Journal of the Korean Nuclear Society
Volume 28, Number 5, pp. 431～439, October 1996

Quantification of Plant Safety Status

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(Received August 29, 1995)

Abstract

In the process of simplifying the complex state of the plant into a binary state, the information loss is inevitable. To minimize the information loss, the quantification of plant safety status has been formulated through the combination of the probability density function arising from the sensor measurement and the membership function representing the expectation of the state of the system. Therefore, in this context, the safety index is introduced in an attempt to quantify the plant status from the perspective of safety. The combination of probability density function and membership function is achieved through the integration of the fuzzy intersection of the two functions, and it often is not a simple task to integrate the fuzzy intersection due to the complexity that is the result of the fuzzy intersection. Therefore, a methodology based on the Algebra of Logic is used to express the fuzzy intersection and the fuzzy union of the arbitrary functions analytically. These exact analytical expressions are then numerically integrated by the application of Monte Carlo method. The benchmark tests for rectangular area and both fuzzy intersection and union of two normal distribution functions have been performed. Lastly, the safety index was determined for the Core Reactivity Control of Yonggwang 3&4 using the presented methodology.

1. Introduction

Since TMI accident, the operation technology has been emphasized for the guarantee of the plant safety. To cope with the accident safely and quickly, the capability of the operator to respond to event is important. To improve the operator capability to respond to event, therefore, adequate emergency operating procedures and operator training according to those procedures are essential. While the emergency operating procedures in past time were event-oriented, in recent time those procedures have been being diverted to symptom-oriented procedures which can be used when multiple events which exceed the design criteria have occurred, and the importance of the Safety Parameter Display System (SPDS) accordingly is being embossed.

According to Standard Review Plan[1], the principal purpose and function of the SPDS is to aid control room personnel during abnormal and emergency conditions in determining the safety status of the nuclear power plant and in assessing whether abnormal conditions warrant corrective action by operators to avoid a degraded core. During emergencies the SPDS serves as an aid to evaluating the current safety status of the plant, executing function-oriented emergency procedures, and monitoring the impact of engineering safeguards or mitigation activities. The SPDS also operates during normal operations, continuously displaying information from which the plant safety status can be readily and reliably assessed.

In Yonggwang nuclear power plant, units 3 and 4 (YGN 3&4), the Critical Function Monitoring System (CFMS) in Plant Monitoring System (PMS) performs the function of SPDS[2]. In CFMS, the parameters important to plant safety are sorted into and displayed by 9 groups of Core Reactivity Control, Core Heat Removal, Containment Integrity, RCS Inventory Control, RCS Heat Removal, Radiation Emissions Control, Containment Isolation, RCS Pressure Control and Maintenance of Vital Auxiliaries, and the parameters of each group are compared with setpoints to annunciate the safety status of each group by alarm. To monitor the critical function of each group, the operator needs to monitor and estimate the several plant parameters.

Currently, the majority of the plant safety status is expressed by alarm system in conjunction with digital or analog displays. Among this, the alarm system compares the measured values of safety-related parameters with the pre-determined setpoints, and generates the alarm which indicates the safety status of plant. In this process, information is lost by simplifying the complex state of plant into a simple binary state[3]. To minimize the information loss, the quantification of plant safety status has been formulated through the combination of the probability density function arising from the sensor measurement and the membership function representing the expectation of the state of the system. Therefore, in this context, the safety index is introduced in an attempt to quantify the plant status from the perspective of safety.

In fuzzy set theory, the membership function expresses the expected, possible or desired state of the system. Hence, the desired state of the plant parameter is expressed in the form of membership function. Sensor data are acquired as random data in the form of probability density function. The combination of the probability density function and the membership function can yield the quantitative description of how well our expectations are met by our observations.

The combination of probability density function and membership function is achieved through the integration of the fuzzy intersection of the two functions, and it often is not a simple task to integrate the fuzzy intersection due to the complexity that is the result of the fuzzy intersection. Therefore, a methodology based on the Algebra of Logic is used to express the fuzzy intersection and the fuzzy union of the arbitrary functions analytically. These exact analytical expressions are then numerically integrated by the application of Monte Carlo method.

