# Uncertainty Combination method for Reactor Trip System

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## 1. Introduction

A nuclear power plant has a reactor trip system that enables automatic reactor trip when at least one of the important plant variables exceeds predetermined set values. These setpoints of the reactor trip system shall be set to consider the measurement uncertainty of the instrument channels. If the reactor trip setpoints are set too conservatively, an unnecessary reactor trip may occur which reduces the plant's safety and operability. So the measurement uncertainty of the instrument channel should be evaluated appropriately.

## 2. Current Method and Deficiency

### *2.1 Current Method*

The current uncertainty for the reactor trip system setpoints in nuclear power plants complies with the uncertainty combination methodology of IEC 61888[1] and ISA67.04.01[2]. NRC endorsed ISA67.04.01 through RG1.105[3]. The combining formula for uncertainty in IEC is represented by Eq. (1).

$$CU_{IEC} = \sqrt{A^2 + B^2} + C \tag{1}$$

where

A, B : a certain confidence level of uncertainty of the input elements constituting the channel uncertainty, which is random, independent, and has the characteristics of a normal distribution.

C : bias or dependent uncertainty

However, Eq. 1 does not deal with the uncertainties of the input elements which are random and independent but do not have the characteristics of a normal distribution (e.g., a rectangular distribution). To treat non-normally distributed terms ISA 67.04.01 added a new term F as in Eq. 2. Normally distributed uncertainties are combined by the SRSS (Square Root of Sum of Square) method, and non-normally distributed uncertainties are arithmetically combined to the SRSS term.

$$CU_{ISA} = \sqrt{A^2 + B^2 + C^2} + |F| + L - M \tag{2}$$

where

A, B, and C : random, independent, and normally distributed terms with a certain level of confidence

F : non-normally distributed uncertainties with a certain level of confidence and/or biases (unknown sign)

L, M : bias with the known sign

### *2.2 Comparison with Current Method with Monte Carlo Simulation*

The example is a simple additive model.

$$y = x_1 + x_2 + x_3 + x_4 + x_5 \tag{3}$$

The first three input quantities have normal distributions with a standard deviation of 1. The last two input quantities have rectangular distributions with standard deviations of 2 and 10 respectively. Sometimes only lower limits and higher limits are presented instead of mean and standard deviation. In that case, it is reasonable to assume a rectangular distribution[4, 5, 6].

Monte Carlo simulation can give the almost exact combined uncertainty. Monte Carlo simulation has been done written in the Python language and gives the combined uncertainty with a lower 2.5% value of -17.79 and a higher 2.5% value of 17.77. The standard deviation is 10.34.

The combined uncertainty obtained from Eq. 2 with a 95% confidence level is 23.14. This uncertainty is 30% higher than the uncertainty obtained from the Monte Carlo simulation. This means that the current method can't deal with non-normally distributed uncertainties appropriately.

Reference [7] provides a procedure to validate the result calculated by the GUM95 method[4] with the Monte Carlo method. First, $d_{low}$ and $d_{high}$ are calculated using Eq. 4 and Eq.5.

$$d_{low} = |\, y - U(y) - y_{low} \,| \tag{4}$$

$$d_{high} = |\, y + U(y) - y_{high} \,| \tag{5}$$

where y is an expected value of the object to be measured, U(y) is the channel uncertainty calculated by other methods, and $y_{low}$ and $y_{high}$ are 2.5% and 97.5% values calculated by Monte Carlo simulation.

The numerical tolerance of the uncertainty, or the standard deviation, can be obtained by expressing the standard uncertainty as $c \times 10^l$, where c is an integer with a number of digits equal to the number of significant digits of the standard uncertainty and $l$ is an integer. Then the numerical tolerance δ is expressed as:

$$\delta = \frac{1}{2}\, 10^l \tag{6}$$

If $d_{low}$ and $d_{high}$ both are less than the numerical tolerance, then the result is validated and accepted.

Otherwise, it is determined as not validated. Two significant digits from the standard uncertainty is taken and the numerical tolerance turns out to be 0.5. For this case y = 0, $y_{low}$ = -17.79 and $y_{high}$ = 17.77 from the Monte Carlo simulation. $d_{low}$ and $d_{high}$ are 5.35 and 5.37, respectively. These values are greater than the numerical tolerance of 0.5. The uncertainty calculated by the ISA method can not be accepted.

