ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOMS030

EVENT TREE MODEL FOR SAFETY RELIABILITY ANALYSIS OF HIGH ENERGY ELECTRON 1.2 GeV RADIATION MONITORING SYSTEM DESIGN*

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Abstract

The SPS Radiation Monitoring System II (SPSRMS-II) has been designed to measure the ionizing radiation which is generated from the high-energy electron 1.2 GeV. SPSRMS-II design shall be performed to assure an adequate performance system to prevent the radiation exposure of workers and the public in the synchrotron facility. The research purpose is to evaluate the frequency of failure of real-time radiation monitoring system design that might be happened from the abnormal case which is unable to transfer the important radiation dose continuously. An Event Tree Analysis (ETA) had been approached to evaluate the safety reliability of the SPSRMS-II which is a method of deducing possibilities and outcomes in chronological order. The chance of unfavourable consequences that can cause harm and result from the chosen initiating event has been determined using this method. The scenario results showed that reliability was increased from 99.9197%±19.5921% to 99.9217%±19.5928% (95% confidential level) after adding redundancy in all the devices. The reliability assessment results of SPSRMS-II are presented.

INTRODUCTION

High electron energy 1.2 GeV provides radiation from infrared (IR) to low-energy X-rays for various user programs. It comprises a 40-MeV linac, a 1.2 GeV booster, a 1.2 GeV storage ring, and a transport line connecting the booster and the storage ring [1]. The bremsstrahlung of runaway electrons driven by a strong electric field in the environment produces X-rays, gamma-rays, and neutron radiation in a synchrotron facility [2]. For detecting and measuring radiation, a range of equipment are determined.

For each hazard scenario, a Safety Instrumented Function (SIF) is developed to first recognize the need and then act to get the system to a safe state. The level of risk reduction that a SIF is required to provide is defined by the Safety Integrity Level (SIL). SIF provides SIL, which represents the degree of risk reduction. The appropriate SIL is critical for ensuring the desired level of safety while designing a SIF [3]. A higher SIL level typically means a more sophisticated system with greater installation and maintenance expenses [4]. However, the study of SIF and SIL for high-energy electron facilities was very limited. Researchers have recently proposed the ETA technique as one of the quantitative risk management techniques; however, practical applications of ETA to the risk management of high-energy electrons of 1.2 GeV in this study remain limited.

This study will undertake a preliminary investigation of the linked instrument in radiation detection and measurements and safety reliability analysis of high-energy electron 1.2 GeV radiation monitoring system design using the event tree model to evaluate the frequency of failure per year, the probability of failure, and the reliability. The results of this study provide physical insight into the complex system of radiation monitoring of the proposed design.

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METHODOLOGY

Risk Analysis

A checklist technique can be used to verify what the most potential risk is. The historical data was used to evaluate it at the beginning stage.

Mean Time to Failure (MTTF)

Mean Time to Failure (MTTF) measures the reliability of non-repairable items and equals the meantime expected until the first failure of a component, assembly, or system. First, the total work of the instrument was calculated using Eq. (1) follows [5]:

$$\text{Total work} = \text{Total workday x Total work hour} \quad (1)$$

After that, Eq. (2) was used to calculate MTTF.

$$\text{MTTF} = \text{Total work / Total unit of instrument(s)} \quad (2)$$

Failure Rate

In the calculations of reliability engineering, the failure rate (λ; Lambda) is considered to represent the expected failure intensity assuming the component is fully operational in its initial condition. The formula [Eq. (3)] is given for repairable and non-repairable systems respectively as follows [5]:

$$\text{Failure rate per unit } (\lambda) = 1 / \text{MTTF} \quad (3)$$

Reliability

The reliability of a system follows an exponential failure law, which indicates that as the period considered for reliability calculations passes, the reliability of the system decreases. Eq. (4) was used to calculate the reliability [5].

$$\text{Reliability } (R(t)_1) = e^{-\lambda t} \quad (4)$$

Then, the failure probability of the unit instrument was calculated using Eq. (5) [5].

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$$\text{Failure } (F(t)) = 1 - R(t) \quad (5)$$

Due to some improvements, there will be redundancies for certain instruments. The reliability of redundant instruments was calculated using Eq. (6) [5].

$$\text{Reliability (t) with redundant} = (R_1+R_2) / (R_1 x R_2) \quad (6)$$

Where R_1 and R_2 are the reliability of the first and second instruments, respectively, and n is the total unit of instrument.