The benchmark tests for rectangular area and both fuzzy intersection and union of two normal distribution functions have been performed. Lastly, the safety index was determined for Core Reactivity Control of YGN 3&4 CFMS using the presented methodology.

2. Methodology

2.1. Quantification of Safety Status

The majority of the plant safety status is expressed by alarm system in conjunction with digital or analog displays. In the current alarm system of nuclear power plant, the measured value of the sensor is continuously compared with the setpoint which is determined by safety analysis or operating experience. And if the measured value exceeds the setpoint, an alarm is initiated to inform the operator. In such alarm system, however, information is inevitably lost during the process of simplifying the complex state of plant into a simple binary state.

Figure 1a shows the information loss of current alarm system, where X-axis and Y-axis represent, respectively, the measured value and alarm status as 0 and 1. The alarm is initiated when the measured value exceeds S which represents setpoint. When the measured value is x_1 or x_2 alarm is not initiated, and when the measured value is x_3 alarm is initiated. Although the alarm is not initiated when the measured value is x_1 or x_2, it is clear that x_2 is severer than x_1, which is closer to setpoint. But this situation cannot be described by current alarm system, and accordingly the information is lost. To minimize the loss of information, a function which represents the degree of danger of the plant is introduced and is shown in Figure 1b by using the concept of membership function of the fuzzy set theory. The difference between Figure 1a and 1b is that degree of danger is represented from 0 to 1, continuously. In Figure 1b, x_1 and x_3 are same status as Figure 1a, which are 0 and 1, respectively, and x_2 represents the degree of danger of the plant by, approximately, 0.3. The loss of information shown in Figure 1a, therefore, can be reduced.

The safety status of the plant can be quantified using this concept because the safety status is opposite concept of alarm status. Figure 1c shows the function which represents the degree of safety which is opposite concept of the degree of danger.

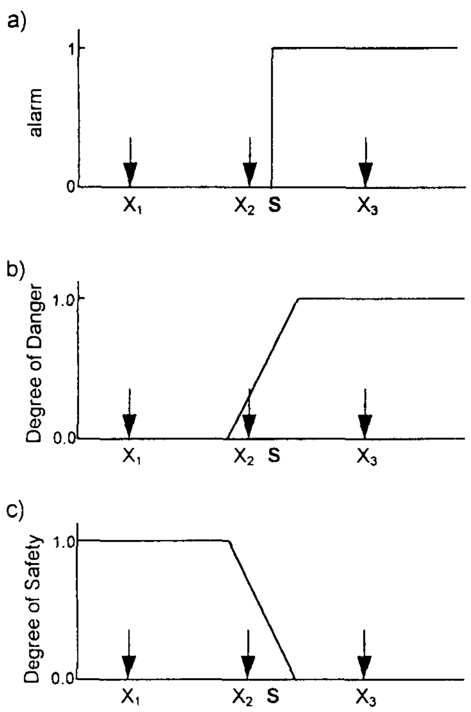

Fig. 1. Information Loss of Alarm System

In fuzzy set theory, the membership function expresses the expected, possible or desired state of the system. Hence, the desired state of the plant parameter is expressed in the form of membership function. Sensor data are acquired as random data in the form of probability density function. The combination of the probability density function of sensor data and the membership function of the plant parameter can yield the quantitative description of how well our expectations are met by our observations. The combination of the probability density function and membership function is achieved through the integration of the fuzzy intersection of the two functions. Based on this concept, the safety index is introduced to quantify the safety status of the nuclear power plant as follows.

