STUDY ON OPTIMIZATION OF I&C ARCHITECTURE FOR RESEARCH REACTORS USING BAYESIAN NETWORKS

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ABSTRACT
The optimization in terms of redundancy of modules and components in Instrumentation and Control (I&C) architecture is based on cost and availability assuming regulatory requirements are satisfied. The motive of this study is to find an optimized I&C architecture, either in hybrid formation, fully digital or analog, with respect to system availability and relative cost of architecture. The cost of research reactors I&C systems is prone to have effect on marketing competitiveness. As a demonstrative example, the reactor protection system of research reactors is selected. The four cases with different architecture formation were developed with single & double redundancy of bi-stable modules, coincidence processor module, and safety or protection circuit actuation logic. The architecture configurations are transformed to reliability block diagram (RBD) based on logical operation and function of modules. A Bayesian Network (BN) model is constructed from RBD to assess availability. The cost estimation was proposed and reliability cost index RI was suggested.

1. Introduction
This research was performed for reliability analysis and cost estimation of (I&C) architecture of a reactor protection system, particularly installed in research reactors. This effort would be extended for standardization of such architecture based on the cost of architecture per unit power or some other index for research reactors. The level of reliability, which would be sufficient for protection, control, and monitoring systems in case of low power research reactors, should be found out. Architecture meeting this level of reliability should fulfill all the regulatory requirements as well as operational demands with optimized cost of construction. The need for this research was fondled to meet the demand for low power research reactor by educational and research institute, which is increasing steadily.

Research reactors are categorized into two broad categories, Low power research reactors and medium to high power research reactors. According to IAEA TECDOC-1234, research reactors with 0.250-2.0 MW power rating or 2.5-10 x 10^{11} n/cm^2.s flux are termed low power reactor. Research reactors operating between the range of 2-10 MW power rating or 0.1-10 x 10^{13} n/cm^2.s are considered as medium to high power research reactors [1]. Multipurpose research reactors, bases on other standards (IAEA NP-T-5.1), operating between the ranges of power few hundred KW to 10 MW are also termed as low power research reactor [2, 3]. It is important to focus on optimization between cost and reliability. as the system availability does not enhance very much as compared to increase of cost after certain level of reliability. It is also proposed that required level of reliability may also be obtained with hybrid (analog & digital) architecture with reduced cost.

The purpose of this research, in this article, was to identify a configuration of architecture which gives highest availability with maintaining low cost of manufacturing. In this regard, four configurations of a single channel of RPS are formulated in the current article and Bayesian network models were developed to get the unavailability. The cost estimation based on the discretized concept for I&C components is also described in the section 3 under reliability and cost optimization heading.

2. System I&C Architecture
Instrumentation and Control (I&C) systems play direct role in controlling, protecting and monitoring unit operation. Reactor Protection System (RPS) inserts the reactor trip signal shutdown control rods to shut down the system, when operating parameters passes the set points.

Architecture of RPS consists of field sensors, Bi-stable Processors (BP), coincidence logic, and circuit breakers to release control rods. The signals generated by the sensors are converted to a pulse or digital volt and then these are compared with set points in Bi-stable Processor (BP). BP sends signal to Coincidence Processor (CP) after assessment, if it is 1. CP initiates the trip output if the 2 out of 3 (2oo3) or 3 out of 4 (3oo4) coincidence logic is met.

Four RPS I&C channel architecture configurations were developed for this study and transformed to Reliability Block Diagram (RBD) for modeling ease in Bayesian network, as shown in figure 1. architecture 1, a baseline composition for comparison purpose, consists of a single bi-stable processor BP_A and single coincidence processor CP_A and circuit breakers to trip with 2/3 logic. This configuration is very basic for a channel and has no inter-channel redundancy. Inter-channel redundancy means redundant modules within a channel whereas intra-channel redundancy is based on number of channels. In architecture 2, redundancy is added in bi-stable processors to evaluate the impact on single channel. In order to observe the sensitivity of CP module on single channel failure, coincidence processors is added in the channel for case 3. Architecture 3 configuration consists of a bi-stable processor BP_A, redundant pair of CP processors CP_A1 & CP-A2 and circuit breakers to trip with 2/3 logic. Architecture with inter-channel redundancy of BP &CP modules is depicted in (4) of figure 1.

RBD of proposed I&C architecture configurations was converted to BN models preserving all the functions and logics of system [4]. BN models, as shown in figure 2, show the propagation of failure from transmitter & Sensor to circuit breaker actuation. Two failure states for each component are considered in this study, which are 0 and 1. State 0 represents the failure state and 1 represents the perfect is representing a node and Node Probability Table (NPT) is prepared for every node based on operational logic and failure data [5, 6].

