Risk-Informed Comparative Study of I&C Architectures for Research Reactors

Kyungho Jin[1], Rahman Khalil Ur[2], Gyunyoung Heo[1*]

[1]*Kyung Hee University, 1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do,17104, Korea*
[2]*Centre for Nuclear Safety, Pakistan Nuclear Regulatory Authority, Islamabad, 44000, Pakistan*

*Corresponding Author: gheo@khu.ac.kr

The digital I&C system has been gradually introduced into the nuclear facilities due to the obsolescence of analog components and its functional utilities. Though the compactness of system and advancement of functions are the features of digital systems over analog systems, nevertheless it owes a high cost. Therefore, the cost-optimization of digital I&C systems for small-sized reactors (for educational or research purposes) becomes significant considering its high proportion of cost compared to the commercial large-sized Nuclear Power Plants (NPPs). In order to optimize the use of digital components/systems in small-sized reactors, it is essential to develop a various configurations of I&C architectures to find a suitable configuration with respect to the reliability and the cost. I&C architecture design, which can provide reasonably high level of availability, satisfying the safety requirements, and having low design cost, can be termed optimized one. We, authors have published that risk-informed I&C design approach has been applied for design of RPS (Reactor Protection System) of research reactors. In this paper, we have applied this approach for protection system of TRIGA reactor. TRIGA is a typical low-power reactor and the analog RPS of TRIGA consists of BP (Bi-stable Processor), CP (Coincidence Processor), IC (Initiation Circuit) and AC (Actuation Circuit) which is composed of relay. Several I&C architectures were developed to perform the reliability & sensitivity analysis depending on the combinations of channels and components. Bayesian network has been used to analyze the failure probability of I&C architecture configurations based on the failure data in NUREG/CR-6928. The cost of each architecture was also estimated to find a correlation between architecture reliability and cost.

I. INTRODUCTION

There are a number of variables that are measured to monitor operation and status of NPPs during normal operation. In addition, operators have operated NPPs safely through controlling reactor using this information, which is obtained using I&C (Instrumentation and Control) systems of regulating, protection, monitoring and other systems. Recently, the digital components for I&C systems has been gradually introduced into the nuclear facilities due to the obsolescence of analog components and its functional utilities however, to introduce digital components into the facilities have become a major factor in rising its costs. In terms of the digital system, it has the advantage to treat various and huge data generated from plants over traditional analog system.

The functioning of I&C systems of research reactors, which are used for generation of isotopes, education and research, is similar to commercial power plants except for size or capacity. Though the compactness of system and advancement of functions are the features of digital systems over analog systems, nevertheless it owes a high cost. Research reactors are more sensitive to the cost of I&C systems compared to commercial power plants, therefore it is needed to develop optimized design approach that meet the regulatory safety requirement and minimize cost of the systems for research reactors. Rahman and Heo have proposed RI (Risk Index) value which can determine optimized point for design of I&C systems in terms of both of cost and reliability for research reactors (Ref. 1, 2).

In this paper a typical research reactor, TRIGA (Training, Research, Isotopes, General Atomics), was analyzed to optimize both of its cost and reliability based on the proposed method. RPS of TRIGA (Base) was analyzed using failure data and cost information of each component. In addition, comparative RPS architectures, which were composed of only analog components, and RPS architectures with digital BP were formulated to compare with the base RPS architecture. The failure data, which was suggested in NUREG/CR-6928 (Ref. 3), was used to estimate RPS failure probability using Bayesian network (Ref. 4) and the cost for RI value is depending on the number of components because of characteristics of TRIGA RPS. All comparative RPS architectures were simplified to apply the proposed method and the number of components, channel and trip logic was varied to estimate reliability and cost of RPS.

II. RISK-INFORMED DESIGN FOR RESEARCH REACTORS

The holistic risk-informed design procedure, proposed by Rahman and Heo (Ref. 1, 2), for I&C architectures of research reactors is shown in Figure 1. First, a base I&C architecture is configured and various comparative architectures are formulated to compare with the base. Reliability and cost of comparative architectures are analyzed and RI values are calculated to optimize its cost and reliability.

