Availability analysis of nuclear power plant system with the consideration of logical loop structures

MATSUOKA Takeshi[1, 2]

1. *Mechanical Systems Engineering, Department of Engineering, Utsunomiya University, 7-1-2 Yoto, Utsunomiya City, 321-8585 Japan (mats@cc.utsunomiya-u.ac.jp)*
2. *College of Nuclear Science and Technology, Harbin Engineering University No.145-1, Nantong Street, Nangang District, Harbin, Heilongjiang Province, 150001 China*

Abstract: Nuclear power plants have logical loop structures in their system configuration. The typical example is a power source system, that is, a nuclear plant generates electricity and it is used for the operation of pumps in the plant. For the reliability or availability analysis of nuclear power plants, it is necessary to treat accurately logical loop structures. Authors have proposed an exact method for solving logical loop structure in reliability analysis, and generalized method has recently been presented. A nuclear power plant system is taken up and essential parts of logical loop structures are modeled into relatively simple form. The procedure to solve a loop structure is shown in which the proposed generalized method is applied, and availability of the system with loop structure is accurately solved. The analysis results indicate that reconsideration of present plant operating procedure should be made for the increase of safety of nuclear power plant in case of "Loss of offsite power" incident. The analysis results also show an important role of loop structures for maintaining the overall system availability. The analysis procedure is also useful in effectively designing high reliable systems.

Keyword: logical loop; availability analysis; reliability analysis; safety of nuclear power plant

1 Introduction

Nuclear power plants have logical loop structures in their system configuration. The typical example is a power source system, that is, a nuclear plant generates electricity and it is used for the operation of pumps which supply water to reactor core for the production of steam and electricity. Without an offsite electric power supply, a nuclear power plant can continue its operation. Another example is a component cooling water system. Without the cooling water, main components cannot continue their operation and generation of electricity has to be ceased. Cooling water is supplied by pumps which are driven by electricity. Supply of lubricating oil is also in the same situation.

For the reliability or availability analysis of nuclear power plants, it is necessary to treat accurately these logical loop structures. It has been pointed out that careful attention has to be made for solving loop structured systems [1].

The reliability or availability of a system is obtained by solving Boolean equations, which express the system configuration. For a system, which has logical loop structure(s), the Boolean relations have to be described with unknown variable(s). The number of unknown variables equals to the number of essential logical loop structures existed in the system. If we try to solve the Boolean equation(s) with unknown variable(s), we encounter infinite circulation of the unknown variable(s). Logical loop was not generally solved in terms of the arithmetic operators of Boolean algebra. Many attempts [2-5] have been proposed.

Authors have proposed an exact method[6] for solving logical loop structure in reliability analysis, and recently generalized method[7] has been presented. The concepts of “support gap” and “Takeover” phenomenon are introduced in the generalized method.

A nuclear power plant system is taken up and essential parts of logical loop structures are modeled into relatively simple form. The model is analyzed by the proposed generalized method.

It is possible to continue power generation during the loss of offsite power (LOSP) and analysis result

Received date: December 27, 2012

shows high degree of availability is maintained for the auxiliary power supply with the reactor operation, in case of loss of offsite incident.

The analysis result of nuclear power plant model shows an important role of loop structures for maintaining the overall system availability. For the evaluation of the safety of nuclear power plants, it is necessary to accurately treat loop structures. And the analysis procedure is also useful in effectively designing high reliable systems.

2 Procedure to solve a loop structure system

As a fundamental configuration of a loop structure, we take up a system shown in Fig. 1. Components S1 and S2 are self sustained type (SS-type) components and components A, B and C are G-type components, which require support for their operation. Time sequence of their starts of operation is $t_{s1} = t_{s2}(=t1) < t_B(=t2) < t_A(=t3) < t_C(=t4)$, for example.

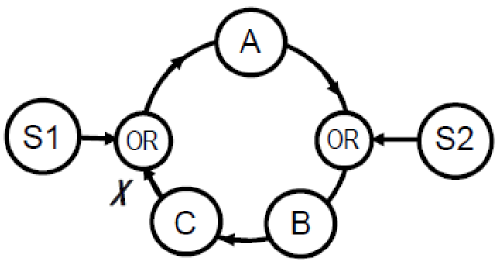

Fig.1 A fundamental loop structure.

