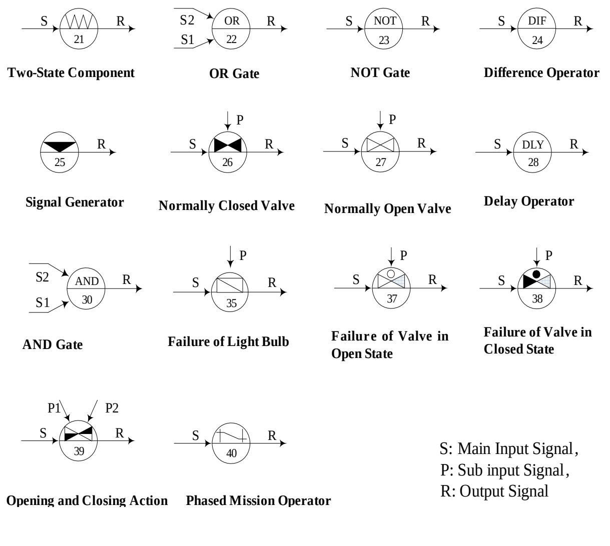

Fig. 1 Symbols of operators in GO-FLOW chart.

2.2 Modeling the auxiliary feed water system with GO-FLOW

This paper takes the Auxiliary Feed Water System (AFWS) of a 3-loop PWR of NPP as an example to show how to model complex system by GO-FLOW.

As one of the engineered safety features, the AFWS includes many types of equipments and serves as an important part in nuclear safety. As shown in Fig.2, the simplified AFWS consists of an auxiliary water tank (01BA), two motor-driven auxiliary feedwater pumps (01PO and 02PO) with 50% of rated flow, one turbine-driven auxiliary feedwater pump (03PO) with 100% of rated flow, valves (motor-driven isolation valve, common valve, and check valve), orifice plates and corresponding pipes.

The main objective of the AFWS is to maintain the water level of steam generators (SG1, SG2 and SG3) so as to discharge the reactor’s residual heat. The AFWS mainly acts as the backup system in circumstances where the main feed water supply of steam generator fails under abnormal operating conditions, such as on-site power failure, main feed water line break or main steam line break.

Figure 3 shows the GO-FLOW model of the AFWS, where, the valves with switches (for example, 012VD) is represented by type 39 operator, and the check valves and electric isolation valves without switches (such as 01VD and CV1) are modeled by type 21 operator. Type 26 and 35 operators indicate failures in startup and running of all pumps (such as 01PO) in the system. Besides, the elements with high reliability, such as storage tank and orifice plates, are represented by type 21 operator. Type 25 operator shows the output of signal generator and type 39 operator needs two auxiliary inputs both modeled by type 25 to control the ON or OFF state of a component. The signal generator that connects as sub input signal to a type 35 operator signifies time points. The intensity of the final output in the GO-FLOW chart represents the availability of the AFWS that can successfully supply water to at least one steam generator.

The GO-FLOW methodology can be applied in the quantitative analysis of system reliability with timing series and multi-states. The time points corresponding to the system reliability changes with timing series should be pre-defined according to the dynamic characteristics, such as equipment out-of-service for maintenance, accident process, system responses and the operator’s intervention on system.

Table 1 shows the parameters for the reliability analysis of the AFWS. The component reliability parameters are those stipulated by IAEA[10], where P_g

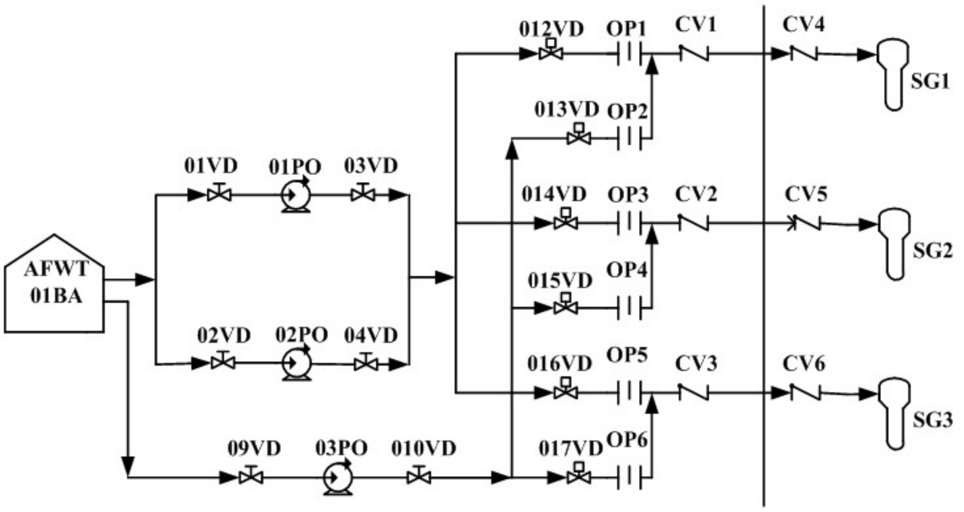

Fig.2 System configuration of the AFWS.

