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Unavailability Analysis of *OPΔT* & *OTΔT* Channel by Direct Simulation Method

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직접 모의방식에 의한 *OPΔT* & *OTΔT* 찬넬의 비가용도 분석

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Abstract

In this paper, we suggest the simple and practical direct simulation method for the system reliability calculation In the aspect of system unavailability calculation, this method can simplify the calculation process by applying the hard-wired system fault tree. For the calculation purpose, we use the ESCAF which is developed by Mr. Laviron in France. As a consequence, we estimate the unavailability of *OPΔT* & *OTΔT* channel in W PWR plants as a value of 8.17576×10^{-9} from IEEE std. 500-1977's reference data. In our calculation, the processing time is no more than 25 sec.

요 약

본 논문에서는, 임의의 계통신뢰도를 매우 단순화시킬 수 있는 직접 모의 방법을 제시하였다. 계통의 비가용도 측면에서, 본 방법은 고장수목을 하드웨어적으로 구성함으로서 계산과정을 단순화시킬 수 있었다. 계산도구로는 프랑스의 Laviron씨가 개발한 ESCAF을 사용하였다. 금번 연구에서는 PWR 발전소의 *OPΔT* & *OTΔT* 찬넬의 비가용도를 IEEE std. 500-1977의 제시된 자료를 근거로 계산하였으며, 그 값은 8.17576×10^{-9}로 나타났다. 또한 계산시간은 25초 미만이었다.

I. Introduction

In the safety and economic aspects of nuclear power plant operations, system reliability is one of the most critical parameters. In the classical concept, nuclear power plant systems are designed with multiple redundancies to ensure very high levels of reliability and safety. These redundancies are needed to accommodate failure of one or more system components and to increase in-service testability and maintainability.

Several methods have been developed for analyzing system design to check whether the requisite reliability has been achieved. Unfortunately, exact reliability measures for large complex systems such as nuclear power plants are often difficult and tedious to compute. In this paper, we present a direct simulation method which evolved from fault tree analysis (FTA) to analyze the PWR system safety. It can identify the potential accidents in a system design

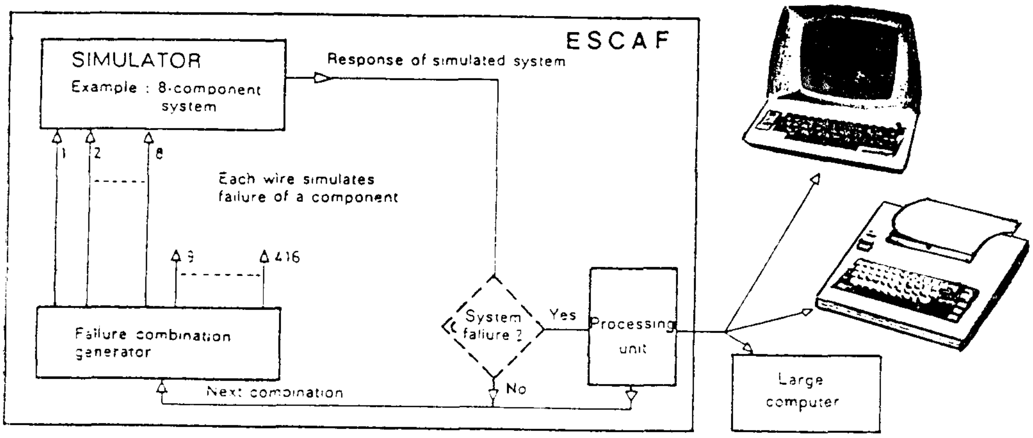

Fig. 1. System Configuration of ESCAF

and can help to eliminate costly design changes and retrofits, and also it can predict the most likely cause of system failure in the event of a system breakdown.

The analyzing tool used in this study is so called ESCAF(Electronic Simulator to Compute and Analysis Failures).

ESCAF is a microprocessor-based processing unit which is developed by CEA in France.

The principal configuration of this system is shown in Fig. 1.

II. Fault Tree Evolution

The goal of fault tree construction is to model the system condition that can result in the undesired event. The fundamental logic gates for fault construction are the OR and the AND gates.