The system shown in Fig. 1 can be expressed by the next Boolean equation.

$$X=\{(S1+X)\cdot A+S2\}\cdot B\cdot C \quad (1)$$

The X is a set representing the state in which output of C exists. Elements A, B, C, $S1$, $S2$ are sets representing the state in which corresponding components are in operating states. “Operating state” is rather conceptual at this stage. Concrete expressions are identified after solving the equation (1). The equation (1) is constructed with the condition that G-type components require supports for their operation. The equation (1) contains all the possible operating states of component C at any given time.

Open the brackets,

$$X= S1\cdot A\cdot B\cdot C + A\cdot B\cdot C\cdot X +S2\cdot B\cdot C \quad (2)$$

Element X appears in the second term of the right hand side, that is, output X itself is used as an input. Then the second term represents a loop structure. The form expressed by equation (2) does not change after repeating the substitution of X into the right hand side of equation (2). This is the situation that infinite circulation of unknown element appears in the process of solving a Boolean equation with unknown element(s).

But, the equation can be directly solved with the aids of Boolean fundamental theorems. The solution of the general form becomes as follows [7], which is accompanied with indefinite elements m_k .

$$X=f_1(\alpha_1,\cdots,\alpha_n)X+\cdots+f_k(\alpha_1,\cdots,\alpha_n)X+g(\alpha_1,\cdots,\alpha_n)$$
$$\Rightarrow X=m_1\cdot f_1(\alpha_1,\cdots,\alpha_n)+\cdots+m_k\cdot f_k(\alpha_1,\cdots,\alpha_n)X+g(\alpha_1,\cdots,\alpha_n) \quad (3)$$

Then, the solution of equation (2) becomes,

$$X=S1\cdot A\cdot B\cdot C+m\cdot A\cdot B\cdot C+ S2\cdot B\cdot C \quad (4)$$

The first term is operating state produced by non-loop connection from S1 to C, and the third term is also by non-loop connection from S2 to C. The second term is loop operating state, components A, B and C are mutually supported. It was revealed that indefinite element m equals universal set ($=I$) [7].

Concrete expression of loop operating state is obtained as follows. Select a component started first among the loop. Identify the operating state of this component at the starting time. It can be determined, because a loop connection is not established at that time and the component is supported by a SS-type component outside of the loop structure. Then, successively determine operating state of connected components along the connecting order, till loop operating state is established. In this case, “takeover” phenomenon is used for identifying the operating state of a component which makes loop structure [7]. An indefinite element m is set to be I. Detailed explanations are given in the references [7, 8], and concrete expression has been obtained as follows.

$$X(t)=S2(\tau_3)\cdot S1(t)A(t)B(t)C(t) + S1(\tau_4)\ S2(\tau_3)\cdot A(t)B(t)C(t) + S2\ B(t)C(t) \quad (5)$$

Above equation is the expression for any time after the establishment of loop operation. Where, τ_3, τ_4 are fixed time and not a variable, and they are distinguished from variable t.

For the following example system, analysis procedure can be simplified as shown in section 5.

3 Example system

A typical BWR type nuclear power plant system is taken up and analysis is performed. Figure 2 shows a general layout of BWR system. Only essential parts of loop structures are expressed, and it is seen there are five essential loop structures, main steam and feedwater loop, electric power supply, component cooling water supply, steam extraction, and lubricating oil system.

In Fig. 2, red arrows indicate electric power supply. If components have red arrow, they require electricity for their operation. Blue arrows indicate cooling water, and components require to be cooled by water, when they have blue arrow. Green lines indicate extraction steam lines. Reactor feedwater pump needs lubricating oil for its continuous operation.

For the start of plant system, offsite power (external electric power source) is used for the start of each component, and after establishing the plant power generation, the operation can be continued without the supply of offsite power. Emergency power supply system is started when offsite power is not available and the reactor is stopped. It is used for the removal of decay heat in an emergency situation.