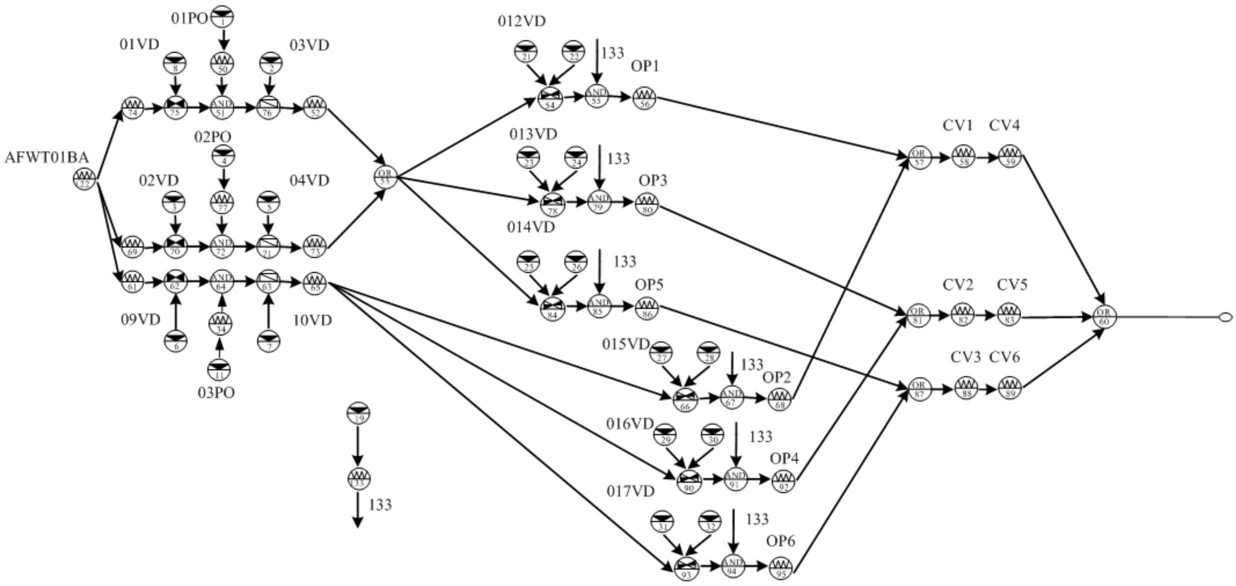

Fig.3 GO-FLOW chart of the AFWS.

Table 1 Parameters of main components in the AFWS

Physical Component	Identification ID	Operator Parameter
Motor-driven Isolation Valve	012VD~017VD	P_g=0.99955
Common Valve	01VD~04VD/09VD~10VD	P_g =0.99989
Check Valve	CV1~ CV6	P_g =0.99998
Motor-driven Auxiliary Feedwater Pump	01PO / 02PO	P_g=0.99954 λ =0.000059
Turbine-driven Auxiliary Feedwater Pump	03PO	P_g=0.99939 λ =0.0000076
Orifice Plate	OP1~ OP6	P_g =0.99970

and λ represents the probability of successful operation and the failure rate, respectively.

To illustrate the application of the GO-FLOW methodology for online maintenance, a practical system configuration is shown in Fig. 4. Other components in the AFWS are assumed to be always at a default operating state. Five time points are considered to describe the dynamic characteristics of the AFWS in different maintenance periods, and each phase can represent definite time intervals respectively (such as mean time to repair).

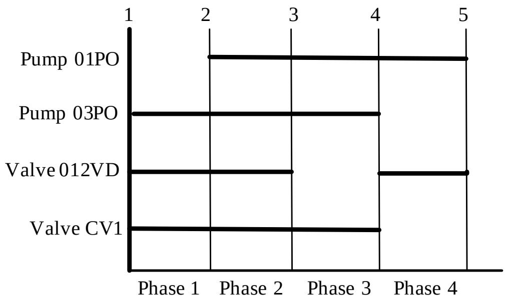

Fig.4 Components' service condition in different phase.

Reliability parameters will be given to each GO-FLOW operator once the GO-FLOW model is completed. The analysis result can be obtained by the GO-FLOW software in one computer run. Figure 5 depicts, in the form of line graph, the failure probability and variation tendency of the AFWS at different time points.