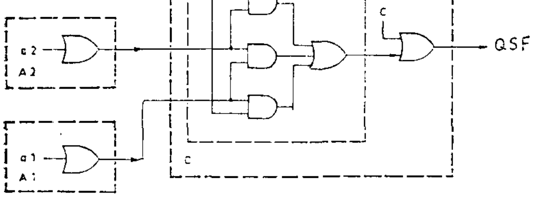

Fig. 2. 2/3 Logic Diagram

As an example of these logic gates development, we can realize the 2/3 state logic as Fig. 2.

If we describe the functional state diagram from the point of component failure, it will be represented like Fig. 3.

In the Fig. 3, we can classify the three states as follows;

—perfect system operation (P.S.O)

—system operation with components failures (S.O)

—system failure due to components failures (S.F)

From the point of safety operation, we are interested in the last state (S.F).

As a result of Fig. 3, we can describe the canonic form of this system as follows.

$$QSF=\begin{pmatrix} \bar{a}_3 & \bar{a}_2 & \bar{a}_1 & c \\ \bar{a}_3 & \bar{a}_2 & a_1 & c \\ \bar{a}_3 & a_2 & \bar{a}_1 & c \\ \bar{a}_3 & a_2 & a_1 & \bar{c} \\ \bar{a}_3 & a_2 & a_1 & c \\ a_3 & \bar{a}_2 & \bar{a}_1 & c \\ a_3 & \bar{a}_2 & a_1 & \bar{c} \\ a_3 & \bar{a}_2 & a_1 & c \\ a_3 & a_2 & \bar{a}_1 & \bar{c} \\ a_3 & a_2 & \bar{a}_1 & c \\ a_3 & a_2 & a_1 & \bar{c} \\ a_3 & a_2 & a_1 & c \end{pmatrix} \quad (1)$$

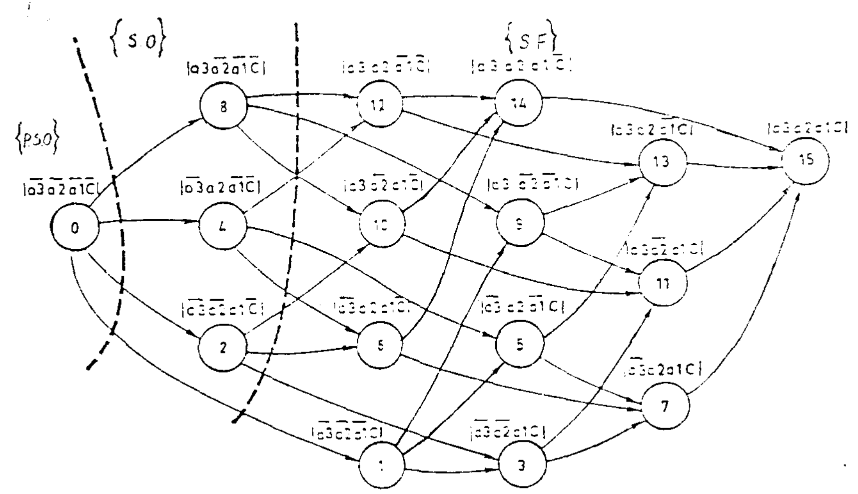

Fig. 3. Functional State Diagram of 2/3 Logic

where QSF represents system failure due to components (a_1, a_2, a_3) and cable (c) failures. So, each of lines means the failure states of system and the symbol | | means the sum of the cut set of each lines. If we consider the minimal cut set which is a combination of elementary component failures leading to system failure but such that are not a subset of the events of any other cut set, we can represent as follows.

$$\mathrm{QSF}[\phi(x)=F]=\begin{vmatrix} c & \\ a_1 & a_2 \\ a_1 & a_3 \\ a_2 & a_3 \end{vmatrix} \tag{2}$$

III. Calculation of System Failure Probability

For the calculation of system failure probability, we assume the simple logical equation as follows.

$$P_T=\begin{pmatrix} P_1 \\ P_2 \\ P_3 \end{pmatrix}$$

Where, P_T represent the system failure and P_1, P_2, P_3 represent the each component failure.