One reactor feedwater pump is turbine driven pump and it can be operated by extraction steam without any electricity. The other reactor feedwater pump is motor driven pump. Both pumps require lubricating oil for their continuous operation. The axis of oil pump is directly connected to the axis of feedwater

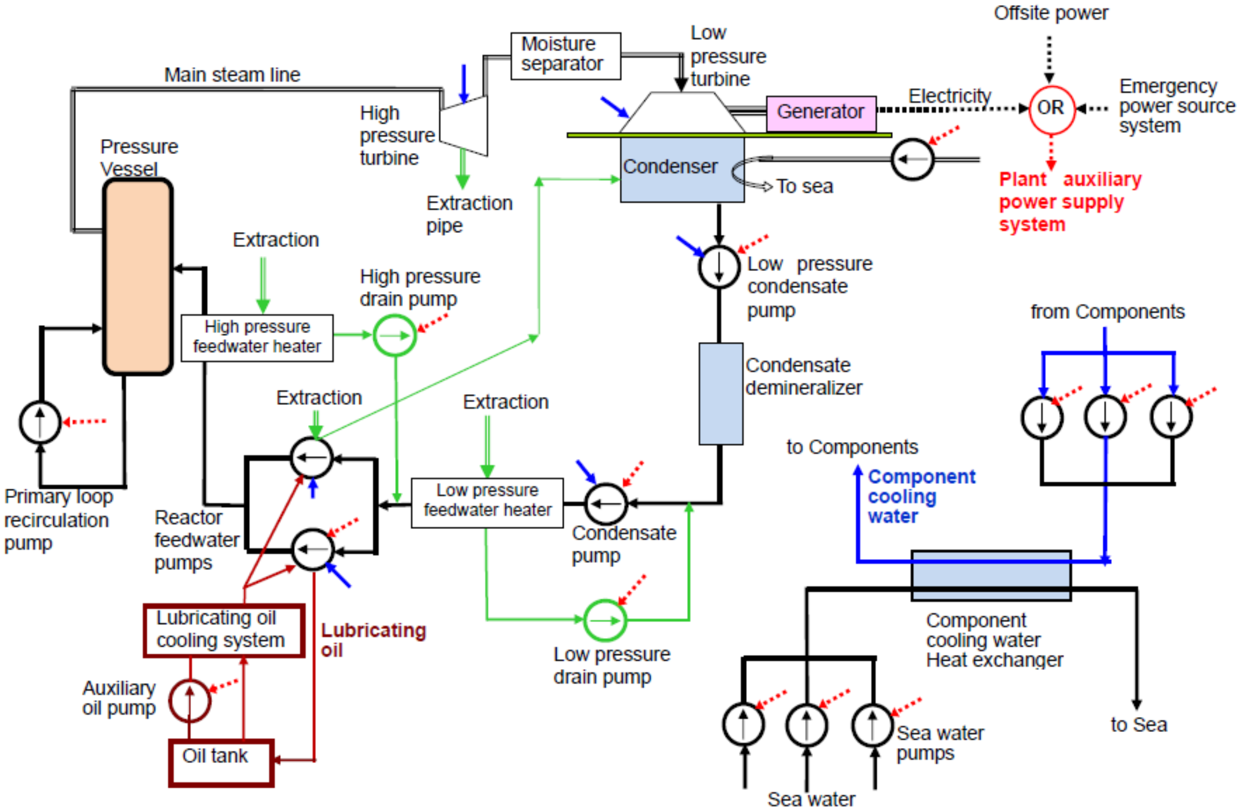

Fig.2 General layout of BWR nuclear power plant (loop structure).

pump, and it works without any electricity. Component cooling water is circulated by the forces of many pumps driven by electricity.

4 Expression by the Boolean equations and their solution

The system configuration is simplified and expressed in Fig. 3. Attention has to be made for the expression of this figure. The arrows which connect components express the supporting relations.

The following aberrations are used in Fig.3.

PRP: primary recirculation pump,
RPV: reactor pressure vessel,
HPT: high pressure turbine,
EXP: extraction pipe,
LPT: low pressure turbine,
GEN: generator,
OSP: offsite power,
EPS: emergency power source,
SWP: sea water pump,
CON: condenser,
LCP: low pressure condensate pump,
CP: condensate pump
LFH: low pressure feedwater heater
FP1: feedwater pump 1,
HFH: high pressure feedwater heater,
CP1: component cooling water pump 1,
SP1: sea water pump 1,
CCH: component cooling water heat exchanger.