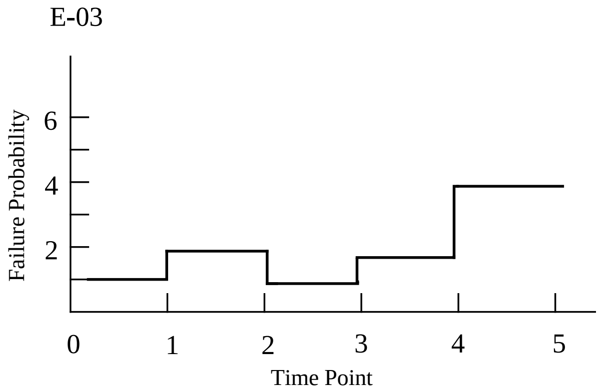

Fig.5 System availability variation curve.

At time point 1, the failure probability of system increases because the pump 01PO is out-of-service.

At time point 2, 01PO is put into operation after maintenance，as a result then the failure probability increases compared with the initial time.

At time point 3, the failure probability slightly increases (but not as high as the case in phase 1) This is owing to the fact that valve 012VD is out-of-service, whose contribution to the system reliability is less than pump 01PO.

At time point 4, an increasing tendency in the failure probability can be observed. This is mainly due to the fact that the two components (*i.e.* pump 03PO and valve CV1) are both out-of-services after 012VD is put into operation. This results in the system's redundancy declining so much causing the failure probability to increase remarkably.

3 Operator support system for online maintenance

3.1 Functions of an operator support system

An operator support system is designed with the following three main functions:

1) Offline reliability evaluation by safety engineers

As shown in Fig. 6, the safety engineers can use the operator support system offline to evaluate whether a maintenance plan can be acceptable by simply inputting the information of the equipments which will be out-of-service for maintenance.

The operator support system will map the equipment maintenance plan into system configuration, modify the GO-FLOW models and then calculate the results quantitatively.

Finally, the evaluation results at each time point will be shown to the safety engineers in graphical formats.

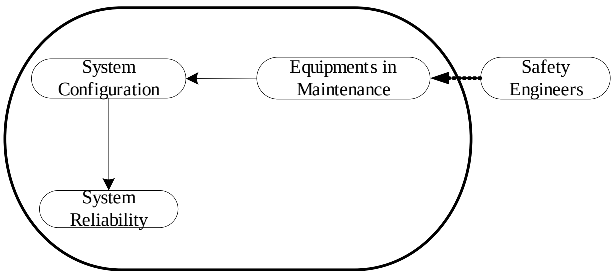

Fig. 6 Reliability evaluation by safety engineers.

2) Reliability evaluation by main control room operators

As shown in Fig.7, the operators in main control room (MCR) can use the operator support system online to evaluate whether a future operating status is acceptable from the system reliability point of view. The operators can predict the effect of equipment or equipment combination out-of-service according to the operating procedures they will undertake.

The operator support system will update the system configuration, modify the reliability model, calculate the system's reliability and indicate any unacceptable system configuration to the operators.

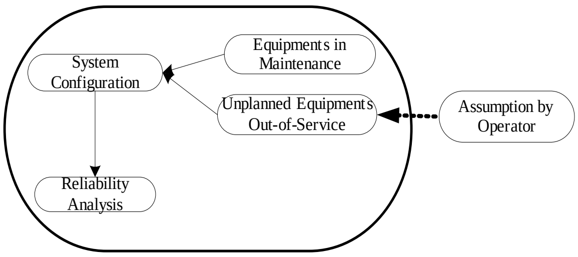

Fig.7 Reliability evaluation by MCR operators.

3) Reliability monitoring by main control room operators

As shown in Fig.8, the operator support system will be connected with a fault diagnosis system. The operator support system will automatically receive information regarding the equipments' states, update the system configuration, modify the reliability model and analyze the results.

When there are anomalies in the system reliability level, the operator can track back to the system configuration to find out the unplanned equipments out-of-service and also investigate the root cause of the fault with the aid of the fault diagnosis system.

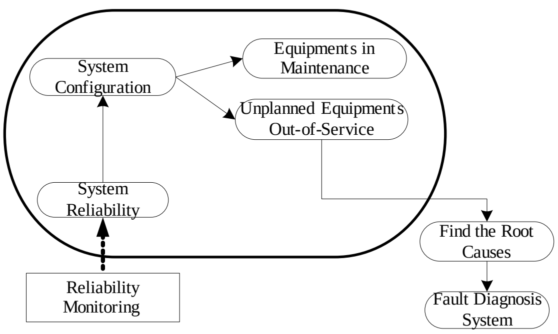

Fig.8 Reliability monitoring by MCR operators.