We can write this equation as follows.

$$P_T=\begin{pmatrix} P_1 \\ P_2 \\ P_3 \end{pmatrix}=|P_1|+|P_2\bar{P}_1|+|P_3\bar{P}_1\bar{P}_2| \tag{3}$$

Then, it will be converted into the following polynomial form;

$$\begin{aligned} P_T=&P_1(1-P_2+P_2)(1-P_3+P_3) \\ &+P_2(1-P_1)(1-P_3+P_3) \\ &+P_3(1-P_1)(1-P_2) \\ =&P_2(1-P_2)(1-P_3)+P_2(1-P_1)(1-P_3) \\ &+P_3(1-P_1)(1-P_2)+P_1P_2(1-P_3) \\ &+P_2P_3(1-P_1)+P_1P_3(1-P_2) \\ &+P_1P_2P_3 \end{aligned} \tag{4}$$

or

$$\begin{aligned} P_T=&(1-P_1)(1-P_2)(1-P_3)\Big[\frac{P_1}{1-P_1} \\ &+\frac{P_2}{1-P_2}+\frac{P_3}{1-P_3}+\frac{P_1}{1-P_1}\frac{P_2}{1-P_2} \\ &+\frac{P_2}{1-P_2}\frac{P_3}{1-P_3}+\frac{P_1}{1-P_1}\frac{P_3}{1-P_3} \\ &+\frac{P_1}{1-P_1}\frac{P_2}{1-P_2}\frac{P_3}{1-P_3} \end{aligned} \tag{5}$$

As a consequence, the preceeding equation can be generalized as follows.

$$P_T=\prod_{i=1}^{n}(1-p_i)\sum_{r=1}^{c}\sum_{K=1}^{K_r}\prod_{m\in B_{K,r}}\frac{p_m}{1-p_m} \tag{6}$$

where,

K_r : number of cut set of order r

$B_{K,r}$: cut set K of order r.

In the special case, where all the component probabilities are equal to P, this equation can be represented by

$$P_T=(1-p)^n\left[\sum_{r=1}^{c}K_r\left(\frac{p}{1-p}\right)^r\right] \quad (7)$$

Therefore total system unavailability can be calculated by the QSF's output condition as follows.

$$P_T\{\phi(X)=1\}=\prod_{i=1}^{n}(1-p_i)\left[\delta^0{}_x+\sum_{r=1}^{c}\sum_{K=1}^{K_r}\prod_{m\in B_{K,r}}\frac{p_m}{1-p_m}\right] \quad (8)$$

where

$\phi(x)$=state of QSF's output

$\delta_0=1$: $\phi(x)=1$ when system failure occurs

0 : $\phi(x)=0$ when system failure succeeds

c=number of simulation order at which the matrix computation is stopped

This formula assumes that the events or component failures are mutually s-independent: this implies that the failure or repair of one element does not affect the failure or repair of other elements.

IV. System Selection for the Calculation

The specific concern of this paper is the overpower and the over-temperature trip channel integrity in the PWR plants. The thermal overpower trip channel is designed to ensure the operation within the fuel temperature design basis and the thermal overtemperature trip is designed to ensure the operation within the DNB design basis and the hot-leg boiling limit.

If we describe the overpower and the over-temperature trip systems, we can represent as following equation.