Event Tree Analysis (ETA)

The ETA may be used to identify all possible accident situations and sequences in a complicated system by evaluating all relevant unpredicted incidents [6]. Event trees can be contracted in a variety of ways. They usually use binary logic gates, which have only two alternatives such as success/fail, yes/no, and on/off. They usually begin on the left with the beginning event and work their way to the right, branching out as they go.

Safety Instrumented Function (SIF) and Safety Integrity Level (SIL)

Safety Integrity Level (SIL) is a measure of the SIF's performance, in terms of Average Probability of Failure on Demand (PFDavg) [7]. Safety integrity levels are related to the average probability of failure per year (see Table 1).

Table 1: Safety Integrity Level and PFDavg [8]

SIL	PFDavg
SIL-4	$10^{-5} \leq PFD < 10^{-4}$
SIL-3	$10^{-4} \leq PFD < 10^{-3}$
SIL-2	$10^{-3} \leq PFD < 10^{-2}$
SIL-1	$10^{-2} \leq PFD < 10^{-1}$

RESULT AND DISCUSSION

Identifying the Initial Events

Initial events have been selected based on historical data from the high-energy electron 1.2 GeV facility from 2012 to 2022 data. By evaluating the historical data of the facility, the electrical problem would lead to the performance of the radiation monitoring instrument during operating time.

Safety Function Selection

The current condition of the Radiation Area Monitoring System (RAMS) in the SPSs facility provides exposure data in line graph, however; it is not clear enough for users and workers to read. Therefore, this study will develop a new design of the line graph to a digital number and improve the user-friendly interface display. The new design of radiation monitoring systems was called Siam Photon Source Radiation Monitoring System-II (SPSRMS-II).

EPICS IOCs proposed in SPSRMS-II consists of set software components and tools that Application Developers use to create a control system [9]. All the data of exposure rates will be collected and reported directly both in graphical and digital numbers in GUI. The utilization of EPICS IOCs was successfully implemented in 3 GeV synchrotron radiation in Taiwan studied by Cheng et al (2013) [10]. The SPSRMS-II design was presented in Fig. 1.

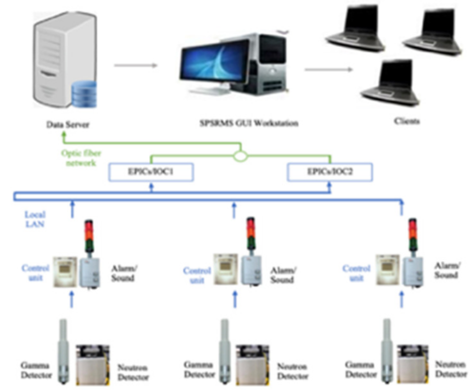

Figure 1: Architecture of SPSRMS-II 1.2 GeV facility.

Reliability Analysis

The reliability diagram of SPSRMS-II is shown in Fig. 2. After the improvement was implemented, the reliability raises from 99.9197 percent to 99.9226 percent. It means that additional devices, such as EPICS IOCs, improve the design's reliability. EPICS IOCs are enormous systems that must be able to transport and store large amounts of data, as well as be dependable and fail-safe. The presence of redundancy in the system confirmed by Ding et al. (2017) could increase the reliability of the system [11].

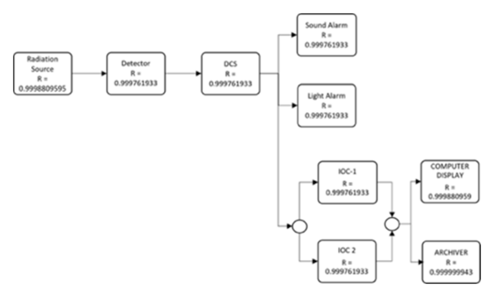

Figure 2: Reliability diagram SPSRMS-II design.

Event Tree Analysis (ETA)

The electricity blackout event was used to analysis in the scenario. Figure 3 shows the structure of the event tree used for identifying RAMS design associated with the case of electricity blackout. The success or failure of the applied monitoring system device has been identified on the top of each branch of the event tree as either "S" for the success event or "F" for the failure event.