## 3. New Method and Validation of New Method

### *3.1 New Method*

To overcome the deficiency of the ISA67.04.01 method which results in an overestimated result when the non-normally distributed input quantities are dominant, we proposed a modified form of the uncertainty combination method used in IEC61888 as follows:

$$CU_{M-IEC} = \lambda \bullet \sqrt{A^2 + B^2 + C^2 + F_1^2 + F_2^2} \quad (7)$$

where

$\lambda$ : compensation factor which considers the contribution of the rectangular distribution and depends on $r_{RN}$

$r_{RN}$ : ratio of uncertainties of rectangular distributions to those of normal distributions

$$r_{RN} = \frac{\sqrt{F_1^2 + F_2^2}}{\sqrt{A^2 + B^2 + C^2}} \quad (8)$$

A, B, and C: random, independent, and normally distributed terms with a certain level of confidence

$F_i$: rectangularly distributed uncertainty with a certain level of confidence

The combined distribution of normal distribution and rectangular distribution is called RN distribution. The shape of RN distribution depends on the $r_{RN}$ values as shown Fig. 1. As $r_{RN}$ approached to zero, then the RN distribution becomes a normal distribution and that becomes a rectangular distribution as $r_{RN}$ approaches infinity.

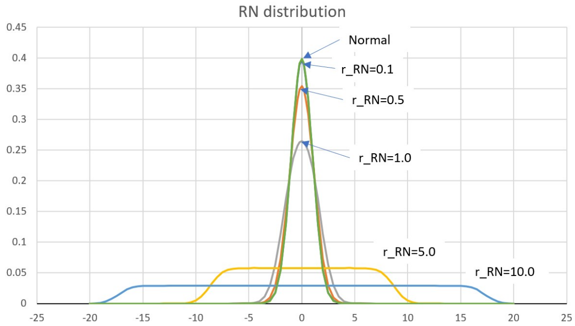


Fig. 1 RN distribution

The compensation factor $\lambda$ is calculated for a set of $r_{RN}$ values by comparing the uncertainty calculated by SRSS term in Eq. 7 and that of obtained from the Monte Carlo simulation. The result is given in Table 1 and Fig. 2.

**Table 1** Compensation factor $\lambda$

| $r_{RN}$ up to value | $\lambda$ | $r_{RN}$ up to value | $\lambda$ |
|---|---|---|---|
| 0.06 | 1.00 | 2.2 | 1.06 |
| 0.2 | 1.01 | 2.6 | 1.05 |
| 0.3 | 1.02 | 3.4 | 1.04 |
| 0.4 | 1.03 | 4.0 | 1.03 |
| 0.5 | 1.04 | 5.4 | 1.02 |
| 0.5 | 1.05 | 10.0 | 1.01 |
| 0.8 | 1.06 | ∞ | 1.00 |
| 1.7 | 1.07 | | |

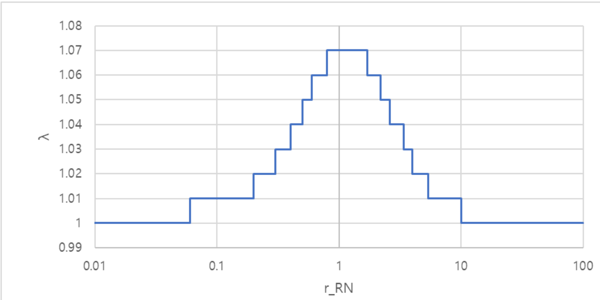


Fig. 2 Compensation factor λ

### *3.2 Validation of New Method*

For the given examples in section 2.2, $r_{RN}$ is calculated to be 1.83 from Eq. (8), and λ corresponding to this value is 1.06 from Table 1. The channel uncertainty is 18.15, which is close to the channel uncertainty -17.79 and + 17.77 calculated by Monte Carlo simulation. $d_{low}$ and $d_{high}$ are 0.26 and 0.38, respectively. These values are smaller than the numerical tolerance of 0.5 and the uncertainty calculated by the new method can be accepted.

## 4. Conclusions

The channel uncertainty calculated using the new method, i.e. modified IEC method, shows good agreement with the Monte Carlo simulation and the numerical tolerance is acceptable. The proposed method could be an alternative method when input elements with the rectangular distribution exist.

## REFERENCES

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