Overpower ΔT setpoint

$$=K_4-K_5\frac{\tau_3 S}{1-\tau_3 S}T_{avg}-K_6$$

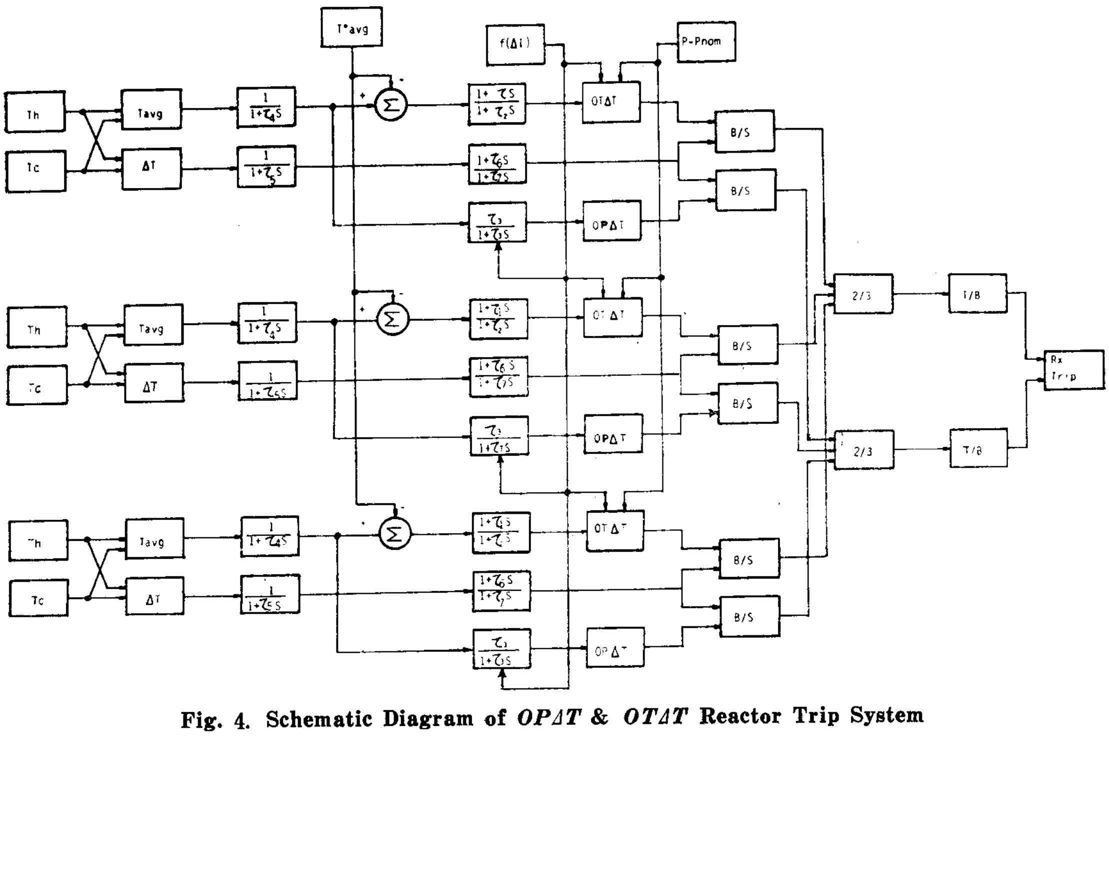

Fig. 4. Schematic Diagram of *OPΔT* & *OTΔT* Reactor Trip System

$$(T_{avg}-T^{avg}{}_{0})-f(\Delta I) \qquad (9)$$

Overtemperature ΔT setpoint

$$=K_1-K_2\frac{1+\tau_1 S}{1+\tau_2 S}(T_{avg}-T^{avg}{}_{nom})$$

$$+K_3(P-P^{nom})-f(\Delta I) \qquad (10)$$

where,

K_1, K_4=A preset value (% of full-power ΔT, 118%)

K_2=A constant based on the effect of temperature on the design limits (% of full-power ΔT/°F)

K_3=A constant based on the effect of pressure on the design limits (% of full-power ΔT/Psi)

K_5=A constant that compensates for piping and thermal time delays (% of full-power ΔT/°F)

K_6=A constant that accounts for the effects of coolant density and heat capacity on the relationship between ΔT and thermal power (% of full-power ΔT/°F)

T^0_{avg}=indicated average reactor coolant temperature at full-power (°F)

T_{avg}=Average reactor coolant temperature (°F)

τ_1, τ_2, τ_3=time constant (seconds)

S =Laplace transform operator (S^{-1})

T^{nom}_{avg}=Nominal average reactor-coolant temperature at full-power (°F)

P =Pressurizer pressure

P^{nom}=Nominal reactor coolant system pressure (P_{sig})

$f(\Delta I)$=A function of the neutron flux difference between upper and lower long ion chamber section (% of full-power ΔT)

Both of the system will trip the reactor when the compensated ΔT in any two channels exceeds the setpoint (three-loop plants (900MWe) have one channel per loop).