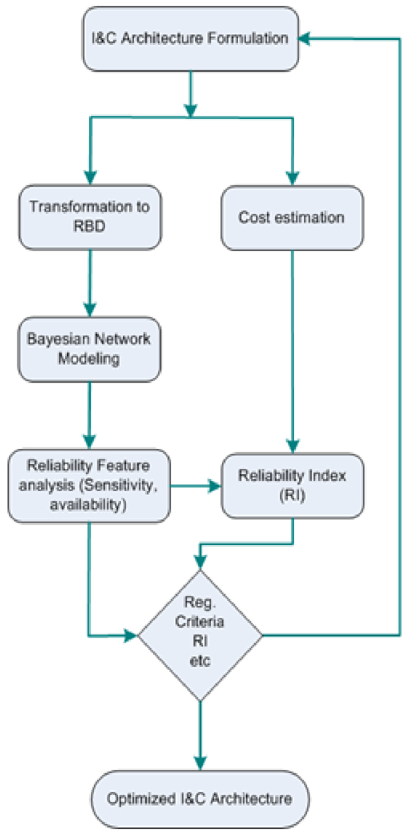

Fig. 1. Procedure for design of risk-informed I&C architectures (Ref. 1)

II.A. Base TRIGA RPS

TRIGA RPS is composed of pressure/temperature sensor, BP (Bi-stable Processor), CP (Coincidence Processor) which generates reactor trip signal for abnormal condition of reactor and IC (Initiation Circuit), AC (Actuation Circuit) which conducts practical reactor trip from the signal of the processor. Two independent channel in TRIGA RPS is designed for redundancy. Simple descriptions of processors and circuits are as follows:

- TT (Temperature Transmitter): Signal required for reactor trip (In this paper temperature transmitter used)
- BP: Comparing the input signal with set point and sending a trip signal to CP when the input signal exceeds the set point
- CP: Comparing the signal from BP and sending an actual trip signal to IC when trip logic is satisfied (1 out of 2)
- IC: Sending a trip signal to AC for practical reactor trip
- AC: Cutting off the current through the control rod for practical reactor trip

A reactor trip signal occurs when trip signal is generated from at least one channel. Control rods are composed of safety, shim, regulating and transient rods. Success criteria of reactor trip is to operate more than 3 rods. In this paper, manual trip and trip reset was excluded for simple design of RPS architectures. Figure 2 shows a simple base TRIGA RPS architecture.

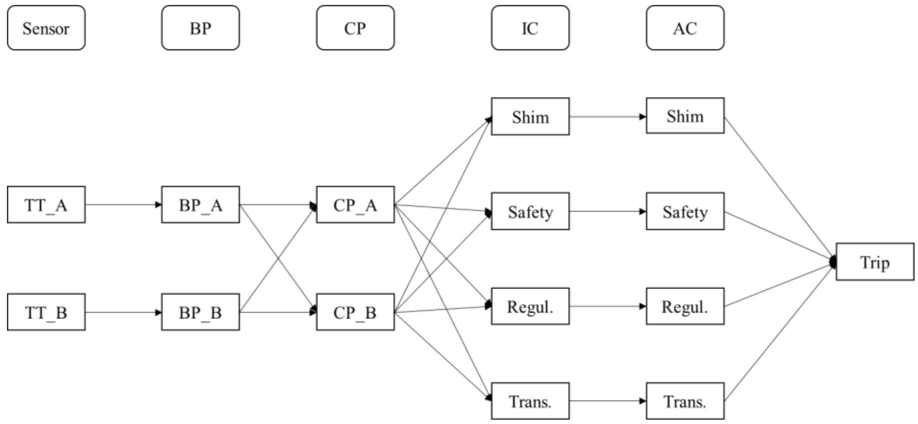

Fig. 2. Basic TRIGA RPS Architectures

It should be noted that all processors and circuits in TRIGA RPS consist of only relays because thermal power of TRIGA is significantly low. The relays used in TRIGA RPS are designed to meet each function of components except for transmitter. Though trip is fail, natural convection is enough for cooling of TRIGA. Thus, the failure rate and cost of the base and comparative architectures of all components is based on data of relay.