The alphabets from A to J are the sequence of the devices in SPSRMS-II design including the path probability of success shown in Table 2. First, for the electricity blackout event, it was calculated assuming that there are 6 events (6 days) of blackouts during the operation time (365 days). Then, the frequency of initial event (I) of the blackout was 0.016438 failure/year ($f_{blackout}$= 6/365= 0.0164384). The probability of instruments functioning (success) during the blackout was noted by P1. It is P (ABCDEFG | electricity blackout) = $(PS_A)(PS_B)(PS_C)(PS_D)(PS_E)(PS_F)(PS_G)$ = 0.999880959. Therefore, the frequency of the event can be

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calculated by multiplying the frequency and probability of the event. For example, P1 has a frequency of failure (f1) of 1.64227 x 10^{-2} failure/year ($f1=f_{blackout}$ x P1).

Table 2: SPSRMS-II Designs Device and Probability

System	Devices	Probability
A	Radiation Source	0.999880959
B	Detector	0.999761933
C	Data Control System	0.999761933
D	Sound Alarm	0.999999943
E	Light Alarm	0.999999433
F	EPICS IOCs-1	0.999761933
G	EPICS IOCs-2	0.999761933
H	Data/Computer Display	0.999880959
I	Data Server/Archiver-1	0.999761933
J	Data Server/Archiver-2	0.999761933

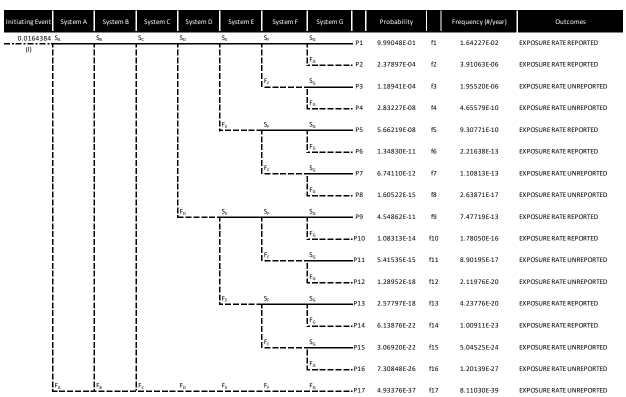

Figure 3: ETA (for electricity blackout) RAMS design.

The RAMS design resulted in the probability of the radiation monitoring failing to report the radiation exposure was 4.933765 x 10^{-37} (f=8.11029 x 10^{-39} failure/year). By using the same step calculation of ETA for the SPSRMS-II design, the probability of failure was decreased to 1.2176 x 10^{-69} (f=2.0015x10^{-71} failure/year). In this study, the presence of EPICS IOCs resulted in a decrease in the failure frequency system the new design reported the radiation exposure rates immediately. Additionally, the redundancy technique was also affecting the decrease of the failure frequency [11].

SIF/SIL Classification

Based on the calculating result of PFDavg, the initial event of blackout in the failure of radiation monitoring design both ARMS and SPSRMS-II design showed in SIL-4. This study resulted higher SIL than previous research by Rao et al (2012) in high-energy electron facility [12]. The proposed design was not changing the SIL; however, the probability and frequency of the event was decreased. According to Gabriel et al (2018), ETA or risk graph was classified in SIL determination and calcination as a simple method and practically cost effective [13].

CONCLUSION

The result showed that the probability of failure of radiation monitoring systems failed to present the radiation exposure rate was 4.933765x10^{-37} (f=8.11029x10^{-39} failure/year) in the RAMS design decreased to 1.2176x10^{-69} (f=2.0015x10^{-71} failure/year) in the SPSRMS-II designs. It is considered that the electricity blackout as the initial event of the scenario yielded SIFs with a SIL-4. It revealed that the safety reliability analysis using an event tree model is an effective tool for assessing and quantifying possible consequences, as well as proposing solutions for unpredictable environmental circumstances like unreported radiation exposure rates.

ACKNOWLEDGEMENTS

This research is supported by Science, Research, and Innovation Fund (SRI fund) in the fiscal year 2022. The authors gratefully acknowledge support from Synchrotron Light Research Institute (Public Organization). We are grateful to thank the SLRI safety division and colleges for supporting this project.

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