Letters “W, X, Y, Z” are used for representing the sets of the existence of corresponding component’s output.

Outputs X, Y, Z are expressed in the following Boolean equations.

$$X=OSP+EPS+W\cdot Y\cdot LPT\cdot GEN \quad (6)$$

$$\begin{aligned}Y&=\{CP1+CP2+CP3\}\cdot X\cdot Y\cdot\{SP1+SP2+SP3\}\cdot X\cdot CCH\\&=\{CP1+CP2+CP3\}\cdot\{SP1+SP2+SP3\}\cdot CCH\cdot X\cdot Y\end{aligned} \quad (7)$$

$$Z=W\cdot EXP \quad (8)$$

In the above equations, italic expression OSP etc. represent sets of operating state of “off site power” and so on.

Equation (7) contains variable Y in the both side. Ii is

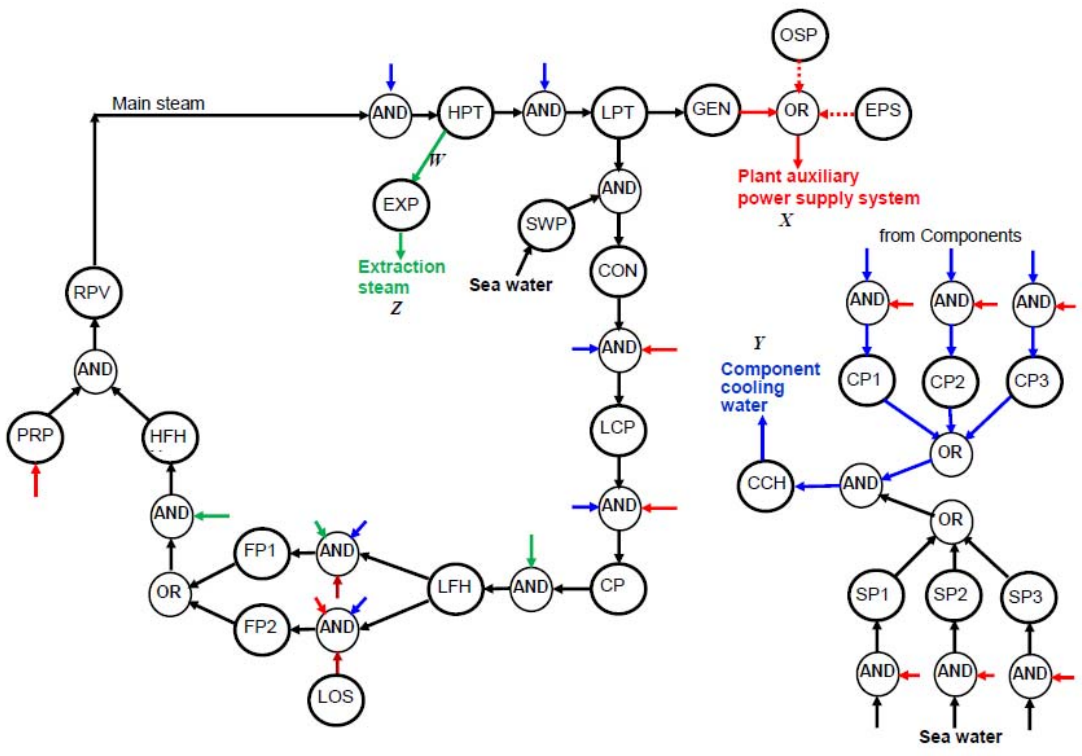

Fig.3 Simplified configuration of loop structure.

transformed into equation (9) by the rule of equation (3).

$$Y=m_Y\{CP1+CP2+CP3\}\cdot\{SP1+SP2+SP3\}\cdot CCH\cdot X \quad (9)$$

Variable W belongs rather large loop structure and is expressed by the next Boolean equation.