2.1. I&C Architecture Analysis

Probabilistic availability analysis of RPS I&C architecture was performed using Bayesian Network. BN result for channel (CHNL) states was obtained for four configurations and results for failure (0) and perfect (1) states are presented in table 1. The probability of failure P(x=0|λ) and as well as probability of success P(x=1|λ) of channel (CHNL) are parameter of interest, which are also called Unavailability and availability of I&C architecture.

Architecture	CHNL	Unavailability (P(x=0|λ))	Availability (P(x=1|λ))
1	(1BP, 1CP)	1.9751E-4	9.998E-01
2	(2BP, 1CP)	3.1525E-4	9.9968E-01
3	(1BP, 2CP)	3.9701E-5	9.9996E-01
4	(2BP, 2CP)	3.1596E-7	0.9999996

Table 1: Availability analysis of I&C architecture configurations using BN models

3. Reliability and Cost Optimization

Reliability features like Unavailability and availability for four cases of architecture can be observed in fig 3 whereas cost analysis is discussed in detail in current heading. In order to estimate the cost of architecture, cost can be discretized into the unit cost for each component and number of components. Cost estimation formula can be proposed in the form of equation (1).

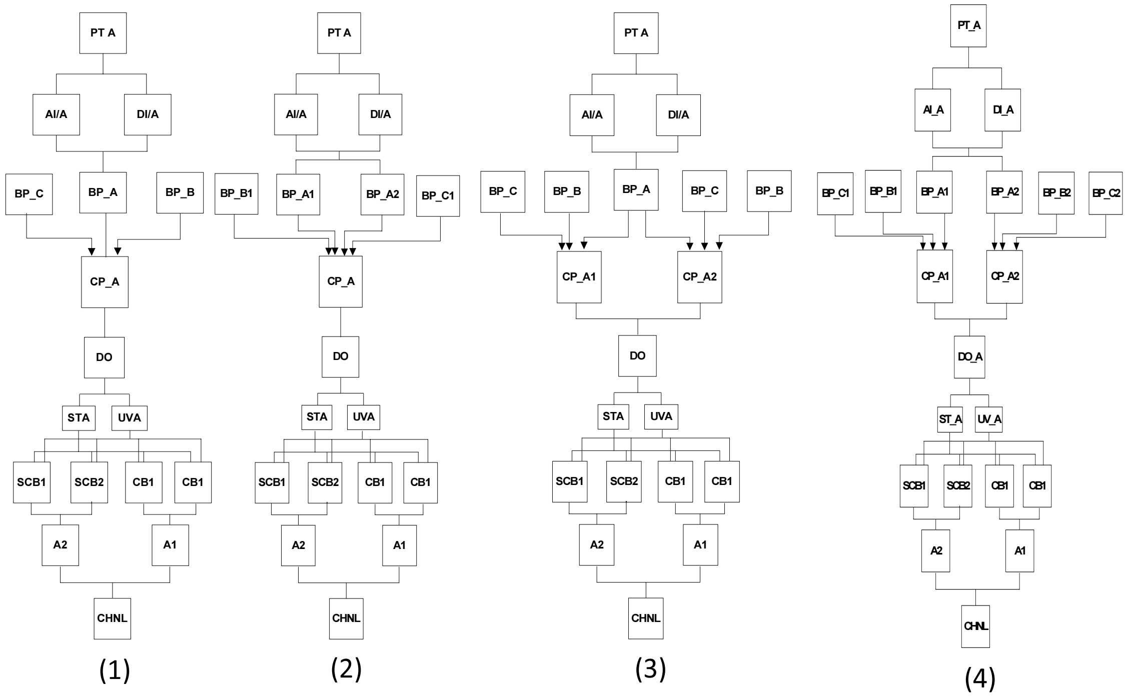

Fig 1. Reliability Block Diagrams of I&C architectures

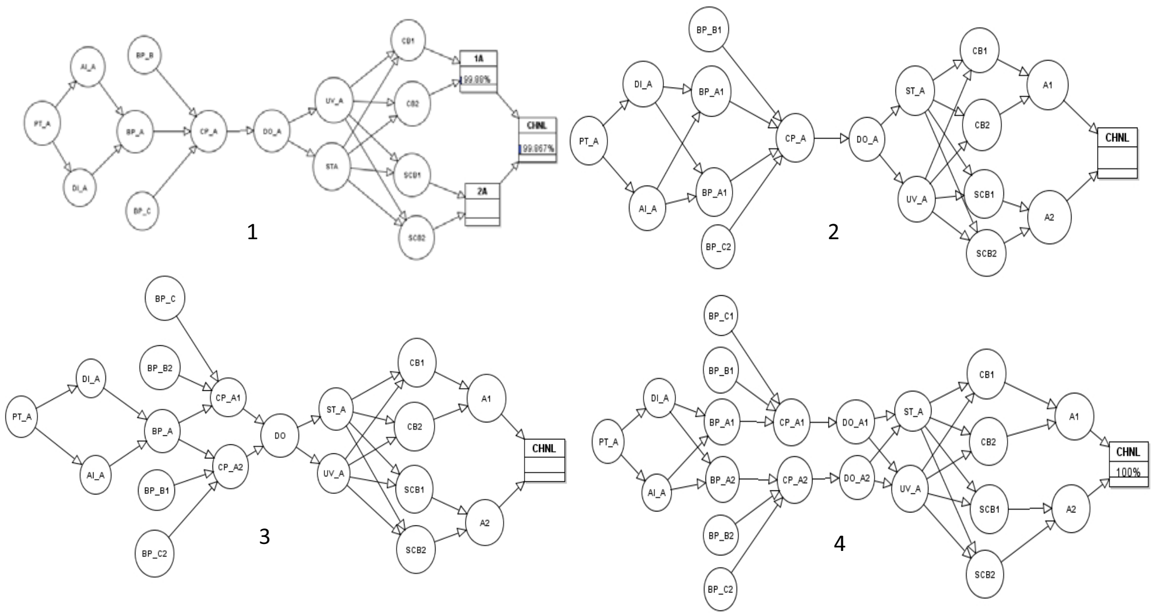

Fig 2. Bayesian network model of I&C architectures