$$si_i = \int \mu_i^*(n_1,n_2,\cdots,t) \wedge P_i(n_1,n_2,\cdots,t)\, dn_1 dn_2 \cdots dt \quad (1)$$

$$SI = \sum_{i=1}^{n} \omega_i \cdot si_i \quad (2)$$

where, si_i : Safety Index of Plant Parameter i, $0 \leq si_i \leq 1$

SI : Overall Safety Index, $0 \leq SI \leq 1$

$$\mu_i^* = P_{i,0} \cdot \mu_i \quad (3)$$

μ_i : Membership Function of Plant Parameter i, $0 \leq \mu_i \leq 1$

P_i : Probability Density Function of Plant Parameter i

$P_{i,0}$: Initial Maximum Value of the P_i

ω_i : Weighting Factor of Plant Parameter i, $0 \leq \omega_i \leq 1$

$\wedge$:Logical Intersection Operation

In equation (1), n_1, n_2, , t represent the measured variables of plant parameters i.e., temperature, pressure, time, etc. The weighting factor, ω_i, represents how each plant parameter influences to plant safety. P_i is the probability density function of the measured value, which can be obtained from vendor, operation data or design document and is normal distribution function, generally. The membership function, μ_i, can be represented by any form to represent the wanted or safe status of the plant parameter, and μ_i^* represents optimum shape of the defuzzified μ_i where values ranged between 0 and 1. The relationship of equation (3) has been used for this case. The concept of safety index is shown in Figure 2.

2.2. Analytical Representation of Fuzzy Union and Intersection of Functions

To obtain the safety index which was defined in equations (1) and (2), the integration of fuzzy intersection of a membership function and a probability density function is needed. However, it is not easy to seek a fuzzy intersection because, in general, a membership function and a probability density function have a very complex form. In the following, we seek an exact analytical representation for the fuzzy union and intersection using principles from the Algebra of Logic and Measure Theory. The approach can be classified within the mathematical area of Inverse Analytic Geometry[4].

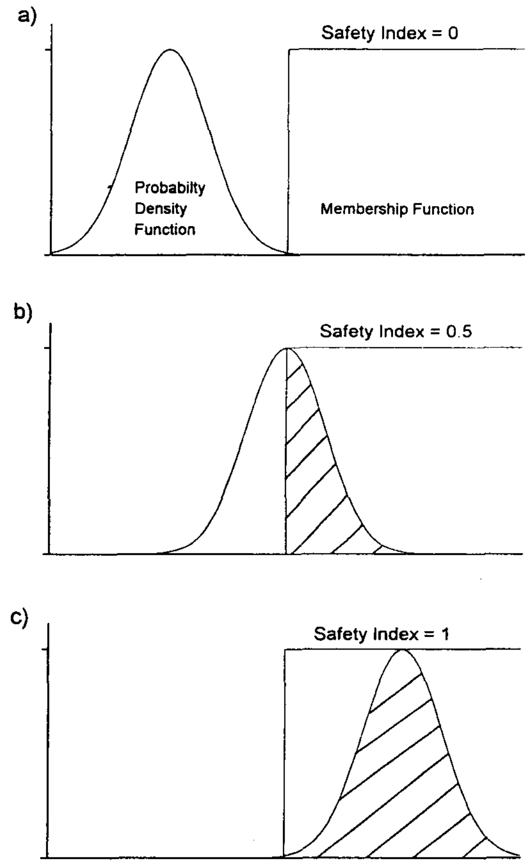

Fig. 2. Fuzzy Intersection of Probability Density Function and Membership Function

Let $F_1(x,y,z)$, $F_2(x,y,z)$,. ,$F_n(x,y,z)$ represent n regions in three dimensional space, such that:

Case 1 : $F_i(x,y,z) \geq 0$, for all $i=1,\cdots,n$

$$\bigvee_{i=1}^{n} F_i = (1/2)^{n-1} \{ M + [\sum_{i=3}^{n} 2^{i-2} F_i] + [\sum_{i=1}^{n-1} | G_i | \} \quad (\geq 0) \tag{4}$$

$$\bigwedge_{i=1}^{n} F_i = (1/2)^{n-1} \{ M + [\sum_{i=3}^{n} 2^{i-2} F_i] - [\sum_{i=1}^{n-1} | G_i | \} \quad (\geq 0) \tag{5}$$