$$\begin{aligned}W&=W\cdot Y\cdot LPT\cdot SWP\cdot CON\cdot X\cdot LCP\cdot CP\cdot Z\cdot LFH\cdot\\&\quad\{FP1\cdot Z\cdot Y+FP2\cdot X\cdot Y\}\cdot LOS\cdot HFH\cdot PRP\cdot RPV\cdot HPT\\&=LPT\cdot SWP\cdot CON\cdot LCP\cdot CP\cdot LFH\cdot\{FP1+FP2\}\cdot\\&\quad LOS\cdot HFH\cdot PRP\cdot RPV\cdot HPT\cdot EXP\cdot X\cdot Y\cdot W\end{aligned} \quad (10)$$

Therefore, it becomes as follows also by the aid of equation (3).

$$\begin{aligned}W&=m_W\cdot LPT\cdot SWP\cdot CON\cdot LCP\cdot CP\cdot LFH\cdot\{FP1+FP2\}\cdot\\&\quad LOS\cdot HFH\cdot PRP\cdot RPV\cdot HPT\cdot EXP\cdot X\cdot Y\end{aligned} \quad (11)$$

Substitute the equations (9) and (11) into equation (6). The variable X is obtained as follows,

$$\begin{aligned}X&=OSP+EPS+m_X\cdot m_Y\cdot m_W\cdot LPT\cdot SWP\cdot CON\cdot LCP\cdot CP\cdot LFH\cdot\\&\quad\{FP1+FP2\}\cdot LOS\cdot HFH\cdot PRP\cdot RPV\cdot HPT\cdot EXP\cdot\\&\quad\{CP1+CP2+CP3\}\cdot\{SP1+SP2+SP3\}\cdot CCH\cdot GEN\end{aligned} \quad (12)$$

The solution becomes as equation (13) by putting $m_X=m_Y=m_W=I$ conditions.

$$\begin{aligned}X&=OSP+EPS\\&\quad+LPT\cdot SWP\cdot CON\cdot LCP\cdot CP\cdot LFH\cdot\{FP1+FP2\}\cdot\\&\quad LOS\cdot HFH\cdot PRP\cdot RPV\cdot HPT\cdot EXP\cdot\{CP1+CP2+CP3\}\cdot\\&\quad\{SP1+SP2+SP3\}\cdot CCH\cdot GEN\end{aligned} \quad (13)$$

Equation (13) gives the relation between the existence of electric power supply and constituent components' operating states, and the relation holds at any time after the establishment of plant power generation (loop operation).

5 Analysis conditions and results

Consider the availability of “Plant auxiliary power supply” after the establishment of plant power generation (that is, loop operating state is established). At time 0 hour, just after the start of power generation, it is assumed that offsite power is still connected and emergency power sources are in standby condition. Set the availability of the electric power supply (Pr(X)) as 1.0 at time 0 hour.

Offsite power is assumed to be stopped at 20 hours after the start of power generation. Then, continue the power generation without offsite power. Just after the stop of offsite power, emergency power sources are started and supply electricity to the plant auxiliary power supply system. At time 40 hours, offsite power source is recovered.

Equation (13) can be simplified by getting together the loop part (LOOP), and component cooling water part (CCW).

$$X=OSP+EPS+LOOP\cdot CCW\cdot GEN \quad (14)$$

where,

$$\begin{aligned}LOOP&=LPT\cdot SWP\cdot CON\cdot LCP\cdot CPL\cdot FHEN\cdot\{FP1+FP2\}\cdot\\&\quad LOS\cdot HFH\cdot PRP\cdot RPV\cdot HPT\cdot EXP,\\CCW&=\{CP1+CP2+CP3\}\cdot\{SP1+SP2+SP3\}\cdot CCH\end{aligned}$$

Failure rates during operation and demand probabilities for the starts of operation are set for the parts from OSP to GEN as shown in Table 1.

