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Evaluation of Periodic Test Frequency for RPS Based on Risk-Benefit

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1. Introduction

The reactor protection system (RPS) of a nuclear power plant (NPP) is employed to detect abnormal (hazardous) condition of the plant and perform automatic safe shutdown of a nuclear reactor. Preventive maintenance of RPS is performed during refueling shutdown period, and then RPS is tested periodically to indentify unrevealed failure of the components between two refueling shutdown of the plant. The RPS could fail in two modes: dangerous failure and safe failure [1]. Failure of a protection system component can remain undetected and interrupt the system to generate reactor trip signal. This incident is known as dangerous failure. On the other hand, a safe failure generates reactor trip signal within the normal range of plant process parameters, which is known as spurious trip of reactor. Human error during surveillance test of RPS can cause spurious trip of the plant [2]. Spurious trip is unexpected because it causes financial loss. Both modes of failure could occur due to random hardware failure as well as maintenance human error. We developed models for RPS to study both of the failure modes. Traditionally, risk analysis is performed without explicit modeling of human error explicitly [2]. Human reliability research mainly focuses upon the control room crew performance for post initiating events [3]. But, the system fails due to human failure during maintenance in addition to random hardware failure of a component. Thus, inclusion of maintenance human error is necessary for a better risk analysis for a safety critical system in NPPs. Risk analysis and spurious trip assessment for RPS were performed employing our models which have been presented in reference paper [4, 5]. This paper focuses how the periodic tests of RPS influences the RPS unavailability and the spurious trip rate of reactor. Our study can help the utilities as well as regulators to determine the optimal surveillance test frequency for a RPS.

2. RPS unavailability estimation

There appears to perform a number of studies to address periodic test and repair errors to estimate unavailability, but those analytical methods are found to be so generic and do not reflect actual maintenance procedures in nuclear power plants [4]. To overcome the shortcomings, a new model was developed which estimates more accurately the component unreliability caused by random hardware failure and human errors in refueling maintenance, periodic surveillance test and repair tasks in a NPP. The estimated average failure probability of each RPS component is used for independent basic event in the fault-tree model for RPS.

The likelihood of the basic events are estimated based on the human error chances in refueling maintenance, periodic tests and repair of safety critical components in NPP. The repetition of the errors in test and maintenance are also considered. Probability of repeating an error is low; however, it might occur in periodical tests causing the component unavailable for a number of cycles of periodic maintenance. Human error probability during periodic maintenance can be quantified by eq. (1) [4] as follows:

$$\varphi = q_{pt} + (1 - q_{pt})q_{pm} \qquad (1)$$

Considering a combined effect of hardware failure and human error, the instantaneous unavailability in the i^{th} $(i > 1)$ interval of operation $(t_{is} < t < t_{ie})$ is expressed by eq. (2) [4]:

$$Q_i(t) = [Q_{i-1}(t_{(i-1)e}) \times \varphi] + \{1 - [Q_{i-1}(t_{(i-1)e}) \times \varphi]\}q_{rd}(t) \qquad (2)$$

$Q_{i-1}(t_{(i-1)e})$ is the probability that the component is in fail state at the end of $(i\text{-}1)^{th}$ interval, and $q_{rd}(t)$ is the hardware failure probability for $0<t<\tau$ (or $i_s < t < t_e$)

A monthly periodic maintenance is performed in a refueling cycle of 18 months period for Korean standard nuclear power plant (OPR-1000). The average unavailability of a component over the time period between two refueling shutdown (T) is estimated based on eq. (3) [4].

$$Q_{avg} = \frac{1}{T}\left\{\sum_{i=1}^{n}\int_{is}^{ie} Q_i(t)\,dt + \sum_{i=1}^{n-1}\tau_{r(i)}\right\} \qquad (3)$$

2.1 Variation of RPS availability with the change of surveillance test frequency

The influence of periodic surveillance tests on RPS unavailability was analyzed. Component unavailability was estimated based on maintenance human error probability in addition to random hardware failure rate. For this study, human error probability 0.002 and 0.001 were assumed to be in refueling maintenance and periodic surveillance tests, respectively. The data for periodically repairable components in the fault-tree are varied to estimate RPS unavailability at different test frequencies. The FTA shows that the RPS average unavailability in Case-2 decreases when periodic surveillance test frequency increases. It reaches to almost a steady level at a high periodic tests frequency which is shown in Fig. 1.