Case 2 : $F_i(x,y,z) \leq 0$, for all $i=1,\cdots,n$

$$\bigvee_{i=1}^{n} F_i = (1/2)^{n-1} \{ M + [\sum_{i=3}^{n} 2^{i-2} F_i] - [\sum_{i=1}^{n-1} | G_i | \} \quad (\leq 0) \tag{6}$$

$$\bigwedge_{i=1}^{n} F_i = (1/2)^{n-1} \{ M + [\sum_{i=3}^{n} 2^{i-2} F_i] + [\sum_{i=1}^{n-1} | G_i | \} \quad (\leq 0) \tag{7}$$

where, $| \; |$: absolute value of the function

$\vee$: logical union operation

$\wedge$: logical intersection operation

$M = F_1 + F_2$

$G_1 = F_1 - F_2$

$G_2 = M - 2F_3 + |G_1|$

$G_n = M - 2^{n-1} F_{n+1} + \sum_{i=1}^{n-1} |G_i| + \sum_{i=3}^{n} 2^{i-2} F_i$

Equations (4) to (7) are conjectures allowing the possibility to express in an analytical way the equations of complicated volumes, surfaces or curves.

2.3. Monte Carlo Method

It is found that the analytical representation found by using equations (4) to (7) normally results in a very complex form of equation. Many times, the normal integration routines are not the most appropriate method to apply since the solution to the equation may not be unique. Therefore, the analytical form of the solution is integrated using the Monte Carlo method to evaluate the exact representation of the fuzzy union or intersection. Hence, the uncertainty arises from the integration routine only not from the representation of the fuzzy union or intersection. However, by adopting other methods, the uncertainty arises due to both the integration as well as the representation of the fuzzy union or intersection itself admitted for evaluation.

A caution of biasing must be taken when applying the Monte Carlo method as an integration scheme [5]. This method can be modified to improve the efficiency of the sampling. This can be achieved with biasing the sampling scheme. However, there are characteristics associated with biasing the sampling scheme. If the sampling scheme is overbiased, it is possible to overshoot the mark and become less efficient than crude sampling. The opposite can happen, if the sampling scheme is unbiased, such that the result depends mostly on infrequent events and low number of observations, its characteristic may not show properly. It is a general characteristic of both cases of biasing that the generated results are, very often, too small. This produces an apparently consistent bias in the results which can be more troublesome than poor confidence intervals in the result.

3. Results

3.1. Benchmark Tests

*The presented methodology of combining prob*ability density function with membership function is applied first to given geometrical shapes. The benchmark tests were performed for the rectangular area (Case 1), the fuzzy intersection of the Gaussian function (Case 2) and the fuzzy union of the Gaussian function (Case 3) given the following functions:

Case 1. Rectangular Area

$x-3\geq 0$, $x-5\leq 0$, $y-3\geq 0$ and $y-5\leq 0$

The ratio of area to sample space is 25 %.

Case 2. Intersection of two Gaussian Functions

$-y+(2\pi)^{-1/2}\cdot \exp(-0.5\cdot(x-42)^2/1^2)\geq 0$

$-y+(2\pi)^{-1/2}\cdot \exp(-0.5\cdot(x-44)^2/1^2)\geq 0$

$y\geq 0$

The ratio of area to sample space is 9.945%.

Case 3. Union of two Gaussian Functions

$y-(2\pi)^{-1/2}\cdot \exp(-0.5\cdot(x\text{-}42)^2/1^2)\leq 0$

$y-(2\pi)^{-1/2}\cdot \exp(-0.5\cdot(x\text{-}44)^2/1^2)\leq 0$

$-y\leq 0$

The ratio of area to sample space is 52.72%.

For above three cases, twenty iterations were done on each cases to show the relative errors and its dependence on the number of samples. These three cases were selected to show that the crude sampling scheme, although may be less efficient than modified scheme, asymptotically approaches the actual values. The results as shown in Figures 3a to 3c indicate that 95% of accuracy required the number of iterations to be about 20000. Three cases represent the situations where the ratio of area to sampling space of 25%, 9.945%, and 52.72%. It appears that the accuracy of Monte Carlo method is highly dependent to the ratio of area to sample space rather than the complexity of a function.