Table 1 Failure data assigned for each part

Part	Failure rates	Demand probability
OSP	$1\text{x}10^{-6}$/h	0.02
EPS	$4\text{x}10^{-6}$/h	0.01
LOOP	$4\text{x}10^{-3}$/h	---
CCW	$2\text{x}10^{-9}$/h	---
GEN	$1\text{x}10^{-3}$/h	---

Failure rate of OSP is set to be equivalent to the occurrence times of LOSP (0.01/reactor.year), and demand probability is equivalent to success probability of OSP recovery after 20 hours. These values are based on the actual nuclear power plant records [9]. Failure rate and demand probability of EPS are deduced from the assumption that EPS consists of double diesel generators ($\lambda=2\text{x}10^{-3}$/h, Qd=0.03/D).

Main contributor to the failure of loop part are four pumps (λ=1x10^{-3}/h). The CCW system has three parallel (redundant) cooling water lines and sea water lines. Each line has one pump (λ=1x10^{-3}/h). Failure of GEN is dominated by one generator (λ=1x10^{-3}/h).

The probability of loop operation at a specific time is calculated by the following equation.

$$Pr(LOOP)= Pr(LPT \cdot SWP.... \cdot GEN) = Pr(LPT) \cdot Pr(SWP)..... Pr(GEN) \quad (15)$$

where, "LPT", etc. are sets of operating state of LPT (low pressure turbine) and so on. The operation of LPT needs steam supply as input. Therefore, concrete expression of component's operating state has to be obtained step by step from the start of operation as mentioned in the end of section 2.

If the probability of loop operating state is settled as 1.0 at the start of loop operation (t_4), loop operation part in equation (5) becomes as follows,

$$S1(\tau_4)\ S2(\tau_3) \cdot A(t_4)B(t_4)C(t_4)=I \quad (16)$$

Loop operation has to be started by the aids of perfect SS-type components, S1 and S2. Then, the condition $S1(\tau_4)= S2(\tau_3)$=I is held, and loop operating state after the start of loop operation becomes,

$$LOOP(t) = A(t)B(t)C(t) \quad (17)$$

It has been seen that the reliability of loop operation can be simply obtained as the products of reliabilities of constituent components of the loop [6]. This means the operating state of the components outside of the loop has no influence to the loop operation, in this case.

If recovery or repair of failed components in the loop part is not considered, the reliability equals to the availability of loop operation (In this case, existence of electric power supply by plant itself).

The relation of equation (14) is modeled into a GO-FLOW chart as shown in Fig. 4. The probability of electric power supply to the plant is obtained by output of operator 14 in Fig. 4. Analysis result is obtained as the blue solid line in the Fig. 5.

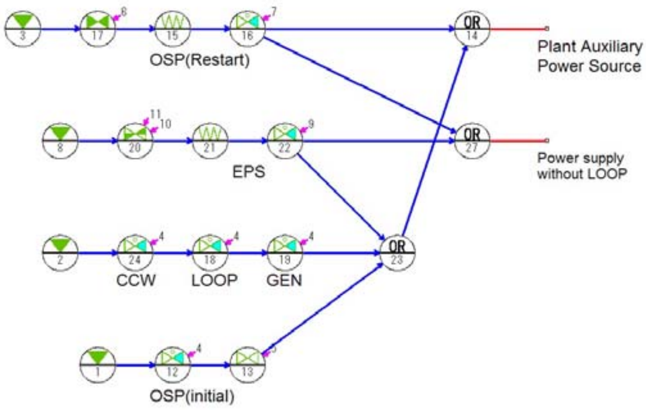

Fig. 4 GO-FLOW chart for the electric power supply.

According to the operating procedure of nuclear power plant, reactor is required to be shut down in case of "Loss of offsite power (LOSP)". This condition is also represented by output of operator 27 in Fig 4. The result is shown by the dotted line in Fig.5. After the reactor shut down, the availability of plant auxiliary power supply system drastically decrease till the recovery of offsite power.