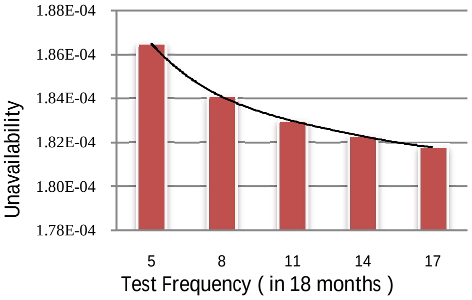

Fig. 1. Change of RPS unavailability with periodic test frequency (maintenance errors considered)

3. Reactor spurious trip estimation

Spurious trip model for process industries was developed which estimates the spurious trip frequency of a process industry [6]. In nuclear power plant, reactor protection system is very complex and different from the protection system of process industries. Human error during surveillance test of RPS generates reactor spurious trip [2]. We developed spurious trip model for reactor protection system, which has been addressed in reference paper [5]. In RPS, LCL Processors get input signal from Bistable Processors and work based on 2oo4 logic configuration employed in each LCL processor. The STR generated by LCL output module is estimated based on eq. (4) [5]:

$$STR_{2oo4} = P_2\Lambda_1 + P_1\Lambda_2 + P_3\Lambda_4 + P_4\Lambda_3 + P_1\Lambda_4 + P_4\Lambda_1 + P_2\Lambda_3 + P_3\Lambda_2 + P_2\Lambda_4 + P_4\Lambda_2 + P_1\Lambda_3 + P_3\Lambda_1 \text{.....(4)}$$

The LCL Output Modules in each channel are connected in such a way that spurious trip rate in each channel is generated by selective 2oo4 (selective two-out-of-four) coincidence logic configuration. STR for a channel is derived by eq. (5) [5]:

$$STR_{S2oo4} = P_2\Lambda_1 + P_1\Lambda_2 + P_3\Lambda_4 + P_4\Lambda_3 + P_1\Lambda_4 + P_4\Lambda_1 + P_2\Lambda_3 + P_3\Lambda_2 \text{.....(5)}$$

P_2 is the failure probability of component-2 in the mean *down-period* before restoration of component-1, which can be estimated for a combined constant failure rate (Λ_2) of component-2 by eq. (6) [5, 6]:

$$P_2 = \int_{t_1}^{t_2} \Lambda_2 e^{-\Lambda_2 t} dt \approx \Lambda_2 (t_2 - t_1) \text{........(6)}$$

Similarly, P_1, the failure probability of component-1 in before restoration of component-2 is estimated for a constant failure rate of Λ_1.

3.1 Influence of erroneous surveillance test on reactor spurious trip rate

Spurious trip rate for RPS component failure has been estimated with consideration of maintenance human error. Spurious trip rate varies with human error probability and frequency of periodic surveillance tests. We performed case studies to observe the influence of RPS surveillance test frequency for certain level of maintenance human errors. Human error probability 0.002 and 0.001 were assumed to be in refueling maintenance and periodic surveillance tests, respectively for our case studies. The variation of STR for different test frequency of RPS has been shown in Fig. 2.

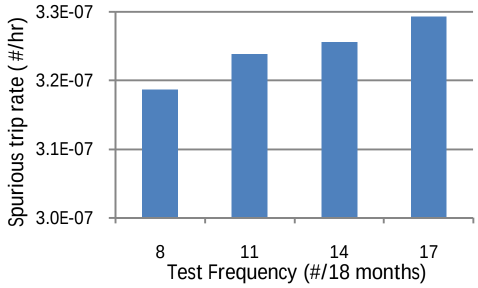

Fig. 2. Variation of reactor spurious trip rate with the change of periodic test frequency considering maintenance errors

4. Conclusion

The study shows the maintenance human error significantly influences the RPS unavailability and reactor spurious trip rate. The reactor STR proportionally changes with the variation of maintenance human error probability, frequency of periodic surveillance tests, and time delay to restore a component. In contrast, RPS unavailability decreases with increasing the frequency of RPS surveillance tests. The periodic test frequency of a reactor protection system can be optimized analyzing the trade-off between RPS unavailability, spurious trip rate, and cost of periodic test. Human error is unavoidable, but efficient maintenance policy and support for the maintenance team reduces the chances of maintenance human errors and the mean restoration time of a component after a failure in a plant.

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