3.2. Quantification of Core Reactivity Control

The safety index was determined for Core Reactivity Control of YGN 3&4 CFMS shown in Figure 4 using the presented methodology as follows.

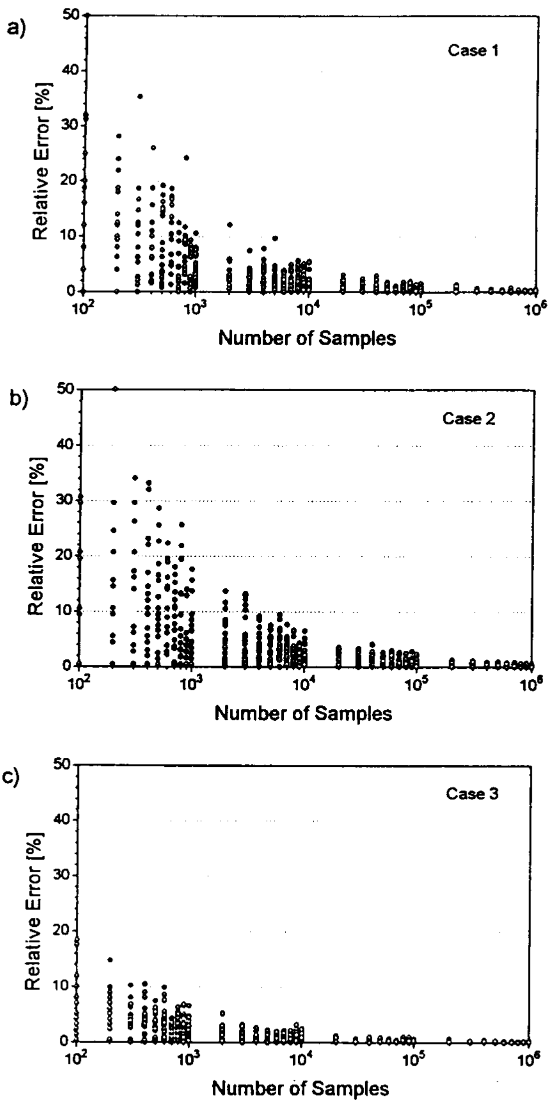

Fig. 3. Distribution of Relative Errors Versus Number of Samples

$$\text{Overall Safety Index} = \frac{1}{3}\,SI_1 + \frac{1}{3}\,SI_2 + \frac{1}{3}\,SI_3 \quad (8)$$