II.B. Comparative RPS Architectures

A variety of architectures is constructed by varying the number of channel and trip logic based on the base architecture. Table I shows the number of components depending on the number of channel and trip logic.

TABLE I. Comparative RPS Architectures

	2 channel		**3 channel**		**4 channel**	
Trip logic	2oo4	Base	2oo4	3oo4	2oo4	3oo4
The number of the components						
TT	2		3		4	
BP	2		3		4	
CP	2		3		4	
IC	4		4		4	
AC	4		4		4	

In Table I, 2oo4 (2 out of 4) represents that reactor trip is success when more than two of four control rods successfully operated. 2 channel and base trip logic represents a base TRIGA RPS architecture.

II.C. Failure and Cost Data

IEC (International Electrotechnical Commission) has recommended that failure probability of a protection system (Failure on demand) are advised to have a value of 1E-04 from 1E-05 (Ref. 5). Table II shows the failure rate of each components that were suggested in NUREG/CR-6928 (Ref. 3).

TABLE II. Failure Data in NUREG/CR-6928

Components	Failure mode	Mean value
Temp. Transmitter	Fail To Operate	4.32E-04
BP (Digital)	Fail To Operate	5.44E-04
Relay	Fail To Operate	2.48E-05

Since TRIGA RPS is composed of only relay, failure and cost data of relay are used for Analog BP, CP, IC and AC. TT in general indicates thermocouple, but cost information of thermocouple cannot be obtained during research, thus it was replaced to RTD (Resistance Temperature Detector) data. Table III shows the relative cost information of each component which is commonly used to construct RPS for research reactors. The cost of components except for relay is represented based on a single relay.

TABLE III. Relative Cost Commonly Used

Components	Relative cost
Relay (Analog)	1 (Base)
BP (Digital)	19,000
CP (Analog)	200
CP (Digital)	Not available
IC (Analog)	18
AC (Analog)	12
TT (Analog)	6

It should be noted that TRIGA RPS is composed of only relay not commonly used components. Thus in this paper, the cost of the base and various comparative RPS architecture is depending on the number of relay not above information. However, analog BP was replaced to digital BP to consider effects of digital component on whole systems. It can be seen that the cost of digital BP is much higher than analog BP (relay of TRIGA RPS) and most of analog components have low costs.

III. RESULTS

First, base TRIGA RPS was compared to comparative RPS architectures which had various channel and trip logic with only relay data. Since the cost of the base RPS with only analog components (relay) is depending on the number of relay and the cost of relay is significantly low, cost evaluation of RPS architectures composed of only relay was not conducted. Below figure 3 shows the failure probability of various analog RPS architectures.

The failure probabilities on demand for the RPS composed of only relay are much lower than the criteria suggested in IEC. When reactor size is increased, relay is replaced with circuit breaker. The failure rate of circuit breaker is higher than relay. In other words, all architectures criteria are satisfied because of very low failure rate of the relay. Thus, it is needed to formulate more detail design of RPS architecture and cost information for large size research reactors because of characteristics of TRIGA, that is a significantly small size research reactor.