3.2 Main Human Machine Interface of the operator support system

The main Human Machine Interface (HMI) was developed for the operator support system. The HMI was developed with the C++ language based on the GO-FLOW analysis software data file. As shown in Fig.9, the HMI is classified into four functional areas as follows:

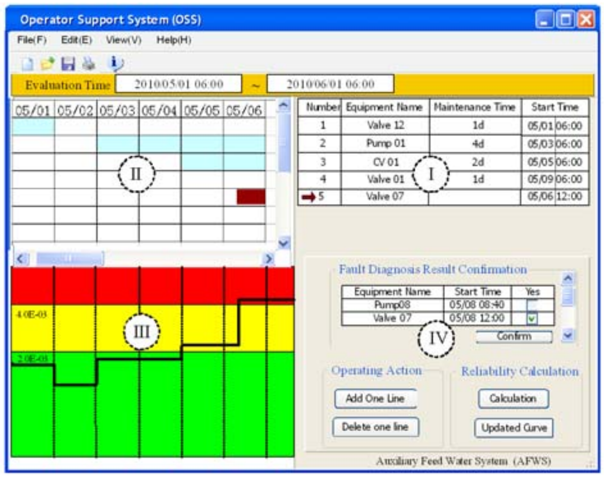

Fig.9 HMI of operator support system.

- Area I

This area is to show the combination of equipments being out-of-service in a diagram form. The parameters include the equipment name, start time for maintenance and Mean Time to Repair (MTR).

- Area II

After inputting the specific information of the equipments for maintenance, the HMI will automatically generate the system configuration with the detailed equipments out-of-service combination in each day in a graphical mode. The planned equipments in maintenance are highlighted in blue color, while red color indicates the unplanned equipments out-of-service detected by the fault diagnosis system.

- Area III

After generating the system configuration, the GO-FLOW models will be updated and calculated automatically. Additionally, the reliability results can be shown in a curve form with three background colors indicating three reliability levels. The boundaries of each reliability level are pre-defined[11]. The red background indicates a high and unacceptable reliability level of the system. Yellow background indicates a relative high but acceptable reliability level of the system, while the green background indicates a safe operating state.

- Area IV

The execution buttons are set in this area. Safety engineers or MCR operators can add or delete the equipments from the maintenance list. When the configuration is accomplished in the offline application of the support system, safety engineers can click the "Calculation" button to obtain the reliability result. A corresponding curve can be automatically generated by clicking "Updated curve" button. In the online application of the operator support system, a button of "Fault Diagnosis Result Confirmation" is designed for the operators to confirm a list of suspected faults which are detected by the fault diagnosis system. The HMI will update the system configuration, modify the reliability models and calculate the system reliability.

3.3 Reliability matrix

A reliability matrix is a table sheet (meant for the safety engineers) with the purpose of providing a rough guide for reliability management in making of the long-term maintenance plans. It is also meant for the MCR operators with the purpose of providing an outlook of the weaknesses in a system's operation which is worthwhile in monitoring the operating conditions.

As shown in Fig.10, the row and column headings are the equipment (*i.e.*, pumps and valves) that will be included in the pre-defined periodic and preventive maintenance activities or in faulty states that can be detected by the operators or the fault diagnosis system.

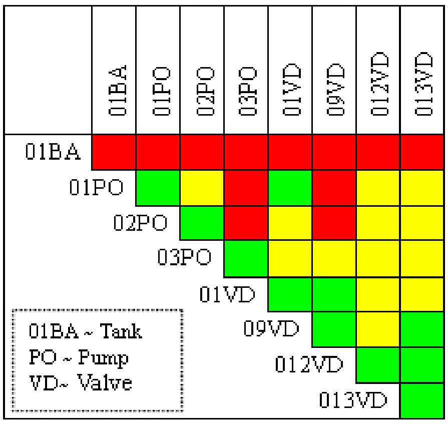

Fig.10 Risk matrix of the AFWS.

The number of the systems is plant specific. Three colors are used in each crossing cell to show the risk level of the system with the combined unavailability of the corresponding two trains. Red indicates the high risk level of the system, which means that the related two trains cannot be taken out-of-service simultaneously. Yellow and green indicate the relative lower risk levels of the system, which mean that the two trains can simultaneously be taken out of service within the certain allowed outage time.

4 Conclusions and future works

In this paper, an operator support system for online maintenance works based on the GO-FLOW[5-8] is presented. The system can be used to assist safety engineers and MCR operators in their maintenance management and operation monitoring.

The operator support system is still under development; there will be a long way for improvement. In particular, the calculation speed of the GO-FLOW is a key issue. This is because when the target system is large, the GO-FLOW models may also become large and complex. Additionally, equipment that are out-of-service may affect many systems in many cases. These may result in long computer calculating time and high computer memory requirements. It is therefore necessary to improve the modeling methodology and reliability calculation algorithm in order to shorten the calculation time.

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