The equation (1) gives cost as the multiple of X and multiple is product of number of components and its unit cost, where X is an arbitrary unit.

$$U_j = \sum_i u_i . n_i . X \qquad (1)$$

Where as U_j is the cost of j^{th} architecture and j varies from 1 to 4. The component unit cost u_i is cost for i^{th} component & modules of Pressure/level Transmitter (PT), Analog Input (AI), Digital Input (DI), Bi-stable Processor (PB), Coincidence Processor (CP), Digital Output (DO), Shunt Circuit (ST), Under Voltage circuitry (UV). The signal/relay finally activates actuation through Circuit Breaker (CB) and secondary circuit breaker (SCB).

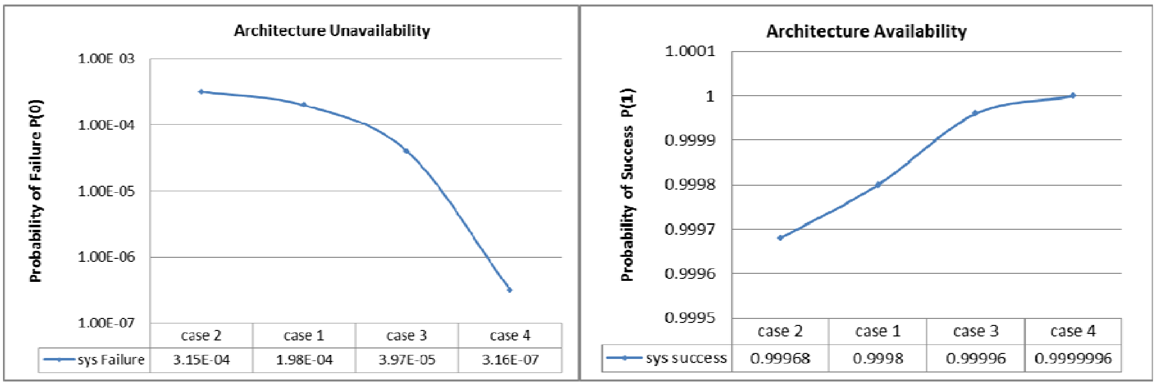

Fig 3. Bayesian Network model of I&C architecture (1) (baseline), (2), (3) and (4)

Number of ith components in architecture is given by ni. The cost is predicted based on formula mentioned in equation 3 and is described in table 2 for architecture 1, 2, 3 and 4. The costs of architecture 1, 2, 3 and 4 were estimated 8.5X, 10X, 10X and 12.5X respectively.

In order to optimize the reliability and cost, system availability, unavailability and cost for four configurations are plotted in the fig 4. The unavailability of system decreases from 1.9751E-4 to 3.1596E-7 for architecture 1 to architecture 4 and availability increases from 9.998E-01 to 0.9999996 (nearly 1). The comparison of architecture cost and unavailability is also depicted.