So, we can represent the schematic diagram of overpower and overtemperature ΔT protection system for the 900MWe PWR plants like Fig. 4 and this schematic diagram can be easily converted to Fig. 5.

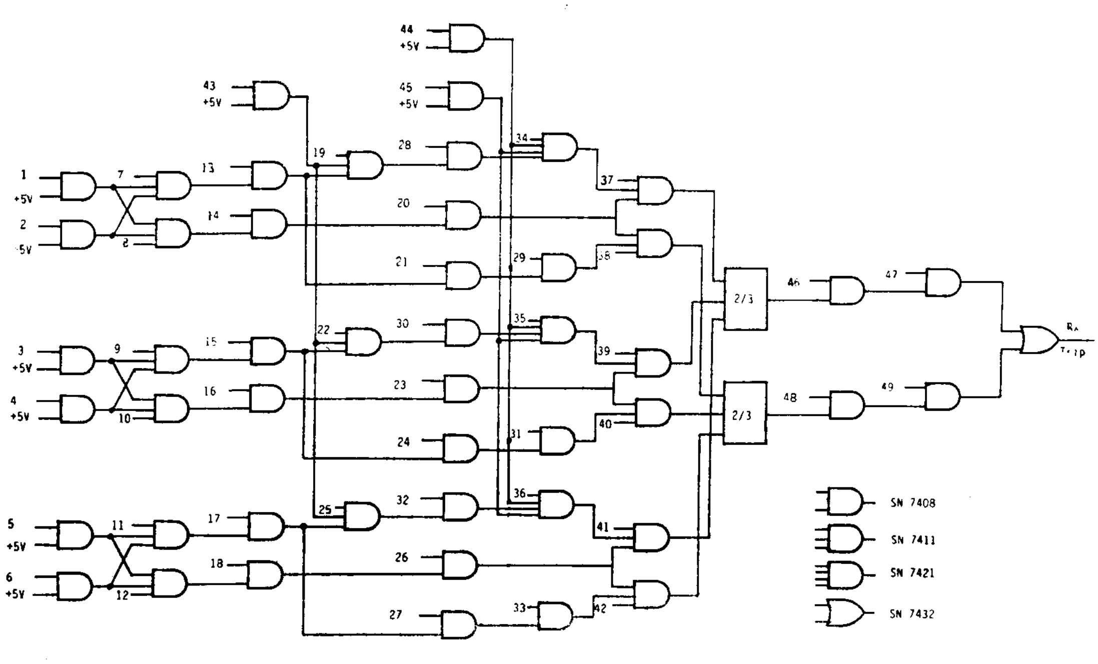

Fig. 5. Logic Diagram of *OPΔT* & *OTΔT* Reactor Trip System

V. Calculation Results and Conclusion

We construtc the system fault tree with digital I.C components easily and obtain the system failure due to components failures directly. Since the ESCAF calculate the failure probability from 1st order to n-th order of equation (6) and print out their results at each order, we can estimate the system unavailability more fast than any other conventional method. This conclusion is not supported by this study. This study did not compare computing time of the ESCAF method with those of other methods.

For the calculation of our study, we use the IEEE std. 500-1977's reference data represented in Table 1. As we calculate the system unavailability, it has their saturated values, 8.17576×10^{-9}, at 4th order.

And total processing time of ESCAF is no more than 25 sec.

Table 1. Component Reliability Data

No. of Component	Reliability datas.
1~6	4.380 E-05
7~12	1.791 E-05
13~36	1.427 E-05
37~42	2.008 E-05
43	2.870 E-05
44	7.475 E-05
45	6.225 E-05
46.48	1.204 E-05
47.49	2.775 E-05

Table 2. Calculation Result

No. of order	Combi-nations	Cut sets	M-Cut sets	system un-availability
1	49	0	0	
2	1176	10	10	8.16837E-09
3	18424	445	0	8.17575E-09
4	211876	12352	2662	8.17576E-09
5	1906884	202824	0	8.17576E-09

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