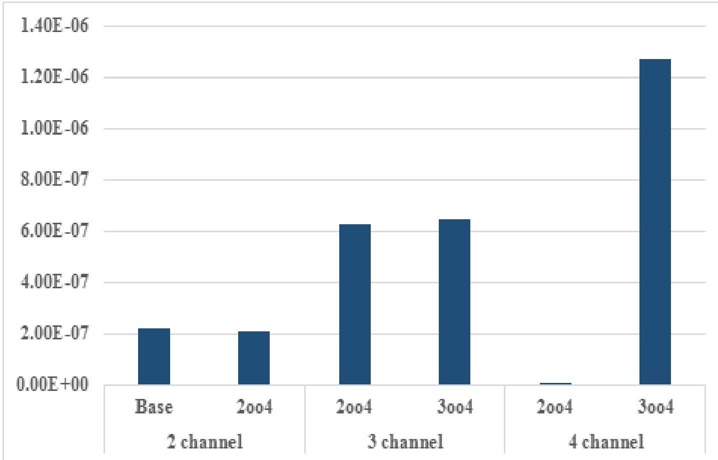

Fig. 3. The failure probability for RPS architectures composed of only relay

Figure 4 shows the failure probability of RPS of TRIGA with digital BP and its cost. Table IV shows the RI values for RPS composed of a digital component to consider the cost of digital BP. Optimized point is determined using RI which can correlates cost and reliability in the form of an index (Ref. 1). RI is formulated as follows:

$$RI_i = \frac{P_i - P_1}{U_i - U_1} \quad (1)$$

Where P_i is an availability of i-th architecture and U_i is a cost of i-th architecture and P_1, U_1 indicates a base architecture. The availability of RPS can be obtained by $(1 - \text{failure probabiltiy})$. It can be determined that the points to be optimized through the ratio of cost and reliability between base architecture and comparative architectures.

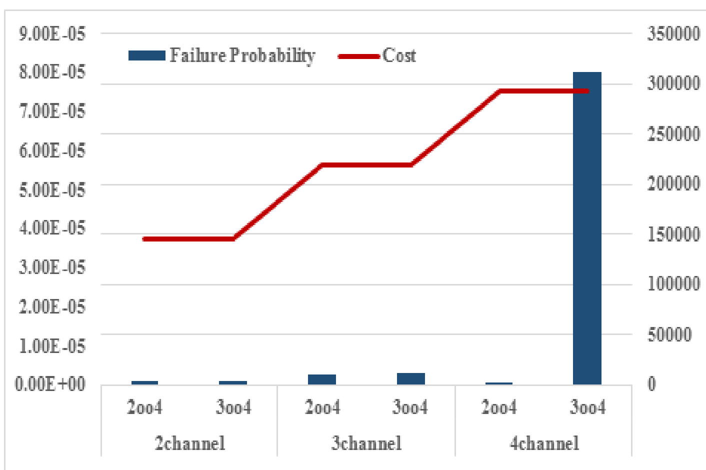

Fig. 4. The failure probability and cost for RPS architectures with digital BP

IEC requirement is satisfied whereas RPS failure probability is increased rather than analog RPS. An architecture, which has 4 channel and 3 out of 4 trip logic, indicates higher failure probability of the RPS. Although requirement is satisfied, this architecture can be eliminated during further analysis because of high failure probability.

TABLE IV. Risk Index (RI) values of RPS architectures with digital BP

Base	2 channel		3 channel		4 channel	
	2oo4	3oo4	2oo4	3oo4	**2oo4**	3oo4
RI	-5.0 E-12	-5.1 E-12	-1.2 E-11	-1.2 E-11	**7.45 E-13**	-2.7 E-10

When only BP is replaced by digital component on the TRIGA RPS, the architecture, which has 4 channel and 2 out of 4 trip logic, indicates the lower failure probability over cost. While the others cost is increased depending on the number of components, failure probability of the RPS is also increased (Negative values). Thus it can be seen that the architecture for 4 channel and 2 out of 4 trip logic is the most efficient architecture.

IV. CONCLUSIONS

In this paper, cost and failure data of TRIGA RPS was used to evaluate RI values to meet regulatory requirement and to ensure competitive cost of I&C architectures for research reactors based on proposed method. All architectures met the IEC criteria because of low failure rate of relay and characteristic of the simplified architectures. In addition, RPS with digital BP also met the IEC criteria and its cost was evaluated to consider reliability and cost at a time. It can be seen that cost and reliability of I&C systems can be optimized through RI values. Since TRIGA has significantly low thermal power, thus more detail design of the architecture and cost information is needed to evaluate more complex and large capacity research reactors.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea Government (MSIP) (Grant Number: NRF-2011-0031773)

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