Components	**Unit price (u*X)**	**Architecture Composition & cost (U=u_i*n_i*X)**			
		1	**2**	**3**	**4**
PT	**0.5**	**0.5*1**	**0.5*1**	**0.5*1**	**0.5*1**
DI	**0.5**	**0.5*1**	**0.5*1**	**0.5*1**	**0.5*1**
AI	**0.5**	**0.5*1**	**0.5*1**	**0.5*1**	**0.5*1**
BP	**1.5**	**0.5*1**	**0.5*2**	**0.5*1**	**0.5*2**
CP	**1.5**	**0.5*1**	**0.5*1**	**0.5*2**	**0.5*2**
DO	**1**	**0.5*1**	**0.5*1**	**0.5*1**	**0.5*2**
ST	**0.5**	**0.5*1**	**0.5*1**	**0.5*1**	**0.5*1**
UV	**0.5**	**0.5*1**	**0.5*1**	**0.5*1**	**0.5*1**
CB	**0.5**	**0.5*2**	**0.5*2**	**0.5*2**	**0.5*2**
SCB	**0.5**	**0.5*2**	**0.5*2**	**0.5*2**	**0.5*2**
$\sum U$		**8.5*X**	**10*X**	**10*X**	**12.5*X**

Table 2: Cost estimation of I&C architecture configurations (1), (2), (3) and (4)

The physical significance can be realized in terms of cost saving. Architecture cost increases from 8.5X to 12.5X and if we consider an arbitrary unit as 100 US dollar, then cost increases by (4X) or 400USD. A reliability index RI can be calculated by equation 2, which will show the increase of reliability per unit of cost. The architecture availability increases at the rate of 4.99E-05 per X unit of cost.

$$RI = \frac{P_n(X=1\|\lambda) - P_1(X=1\|\lambda)}{U_n - U_1} \qquad (2)$$

4. Conclusions and Recommendations

The study was performed to get the cost optimized results in terms of architecture availability. Bayesian network models for four configurations were developed to get the availability analysis and cost estimation model was proposed for the architecture configurations. It was found that reliability can be enhanced at the rate of 5E-05 per X unit of cost.

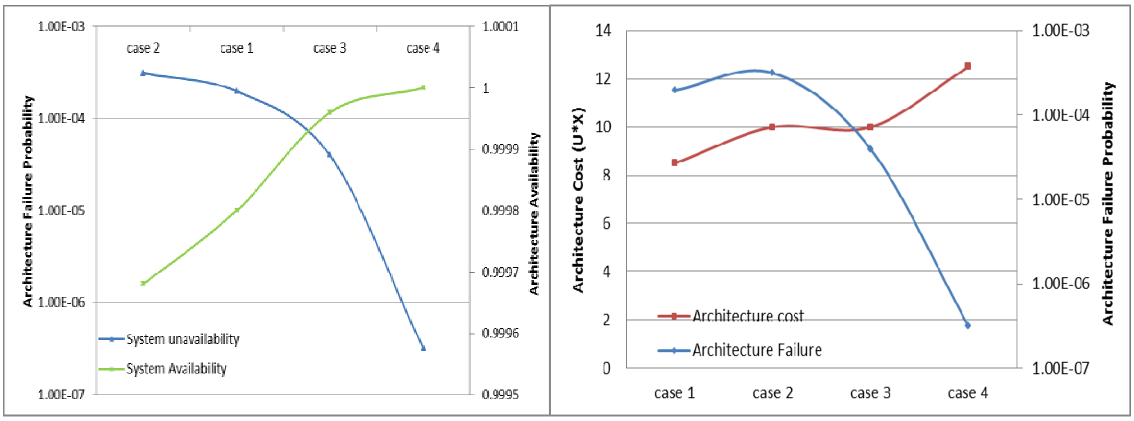

Fig 4. Comparison of cost and reliability features of I&C architectures

If we need to recommend and conclude the architecture configurations based on the reliability only, then we can say that architecture configuration 4 can be designed for the research reactor because it has a very high availability of 0.9999996. On the other, the boundary conditions and constraints on the level of availability should be applied to find the optimized architecture. If we apply a criteria that single channel availability of the order of 1.0E-05 would be sufficient then cost can lead towards decision of architecture. Keep the current scenario in perspective, architecture configuration 3 cane be suggested for research reactor I&C systems, because its cost varies from 10-11 X units while it has availability 0.99996 (unavailability 3.97E-05 per demand).

In future work, this analysis will be continued to find or develop a criteria that what level of reliability would be sufficient. Efforts would be made to make the standardized architecture for research reactors. Use of hybrid architecture consisting of digital & analog component and redundancy would be remedy for prominent failures.

5 References

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