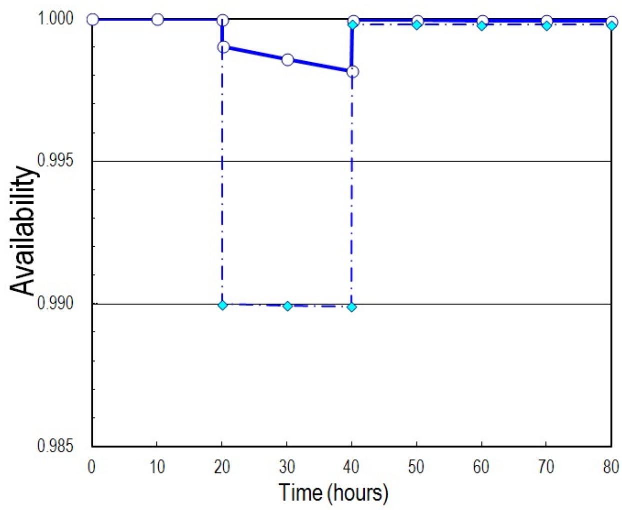

Fig.5 Availability of plant auxiliary power supply system.

Even after the reactor shut down, it is essential to continue the electric power supply to the components of the power plant for the prevention of the reactor core damage, because there is large amount of decay heat in the reactor core.

Above results indicate that it is better to continue the plant operation even after the "Loss of offsite power". Reconsideration of present plant operating procedure should be made for the increase of safety of nuclear power plant in case of "Loss of offsite power" incident.

6 Discussions and Conclusions

In the present analysis condition, the reliability of loop structure is perfect at the beginning and it is required to be operated during the loss of offsite power incident. Then, analysis becomes rather simple. The availability of "plant auxiliary power supply" has been obtained by the equation (13). If the operations of loop structures are occasionally required in the plant operational sequences, analysis procedures become more complicated.

Analysis result shows that high degree of availability is maintained for the auxiliary power supply even without the offsite electric power. It is possible to continue power generation during the loss of offsite power.

It is seen from the equation (13) that "CCW" (component cooling water part) is placed in series to "LOOP"(loop part) and "GEN"(generator). The CCW is a support system to the electric power generation system, but it is equally important for the reliability of electric power generation. The CCW should be designed as reliable as the LOOP part and generator.

The equation (13) also indicates that FP1 (turbine driven feedwater pump) is placed in the equal position to FP2 (motor operated feedwater pump). This means even the turbine driven pump needs electricity for its operation in this plant configuration (loop structure), after all.

Analyses have been performed for the two cases with or without reactor shutdown. The results indicate that reconsideration of present plant operating procedure should be made for the increase of safety of nuclear power plant in case of "Loss of offsite power" incident.

A nuclear power plant system was taken up and modeled into relatively simple form by considering loop structures. The procedure to solve a loop structure has been shown in which the generalized method was applied, and availability of the system with loop structure was rigorously solved.

The analysis result shows an important role of loop structure for maintaining the overall system availability. The analysis procedure is also useful in effectively designing high reliable systems.

References

[1] YOSHIKAWA, H. ed.: Risk assessment and its application to the modern industrial technology, New handbook of risk science, Mimatsu, 2009: 203-206. (In Japanese).

[2] COLES, G. A., and POWERS, T. B.: Breaking the logic loop to complete the probabilistic risk assessment. In: Proceeding of PSA'89, Pittsburgh, PA, USA, April 2-7, 1989: 1155-1160.

[3] MATSUOKA, T.: A method to solve logical loops in the GO-FLOW Methodology. In: Proceedings of PSAM-V, Osaka, Japan, Nov. 27- Dec. 1, 2000: 1461-1465.

[4] YANG, J. E., HAN, S. H., PARK, J. H., and JIN, Y. H.: Analytic method to break logical loops automatically in PSA. Reliability Engineering and System Safety. 56, 1997: 101-105.

[5] VAURIO, J. K.: A recursive method for breaking complex logic loops in Boolean system models. Reliability Engineering and System Safety. 92, 2007: 1473-1475.

[6] MATSUOKA, T.: An exact method for solving logical loops in reliability analysis. Reliability Engineering and System Safety. 94, 2009: 1282-1288.

[7] MATSUOKA, T.: Generalized Method for Solving Logical Loops in Reliability Analysis. In: Proceeding of PSAM-11, Helsinki, Finland, Jun. 25-29, 2012.

[8] MATSUOKA, T.: Method for solving logical loops in system reliability analysis, International Journal of Nuclear Safety and Simulation, 1, 2010: 328-339.

[9] Nuclear safety commission, Report of the loss of all AC power incidents in Nuclear Power Plant, 1993.