where, SI_1 : Safety Index of High Post Trip Power

$$SI_1 = \frac{1}{2}\,si_1 + \frac{1}{2}\,si_2 \quad (9)$$

Si_1 : Safety Index of Startup Count Rate

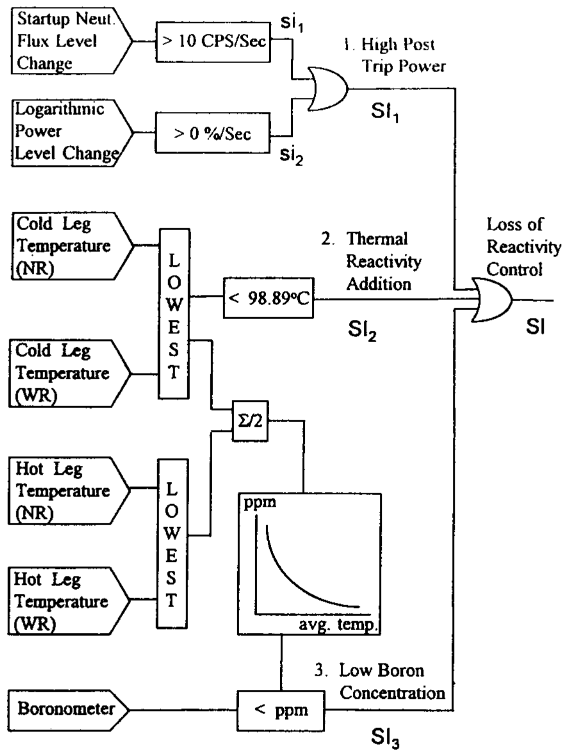

Fig. 4. Core Reactivity Control Alarm Algorithm

Change

Si_2 : Safety Index of Wide Range Power Change

SI_2 : Safety Index of Thermal Reactivity Addition

SI_3 : Safety Index of Low Boron Concentration

The overall safety index of the core reactivity control is defined as equation (8) and composed of safety index of High Post Trip Power, safety index of Thermal Reactivity Addition and safety index of Low Boron Concentration. The weighting factors for three safety indices are assigned to 1/3, each for the purpose of this analysis. However, the appropriate values for these weighting factors can be found by sensitivity analysis. Also, the safety index of the High

Post Trip Power defined as equation (9) is composed of the safety index of Startup Count Rate Change and safety index of Wide Range Power Change, and the weighting factor is assigned to 1/2, respectively.

The membership functions were made based on the YGN 3&4 setpoints. Figure 5 shows the membership functions for Startup Count Rate Change, Wide Range Power Change and RCS Cold Leg Temperature. And the membership function for Boron Concentration is shown in Figure 6. The parameters of the probability density functions which are assumed normal distribution functions were obtained from the results of uncertainty analysis for the sensors [6-9].

While the other parameters are maintained in a steady or safe state, the overall safety index for the variation of Startup Count Rate Change and Wide Range Power Change is shown in Figure 7. As shown in Figure 7, the overall safety index is decreased before the plant parameters reach the setpoints. Therefore, the reactor operator can take appropriate actions before the alarm is initiated if the operator monitors the overall safety index continuously[10].

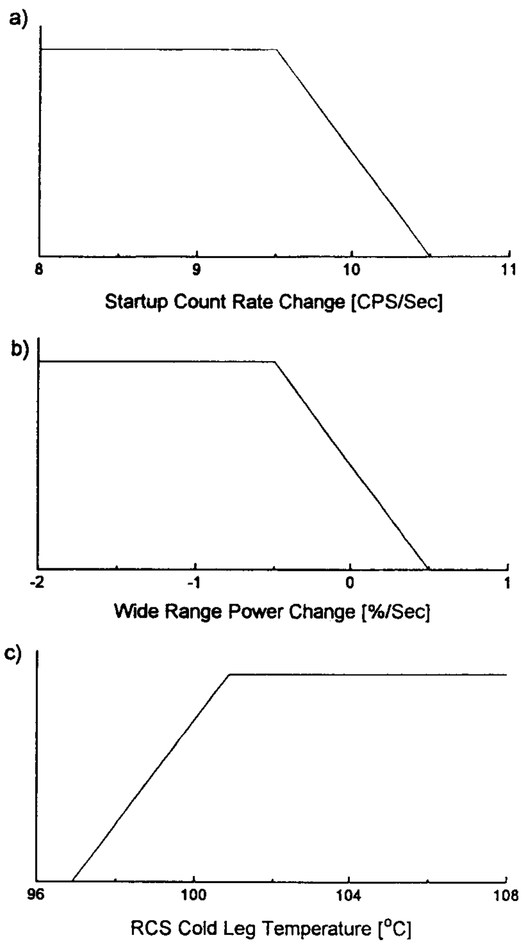

Fig. 5. Membership Functions for Startup Count Rate Change, Wide Range Power Change and RCS Cold Leg Temperature

4. Conclusions and Recommendations

In the process of simplifying the complex state of the plant into a binary state, the information loss is inevitable. To minimize the information loss, the saf-

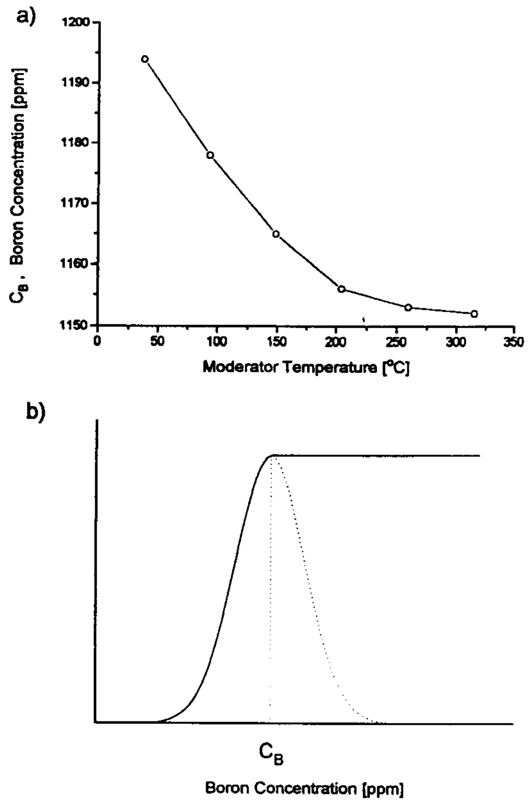

Fig. 6. Setpoint and Membership Function for Boron Concentration

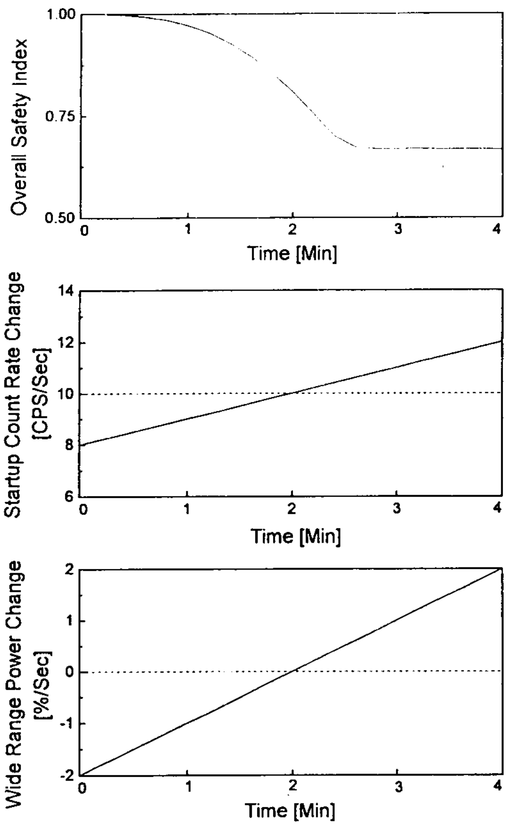

Fig. 7. Changes of Overall Safety Index and Reactor Power Change

ety status of the plant was quantified by synthesizing the measured value of the sensor which is represented as the probability density function and the membership function which describes the desired state of the plant parameter. The safety index was introduced to quantify the plant safety status. The combination of the probability density function and the membership function is done by integrating the fuzzy intersection of them. In this study, the analytical form of the fuzzy intersection was obtained, and then integrated by appling the Monte Carlo method.

The benchmark test was done for the rectangular area and the fuzzy intersection and union of the Gaussian functions. The test results show that the presented methodology of combining probability density function with membership function is resonable. The safety index for the core reactivity control of YGN 3&4 CFMS was obtained by appling the proposed method in this study. The safety index was decreased before the plant parameters reach the setpoints, therefore it means that the reactor operator can recognize the plant safety status and take the appropriate actions before the alarm is initiated.

Because the safety index quantifies the safety status of the plant, it can be applied to the plant operation for improving the plant operability. Instead of evaluating the safety status by monitoring many safety related parameters, the reactor operator can monitor just a few safety indices and take appropriate actions to the direction of increasing the safety index. So it can lighten the burden of the operator.

In order that the safety index quantifies the plant safety status more exactly, the membership functions and weighting factors should describe the plant safety status accurately. These can be obtained from the sensitivity analysis during accident or safety analysis.

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